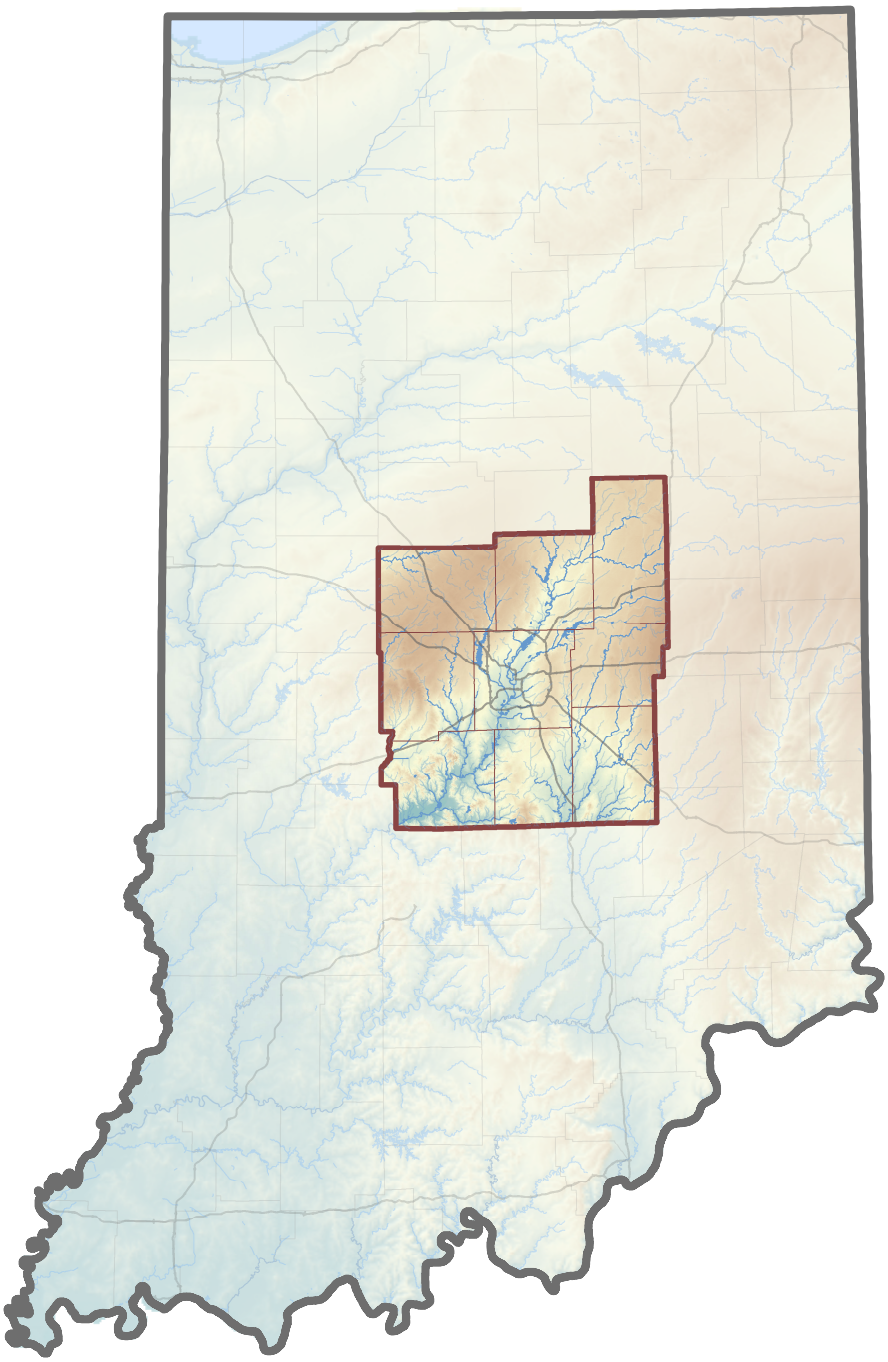
Central Indiana Water Availability



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Central Indiana Water Study

Phase III: Water Availability

Prepared for the Indiana Finance Authority

Prepared by



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Pursuant to Senate Enrolled Act 416 and the State of Indiana's Water Infrastructure Task Force Final Report (dated November 9, 2018), the Indiana Finance Authority has begun to undertake a series of studies to identify water infrastructure needs and solutions, specific to regional areas of the State, as well as efficiencies to be gained through regional partnerships and improved sharing of resources.

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Executive Summary

This technical report presents results of Phase III of the Central Indiana Water Study: the development and results of a water-availability model for the Central Indiana region, including Marion County and the surrounding 8 counties, are presented. Water availability is the combined output from surface water (river and reservoir) and groundwater sources. The model is data driven, based on water withdrawals, return flows, and streamflow records assembled from state and federal databases. The model has a quarterly temporal resolution, and was used to identify spatial and temporal variations in water availability in the Central Indiana region from 2007-2017. The model was combined with the results of the Phase I Demand Study (IFA, 2020) to predict water availability in the year 2070. Critical sub-basins with current deficits in water availability have been identified, and the effects of future demands on those deficits have been assessed. In addition, an assessment of regional water quality based on existing data, and an assessment of groundwater accessibility based on groundwater flow modeling, have been made.

A companion synthesis report that combines and explains the results of the Phase I (Water Demand) and Phase III (Water Availability) studies in non-technical language is available (IFA, 2021).

Current Water Availability

Water availability throughout the Central Indiana region is limited by seasonal low flows that usually occur in the late summer and fall (Quarter 3 and 4). Temporal variations in water demand and returns at wastewater treatment plants are also characterized by relatively large withdrawals and relatively low returns during late summer. Therefore, late summer (Quarter 3) is defined as the critical period for evaluating water availability in the Central Indiana region. Throughout the region, water availability in the driest months depends largely upon the discharges from permitted wastewater treatment plants upstream. Discharge from wastewater treatment plants is as important to maintaining availability as is the natural baseflow.

The Central Indiana region is divided into three (3) major drainage systems, each of which is further divided into sub-basins to analyze spatial variations in water availability. The three major drainage systems include tributaries of the Wabash River, the East Fork White River and tributaries, and the White River and tributaries. Although all four seasons are characterized in this study, excess water availability in a sub-basin is defined by the minimum, Quarter 3, excess availability in million gallons per day, that occurred in the period 2007-2017. A negative value is referred to as a deficit in excess water availability, or simply a deficit.

Deficits in excess water availability in the East Fork White River drainage system are driven by low natural baseflows in streams, and moderate Quarter 3 withdrawals for irrigation. Sub-basins within the tributaries of the Wabash River drainage system are also characterized by low natural baseflow, but there are no deficits in excess water availability from 2007-2017. Deficits in

the White River drainage system are characterized by locally large water withdrawals for public supply and power generation, focused in Marion and Hamilton Counties. Similarly large return flows occur at major wastewater treatment plants, with large withdrawals and returns typically occurring in adjacent basins. Regions with significant deficits in excess availability include Sub-basin 5 (Noblesville through Nora region), and Sub-basin 8 (Indianapolis region). Sub-basin 5 in Hamilton County has a deficit of 37 MGD, due primarily to extreme summer demands for public supply, low summer return flows at wastewater treatment plants, and dewatering of two major quarries. Sub-Basin 8 in Marion County includes large withdrawals for public supply and has a deficit of 54 MGD; major return flows from the Belmont Advanced Wastewater Treatment Plant occur in the adjacent downstream sub-basin (11), which is characterized by large excess availability.

Excess water availability varies between sub-basins, with both positive (excess) and negative (deficit) values. Excess in upstream sub-basins can be used to offset deficits in downstream sub-basins. This is quantified as a cumulative excess availability for a sub-basin, which depends on excess availability in all upstream sub-basins. Minimum, Quarter 3, cumulative excess availability has been positive throughout the period of record, 2007-2017, in each of the three major drainage systems. This highlights the reliance of sub-basins with deficits on excess availability from upstream sub-basins to meet demands.

Future Water Availability

The Phase I Demand Study (IFA, 2020) predicts an increase in water withdrawals of 111 MGD by 2070, with the largest increase predicted in the public supply sector. In general, throughout the region, large increases in withdrawals for public supply will be offset by similar increases in return flows at wastewater treatment plants; water may be withdrawn in one sub-basin and returned in another, but there is little change in cumulative excess water availability. For example, large projected increases in withdrawals for public supply in Marion County are offset by large increases in return flows at Belmont and Southport Advanced Wastewater Treatment Plants downstream.

Hamilton County, the fastest growing region in terms of water demand, is the exception. In this region, the relationship between public supply withdrawals and return flows at wastewater treatment plants is unique, and the deficit in water availability is expected to grow substantially in the future to 61 MGD.

In Marion County, Citizens Energy Group has been expanding future water availability for their service areas to allow for growth, increased resiliency, and less reliance on excess availability in upstream sub-basins. In particular, Citizens Reservoir will increase future water availability by up to 30 MGD. Combined with other recent infrastructure projects, Citizens has increased future water availability by a total of 56 MGD.

Minimal population growth and therefore small increases in withdrawals for public supply are expected in the two other major drainage systems: tributaries of the Wabash River and

East Fork White River and tributaries.

Water Quality

The water quality issues faced in the Central Indiana region are typical of most suburban to urbanized settings. Ambient groundwater quality in the Central Indiana region is well-characterized by the ongoing statewide monitoring activities conducted by the Groundwater Section of IDEM. The assessment of regional groundwater quality, based on current IDEM data, does not limit the potential sources for groundwater supply for a large water utility. The studies of ambient groundwater quality prepared by IDEM (2016), and summarized in this report, provide guidance for identifying or eliminating potential sources for smaller utilities and domestic supplies, where standard treatment costs may be prohibitive.

Groundwater contamination from historic contaminant releases poses a larger threat to groundwater supply, accessibility and availability in the Central Indiana region than ambient conditions. An inventory of potential contaminant sources suggests that impacts to groundwater availability are primarily of concern in Marion County, where many potential and actual contamination sources exist. Contaminant plumes are monitored and tracked through individual state and federal enforcement actions, but there is currently no way to readily access and map all plume data to determine regional impacts to water availability. The potential contaminant source mapping alone accounts for over 11% of the surface area of the outwash deposits in Marion County, which are the primary source of groundwater supply in the county. Substantially more area is covered by known contaminant plumes, but those areas remain un-mapped on a regional scale. No changes in the water availability model were made to account for historic contaminant releases. Any historic contaminant releases must be dealt with on a case-by-case basis, with detailed site investigations, to determine the actual impacts on groundwater availability.

An overview of surface water quality in the region is provided by the current federal 303(d) listing of impaired waterways, which shows most major rivers and streams in the region to be impaired by a large range in chemical, bacterial, and biological parameters. As wastewater treatment plant effluent is indirectly used for water supplies throughout the region, compliance with water quality requirements for wastewater plant effluent is necessary for maintaining and improving surface water quality and providing downstream potable water supplies.

Groundwater Accessibility

Groundwater flow modeling confirms that groundwater production is limited by existing groundwater infrastructure, even in sub-basins where future excess availability exceeds projected demands. Modeling indicates that locally, groundwater supplies can be increased significantly over current use, but more detailed field testing must be conducted to accurately assess the maximum yield from the outwash aquifer. Detailed modeling in Hamilton County shows that

existing infrastructure can support groundwater production at higher rates than currently demanded, but falls short of projected 2070 demands; new wellfields will be required to meet future demands. The detailed study of Hamilton County also confirms the importance of the Martin Marietta mines on water availability and groundwater accessibility. A more thorough understanding of the mining operations, active lifespan, and water use are needed to improve predictions of future groundwater conditions in the region.

Recommendations

The study shows that water withdrawals in the Central Indiana region are occurring near the limit of water availability. Both tributaries of the Wabash River and the East Fork of the White River and tributaries drainage systems have small excess and cumulative excess availability, due to naturally low baseflows. Expanding water supplies in those regions in a sustainable and resilient fashion will be difficult.

In the White River and tributaries drainage system, large centers for water withdrawal include Hamilton and Marion Counties. In the past, adequate water supplies in those regions have depended on excess water availability from upstream sub-basins. Citizens Energy Group has been proactive in increasing water accessibility and availability for resiliency, future growth, and decreased reliance on upstream excess water in their service areas in Hamilton and Marion Counties. Further measures to increase the resiliency of the regional public supply and to allow for growth are recommended. The following recommendations focus on changes to the regulatory framework to monitor water availability, methods for increasing the resiliency of the current water supply, and allowing for growth in the region.

1. Changes to the Regulatory Framework Changes to the regulation of water withdrawals are recommended to improve the State's ability to assess water availability regionally, and to focus monitoring on critical regions where water availability is known to be inadequate. The following changes are recommended:

- Improvements to data management and quality control
- Annual updating of water availability
- Additional reporting requirements for major water users, such as quarries
- Define instream flows
- Develop database of known contaminant plumes

2. Regional Collaboration of Public Water Suppliers We have shown that managing drought conditions in 2012 in the White River drainage system required excess upstream water to be available for use in downstream sub-basins with water deficits. This represents an unofficial form of regional collaboration. An organized regional collaboration of water users would

strengthen the resiliency of the regional water supply. Collaboration could include utilities sharing information regarding real-time water use and returns, short-term forecasts, transfers of water supplies between utilities, and system improvements. Collaborator input and regional impacts should be considered when planning and implementing any significant changes to a water supply system. Further it has been shown that return flows from wastewater treatments are an integral part of excess and cumulative water availability in the region. Organized collaboration between major wastewater treatment plants and water utilities would be beneficial in water-supply planning.

3. Water Conservation The water deficit in the region along the White River extending from Noblesville to Nora (Sub-basin 5) is exacerbated by the relationship between Quarter 3 withdrawals and return flows in the sub-basin: the average ratio of return flows at wastewater treatment plants (23 MGD) to public supply withdrawals (50 MGD) is 0.46, which is significantly smaller than other regions. There is an average of 27 MGD that is withdrawn for public supply, but not returned at wastewater treatment plants, suggesting that it is used for lawn watering. Water conservation measures, either voluntary or mandatory, could be implemented within a Water Management District during a declared drought. In 2012, Citizens Water reduced demand by up to 31% (Citizens, 2013) using a combination of voluntary and mandatory restrictions on lawn watering.

4. Invest in Increasing Water Availability Three methods are available for increasing water availability in the Central Indiana region. These include increasing surface water storage capacity, developing short-term emergency groundwater supplies that draw from groundwater storage, and importing a supply from outside the region.

5. Closely Monitor Climate Change A major uncertainty about future water availability is the impact that climate change will have on streamflow and baseflow in the Central Indiana region. While increased precipitation in the last decade has resulted in increasing streamflow and baseflow, it is unclear whether this trend will continue into the future; available watershed studies that consider climate change provide conflicting results. Natural streamflow and natural baseflow in the region should be monitored and evaluated annually for trends.

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Acronyms and Abbreviations

CCIA Climate Change Impacts Assessment

Central Region Central Indiana Water Supply Planning Region

cfs cubic feet per second

CGM Conceptual Geological Model

CHPS Community Hydrologic Prediction System

Collaborative Central Indiana Drinking Water Collaborative

CREAT Climate Resilience Evaluation and Awareness Tool

CSO Combined Sewer Overflow

DEM Digital Elevation Model

EPA U.S. Environmental Protection Agency

ECHO Environmental Compliance History Online

ET Evapotranspiration

GCM Global Climate Model

GFLOW computer program for modeling groundwater flow

gpd gallons per day

HUC Hydrologic Unit Code

IDEM Indiana Department of Environmental Management

IDNR Indiana Department of Natural Resources

IFA Indiana Finance Authority

IGWS Indiana Geological and Water Survey

iLITH Indiana lithological data set

INAWC Indiana American Water Company

IPL Indianapolis Power and Light

IU Indiana University

IWBN Indiana Water Balance Network

MAE Mean Absolute Error

MCL Maximum Concentration Limit

MGD million gallons per day

MODFLOW computer program for modeling groundwater flow

MWBM Monthly Water Balance Model

NAWQA National Water Quality Assessment Program

NLCD National Land Cover Database

NOAA National Oceanic and Atmospheric Administration

NPDES National Pollutant Discharge Elimination System

NWIS National Water Information System

PART computer program for separating baseflow from streamflow

PCS Potential Contaminant Source

PET Potential Evapotranspiration

RCP Representative Concentration Pathway

Region Central Indiana Water Supply Planning Region

RMSE Root Mean Squared Error

State State of Indiana

Study Central Region Water Study

SWAT Soil and Water Assessment Tool

SWB Soil Water Balance Model

SWWF Significant Water Withdrawal Facility

USACE United States Army Corps of Engineers

USGS United States Geological Survey

VFLUX signal processing software for analysis of temperature profiles

VOC Volatile Organic Compound

WWTP Wastewater Treatment Plant

Glossary

A

alluvium: A general term for clay, silt, sand, gravel or similar unconsolidated detrital material, deposited during comparatively recent geologic time by a stream or other body of running water, as a sorted or semi sorted sediment in the bed of the stream or on its floodplain or delta, as a cone or fan at the base of a mountain slope.

aquifer: A body of rock or sediment that is sufficiently porous and permeable to store, transmit, and yield significant or economic quantities of groundwater to wells and springs.

B

baseflow: The portion of streamflow derived from groundwater discharge to the stream.

C

capture: Pumping an extraction well "captures" water in a zone around the well. Extraction wells can be used to remove contaminated groundwater for treatment and further disposition. Using multiple extraction wells can improve capture of groundwater because of the additive effects on the drawdown of hydraulic head.

capture zone: The area contributing to flow to a well. The shape of the capture zone depends on the average linear ground-water velocity, the rate at which the well is being pumped, the hydraulic conductivity of the aquifer, and the presence of hydraulic boundaries.

conductance: In MODFLOW, conductance is the coefficient that relates the rate of vertical groundwater flux to the head difference between a stream and the underlying model layer.

D

dewatering: The removal of surface waters or groundwater by pumping to facilitate excavations for construction or mining.

discharge: The volume of water that passes a given location within a given period of time.

drawdown: The vertical distance the water elevation is lowered or the reduction of the pressure head due to the removal of water.

E

evapotranspiration: The process by which water is transferred from the land to the atmosphere by evaporation from the soil and other surfaces and by transpiration from plants.

excess water availability: A measure of the water remaining in a basin that could be used for expansion of public supplies, industry, or agriculture without jeopardizing instream flows.

extraction well: An extraction well uses a pump to pull water from a vertical (or occasionally from a horizontal) interval screened in the saturated zone, moving the water to the surface for further disposition (e.g., treatment, beneficial use, etc.).

G

groundwater: Water that occurs beneath the land surface and fills the pore spaces of the alluvium, soil, or rock formation in which it is situated. It excludes soil moisture, which refers to water held by capillary action in the upper unsaturated zones of soil or rock.

H

hydraulic conductivity: A measure of the capacity for a rock or soil to transmit water; generally has the units of feet/day or cm/sec.

hydraulic head: The height above a datum plane (such as sea level) of the column of water that can be supported by the hydraulic pressure at a given point in a groundwater system. Elevation to which groundwater will or does rise in a well or piezometer connected to a point in the groundwater domain. It is a time-dependent variable, varies from point to point within the groundwater domain, and indicates the potential energy of groundwater in any point considered.

I

indirect water reuse: The blending of treated or reclaimed water into a natural water source, such as a river or stream, and the subsequent use of that water as a potable supply.

induced infiltration (induced recharge): Pumping from wells adjacent to rivers or lakes that results in river/lake bed flow to the adjacent aquifer.

infiltration: The flow of water downward from the land surface into and through the upper soil layers.

instream flow: A minimum flow that is retained in a stream to protect ecological health, recreational use, and water quality.

intake: A structure facilitating a surface-water withdrawal.

irrigation: The controlled application of water for agricultural purposes through man-made systems to supply water requirements not satisfied by rainfall.

L

lithology: The description of rocks, especially in hand specimen and in outcrop, on the basis of such characteristics as color, mineralogic composition and grain size.

M

monitoring well: A well designed for measuring water levels and/or testing ground-water quality.

N

natural baseflow: The portion of natural streamflow derived from groundwater discharge to the stream.

natural streamflow: The streamflow that would be measured if anthropogenic effects of surface-water and groundwater withdrawals and return flows were eliminated.

O

outfall: The place where a sewer, drain, or stream discharges; the outlet or structure through which reclaimed water or treated effluent is finally discharged to a receiving water body.

outwash: Deposit of sand and gravel carried by running water from the melting ice of a glacier and laid down in stratified layers.

P

parts per billion: The number of " parts" by weight of a substance per billion parts of water. Used to measure extremely small concentrations.

parts per million: The number of " parts" by weight of a substance per million parts of water. This unit is commonly used to represent pollutant concentrations.

pathlines: Pathlines represent a historical travel log of the groundwater particles. Backward tracking pathlines are used to predict where groundwater at a given location and time is coming from, and how long it took to get there.

piezometer: Device or well, generally of small diameter, that is designed to measure the potential energy level in a point of a water body (stream, lake, aquifer, aquitard, etc.).

porosity: A measure of the water-bearing capacity of subsurface rock. With respect to water movement, it is not just the total magnitude of porosity that is important, but the size of the voids and the extent to which they are interconnected, as the pores in a formation may be open, or interconnected, or closed and isolated. For example, clay may have a very

high porosity with respect to potential water content, but it constitutes a poor medium as an aquifer because the pores are usually so small.

R

recharge: Water added to an aquifer or the process of adding water to an aquifer. Ground water recharge occurs either naturally as the net gain from precipitation, or artificially as the result of human influence.

resistance: In GFLOW, streambed resistance is the coefficient that relates the rate of groundwater discharge to a stream to the difference in hydraulic head between the stream and the underlying aquifer. Resistance, c, is equal to the thickness of the streambed sediments divided by the vertical hydraulic conductivity of the sediments, and has units of time.

return flow: Discharge to surface waters from facilities permitted by the NPDES program, such as wastewater treatment plants.

S

stormflow: The portion of streamflow derived from surface runoff, and excluding baseflow.

stratigraphy: The science of rocks: it is concerned with the original succession and age relations of rock strata and their form, distribution, lithologic composition, fossil content, geophysical and geochemical properties.

streamflow: The flow of water in a stream or river, commonly measured at a USGS station.

sub-basin: A portion of a watershed defined by the drainage region between a downstream USGS station and one or more upstream USGS stations.

surface water: Water supply obtained from streams, lakes, and reservoirs.

T

till: Unsorted sediment deposited directly by glacial ice and showing no stratification.

time-of-travel: The time required for ground water to move from one point beneath the surface to another.

transmissivity: The product of hydraulic conductivity and aquifer thickness; a measure of a volume of water to move through an aquifer. Transmissivity generally has the units of ft^2/day or gallons per day/ ft. Transmissivity is a measure of the subsurface's ability to transmit groundwater horizontally through its entire saturated thickness and it affects the potential yield of wells.

U

unconsolidated: A sediment that is loosely arranged or unstratified, or whose particles are not cemented together.

W

water availability: The portion of the natural baseflow remaining in a stream after instream flow requirements and reservoir releases are accounted for.

water budget: An accounting of water moving into, out of, and accumulating within a given region.

watershed: A land area that channels rainfall and snowmelt to creeks, streams and rivers, and eventually to an outlet point, such as a USGS station.

1 Introduction

The State of Indiana (State) has designated the Indiana Finance Authority (IFA) to coordinate water-related investigations to identify the water infrastructure needs and solutions for specific regions of the State. The Central Indiana region was defined as a critical area for water planning. The goal of the Central Indiana Water Study (Study) is to provide a better understanding of the water resources, both water demand and water availability, in this area. The objective of the Study is to aid in the management, economic development and environmental health of the Central Indiana region. The Study has been subdivided into five phases:

Phase I. Regional Demand

Phase II. Regional Supply

Phase III. Water Availability Modeling

Phase IV. Infrastructure and Cost Analysis

Phase V. Public Education and Outreach

This report is the Phase III assessment of water availability. Current and future water availability in the region are assessed and quantified, based on hydrologic studies and results of the Phase I regional demand study (IFA, 2020).

The water supply used in the Central Indiana region serves almost 30% of the population of the State and comes from diverse sources including withdrawals from the West Fork of the White River, storage in reservoirs, and groundwater from shallow and deep aquifers. The central portion of the state was chosen for evaluation because a group of water utilities has already organized and meets regularly to discuss their water supply, treatment, and regulatory issues. This group of utilities known as the Central Indiana Drinking Water Collaborative (Collaborative), conducts regular meetings to share information. The boundaries of the Collaborative region are the same as the Central Indiana Water Planning Region and include nine (9) counties centered around Indianapolis: Boone, Hamilton, Hancock, Hendricks, Johnson, Madison, Marion, Morgan, and Shelby counties (Figure 1.1).

It is important to assess potential limitations on the future growth of the Central Indiana region. The assessment of water availability presented here focuses on potential limits to the regional water supply. An assessment of available water typically includes estimates of seasonal and annual variability in hydrologic conditions with seasonal variation in water demands. The assessment may consider normal demands and average hydrologic conditions, or more extreme conditions representative of drought. In all cases, the data on which an assessment is based, both hydrological and water-use data, varies in quality and availability. Standard methods for availability assessments require standardized data, which is most often not available. Therefore, ad-hoc approaches to assessing water availability are common; the approach chosen depends on the local data availability and the quality of the data.

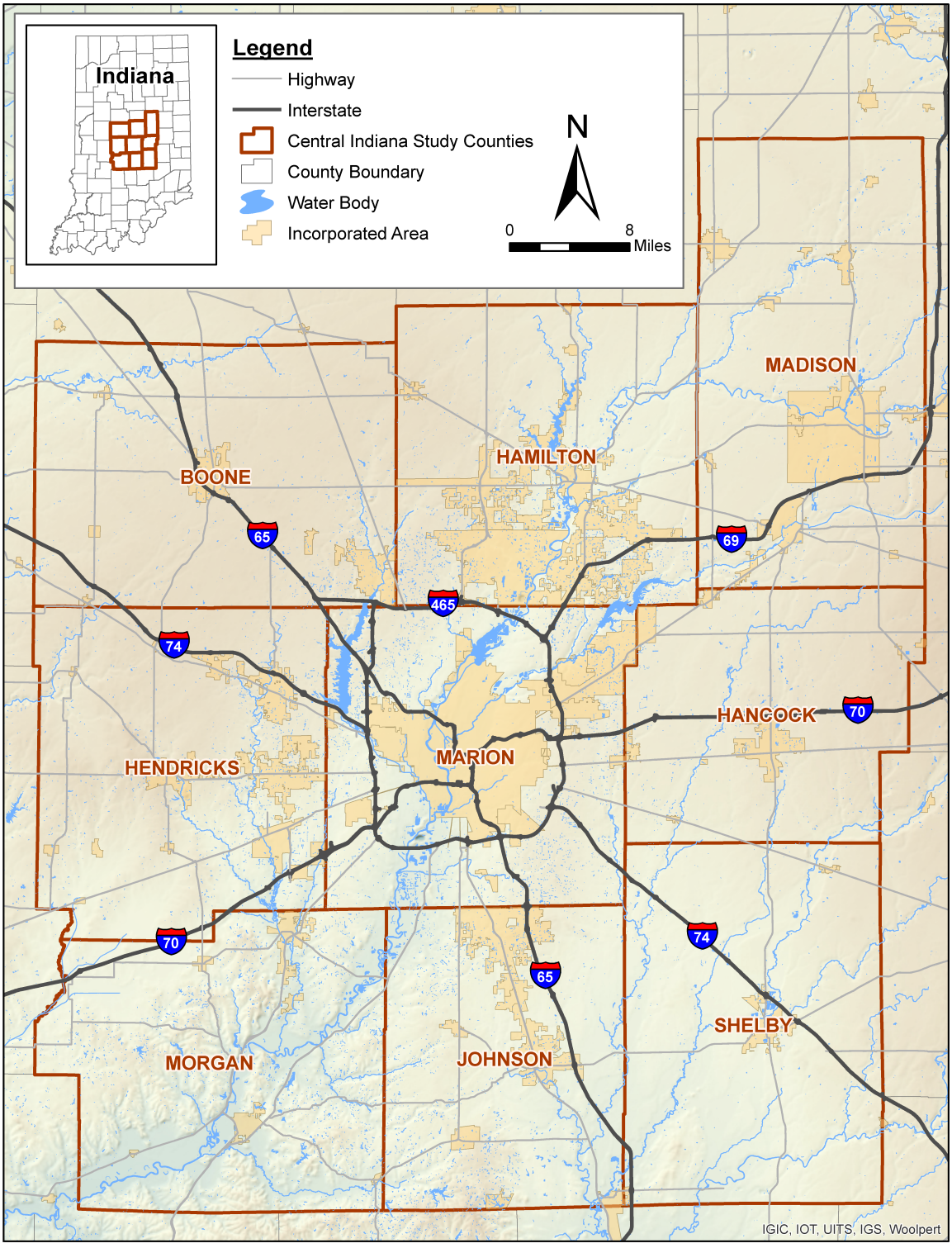

Figure 1.1: Central Indiana Water Planning Region. *Approximate population of 1.93 million people, nearly 30% of the total population of Indiana (2015) (Census, 2010). Central Region includes the following nine counties: Boone, Hendricks, Hamilton, Hancock, Johnson, Madison, Marion, Morgan, and Shelby.*

In the Central Indiana region, more geologic, hydrologic and water-use data is available than ever, and a standardized framework for assessing regional water availability is now possible. Data pertinent to water availability is collected and maintained by a multitude of state and federal agencies and research institutions:

- The Indiana Department of Natural Resources (IDNR) is responsible for the registration of significant water-withdrawal facilities (SWWF) and requires annual reporting of withdrawals, specified by month, by each registered facility; the withdrawal data form the basis for the Phase 1 study of demand, and represent a significant component of the regional water budget. A database of water withdrawals from 1985 to 2018 has been created for our work.

- The local United States Geological Survey (USGS) office in Indianapolis and the USGS Kentucky Water Sciences Center provides real-time monitoring of streamflow and groundwater levels in Indiana. The monitoring network for both streamflow and groundwater levels has been strategically extended as part of this study, to enhance our understanding of the hydrologic system in the Central Indiana region. Daily records from long-term monitoring of streamflow at 25 USGS stations are an essential component of the water-availability model presented here.

- The Indiana Department of Environmental Management (IDEM) is responsible for collecting and maintaining groundwater and surface-water quality data, and for administering the National Pollutant Discharge Elimination System (NPDES) program on behalf of the US Environmental Protection Agency (US EPA); NPDES records of discharge monitoring provide data representing a significant component of the water availability model.

- The Indiana Geological and Water Survey (IGWS) operates the Indiana Water Balance Network, which includes four networked stations within the Central region and an additional four sites in adjacent watersheds. The sites are instrumented to monitor meteorological and environmental conditions and to track trends in water gains and losses. The IGWS also maintains the iLITH database of water-well records, in cooperation of the IDNR, which contains location and lithological information about wells in Indiana. The iLITH data set was used here extensively in developing a geological model of the Central region.

- Purdue University hosts the Indiana Climate Change Impacts Assessment (IN CCIA) Climate Working Group. Collaborators include University of Notre Dame, Ball State University, and Indiana University, as well as over 30 other participating organizations. The working group organizes, develops, and disseminates climate change information throughout the State.

Much data provided by these stakeholders has been integrated into this study. The result is a

framework for water availability assessment that is flexible enough to be modified and improved as new hydrologic data, water-use data, and climate-change projections become available.

1.1 Water Availability, Accessibility, and Quality

There are three considerations in any water supply study: first, we must quantify excess available water which can be used to expand a supply; second, we must determine if the available water is accessible by economically feasible methods; and third, we must determine if the available water is of adequate quality.

Quantifying water availability begins with an understanding of current water use, based on water withdrawal or water demand records. Phase I of the Central Indiana study investigated water use in the region; we make use of that work here in assessing current and future water availability in the region. Assessing current water use is a well-defined problem limited only by the water use data that is available. Indiana has a robust system in place for tracking water withdrawals.

An evaluation of hydrological conditions, which is the focus here, is often more difficult than assessing water use; hydrologic conditions vary seasonally and annually and that variability must be incorporated in the analysis. Hydrologic data can be sparse or missing. A wide array of hydrologic and geologic data must be coupled with a variety of model calculations to identify or estimate the components of any regional water budget. The techniques used and the interpretation of results depends on the hydrologic setting. Further, to assess future water availability, some consideration must be given to the likely effects of climate change on the hydrologic system.

An assessment of available water in the Central Indiana region must consider both groundwater and surface-water sources. The hydrologic system in the region is a combined surface water and groundwater system, with the vast majority of groundwater withdrawals occurring within a corridor of outwash sand and gravel along the major rivers. Outwash is material, typically sand and gravel, carried away from a glacier by stream meltwater and deposited. Surface water flows in major streams provide a lower bound on excess water availability at any time. The available water in excess of current water demands upstream is reflected by streamflow. The excess streamflow could be removed either by surface water intakes or indirectly by groundwater wells.

Evaluating an upper bound on excess availability requires an assessment of water withdrawals from aquifer storage. Much water is stored in the groundwater system of the Central Indiana region. Technically, this water represents excess availability that can be quantified. However, most of that stored water is not accessible by economically feasible means. To be accessible, groundwater must be stored in high transmissivity (high flow rate) formations or aquifers that can be tapped with wells. In the Central Indiana region, the outwash aquifers are the only high-transmissivity features. Groundwater is accessible in many buried sand and gravel lenses and bedrock, but the wells are significantly less productive than those in the out-

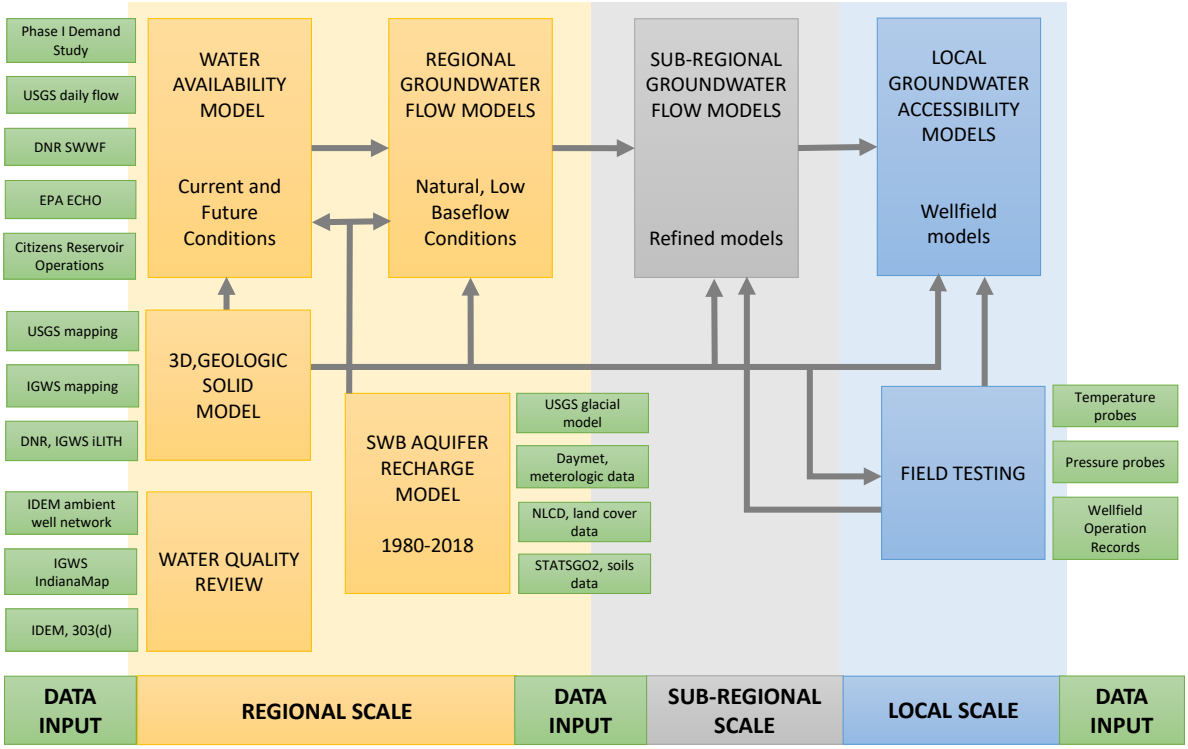

Figure 1.2: Overview of the project scope illustrating spatial scales and interconnection of results.

wash. Groundwater in the unconsolidated till overlying the buried sand and gravel is accessible only at very small flow rates. Accessibility limits the use of stored groundwater in the Central region.

Water quality impacts water availability by limiting accessible water to those that do not have poor water quality, essentially limiting the locations of groundwater withdrawals. Known contaminant sites within the outwash aquifers restricts pumping locations; regions of inorganic contaminants (chlorides, nitrates, and arsenic) restrict pumping location in the buried sand and gravel aquifers.

1.2 Approach and Context

The approach for assessing water availability, presented in this report, relies on standard hydrologic assessments, hydrologic and geologic modeling and simulation, and field testing. The study follows a nested approach aimed at identifying critical features at various spatial scales from regional to local scale. Figure 1.2 illustrates the components of the study, including primary data sources for each effort, the scale of each study component, and how the results are inter-related. Study components illustrated in the figure are described in detail in this report.

1.3 Report Framework

This report is divided into four parts, with supporting appendices. **Part I** presents a hydrologic analysis of the region, and assesses water availability in terms of existing records of streamflow, surface and groundwater withdrawals, and surface-water return flows at, for example, wastewater treatment plants. Water availability and excess water availability are defined and spatially evaluated for current and future water use throughout the Central Indiana region. Appendix A supplements the definition of excess availability and defines the various hydrologic components used in the evaluation through water budget analyses. Complete graphical results of the assessment of current excess water availability by sub-basin, and cumulative excess availability by watershed are presented in Appendix B.

Quantifying regional precipitation, infiltration, and evapotranspiration is necessary to evaluate hydrologic budgets. Appendix C presents results of a Soil-Water-Balance model (SWB) developed by the USGS, which includes the Central Indiana region. The model was adapted for use in the current study, and extended through 2018, as a database for precipitation, and to provide estimates of evapotranspiration and aquifer recharge.

Predicting future water availability requires consideration of the impacts of climate change on the hydrologic system. While there is a current consensus, based on observations and models, that climate change will increase the annual precipitation and average temperatures in Indiana, there is no consensus on how that will impact the hydrologic system, in particular stream flow and baseflow. We investigate effects of climate change on water availability by reference to existing studies.

Projections of water availability into the future are assessed, based on assumptions about impacts of climate change, Phase I predictions of future water use, and prediction of return flows at major treatment plants.

Part II presents a review and summary of existing water quality data of surface water and groundwater, illustrating water quality issues in the region. None of the reported data was collected specifically for this study. We are reporting existing data, primarily assembled by IDEM, that impact water availability.

Part III examines groundwater accessibility in the Central Indiana region. We develop regional models of groundwater flow, and use them to evaluate groundwater accessibility through the existing public supply infrastructure. Hydraulic properties of the regional model are based on existing information, and supplemented by local field studies conducted as part of this project. The regional model provides a hydrologically consistent framework for more detailed, local studies of groundwater flow. An example of how detailed local models can be developed from the regional model is provided as a case-study of the Carmel groundwater supply system.

Work in Part III relies heavily on a geologic model of the region developed for this study. The geologic model is used to define conceptual models of the outwash and buried sand and gravel aquifers, and is described in Appendix D. The geologic model provides an essential tool for integrating available geologic mapping, topography, borings and well logs with a consistent

regional framework. The model is ideal for reviewing local conditions based on existing data, and directing field exploration.

Finally, a field testing program was conducted along major streams in the region to quantify groundwater surface water interaction at sensitive locations. The testing program included installations of piezometers in stream beds, with monitoring of pressure and temperature profiles through time. Results are incorporated into the groundwater accessibility models. A description of the field testing and a summary of all results is presented in Appendix E.

Part IV summarizes the findings of this study and provides recommendations for continued monitoring of water availability and methods to increase availability in the region.

1.4 Inter-Agency Collaboration

Throughout the Phase I, Phase II, Phase III and Phase V work on the Central Indiana Water Study, monthly working group meetings were hosted by the Indiana Finance Authority, with representatives from many state and federal agencies and consultants acting as project partners. The purpose of the inter-agency meetings was to provide updates on each project phase, to coordinate efforts between phases, and to review and discuss methods and results. Regular attendees at the meetings included the following:

Indiana Finance Authority (IFA):

- Sarah Hudson, Director of Water Resources and Infrastructure Planning
- Daniel Lundberg, Project Manager

Indiana Geological and Water Survey (IGWS):

- Shawn Naylor, Director of the Center for Geospatial Data Analysis
- Robert Autio, Research Geologist

Indiana University (IU):

- Sally Letsinger, Ph.D., Research Scientist, Department of Geography

Indiana Department of Natural Resources (IDNR):

- Mark Basch, Section Head, Water Rights and Use Section, Division of Water;
- Ryan Mueller, Director, Division of Water

Indiana Department of Environmental Management (IDEM):

- Mitt Denney, Environmental Specialist, Office of Water Quality, Drinking Water Branch
- Kevin Spindler, Senior Environmental Manager,Office of Water Quality, Drinking Water Branch

United States Geological Survey (USGS):

- Jeff Frye, Deputy Director, Ohio-Kentucky-Indiana Water Science Center
- Jeff Woods, Supervisory Hydrologist, Ohio-Kentucky-Indiana Water Science Center
- David Lampe, Supervisory Hydrologist, Ohio-Kentucky-Indiana Water Science Center
- Randy Bayless, Ph.D. Groundwater Specialist, Ohio-Kentucky-Indiana Water Science Center

Empower Results:

- Jill Hoffman, Principal Owner
- Scott Minor, Senior Environmental Planner

INTERA, Inc.:

- Jack Wittman, Ph.D., VP, Principal Geoscientist
- Theresa Landewe, Senior Scientist
- Rhett Moore, PH, PE, Principal Hydrologist
- Erik Anderson, Ph.D, PE, Principal Engineer
- Oliver Wittman, PG, Geologist
- Pat Jurcek, PG, Senior Hydrogeologist

Part I
Regional Water-Availability Model

To evaluate the spatial distribution of water availability, the Central Indiana region is divided into sub-basins, and water availability is assessed for each sub-basin. ***Water availability*** for a sub-basin is defined here as the portion of the natural baseflow remaining in a stream after instream flow requirements in the sub-basin are accounted for. Instream flows are minimum stream flows required to support the ecological health of the stream, recreational use, and water quality. Water availability may be supplemented by flows released from reservoir storage:

$$\text{Sub-Basin:} \quad Q_{wa} = Q_{nbf} - Q_{if} + Q_{stor} \tag{1}$$

where

Q_{wa} is the water availability within a sub-basin, expressed in million gallons per day (MGD);

Q_{nbf} is the natural baseflow generated within a sub-basin (MGD);

Q_{if} is the portion of the instream flow requirement generated within a sub-basin (MGD);

Q_{stor} is the portion of stormflow stored in reservoirs within a sub-basin and released to supplement streamflow (MGD).

This definition states that the reliable water available for use comes primarily from natural baseflow, which is groundwater discharging to streams. A water supply may be obtained from the natural baseflow either by a surface-water intake, or by capturing groundwater with wells before it discharges to the stream. Natural baseflow varies seasonally, with relatively high flow rates in the winter and spring, and low rates in the summer and fall; thus, water availability also varies seasonally. Stormflow, or the rapid surface runoff that occurs following a precipitation event, is only useful if it can be stored in reservoirs and released to supplement streamflow during low-flow periods.

In this report, we are concerned with evaluating the ***excess water availability*** in a sub-basin, after current water use and return flows are accounted for. If the excess water availability is less than zero, then it is considered a deficit or water shortage. Excess water availability is a measure of water remaining in a basin that could be used for expansion of public supplies, industry, or agriculture without jeopardizing instream flows. Current water use includes surface and groundwater withdrawals in a sub-basin used for public supply or cooling water for energy production, for example. Flows returned to surface waters include, for example, wastewater treatment plant effluent. Impacts of other anthropogenic effects such as land-use changes through time and effects of combined sewer overflow systems (CSOs) on watershed hydrology are not considered explicitly in the analysis. We define excess availability as follows:

$$\text{Sub-Basin:} \quad Q_{ea} = Q_{wa} + Q_{rf} - Q_{ww} \tag{2}$$

where

Q_{ea} is the excess water availability within a sub-basin (MGD);

Q_{rf} is the total of all return flows occurring within a sub-basin (MGD);

Q_{ww} is the total of all surface water and groundwater withdrawals occurring within a sub-basin (MGD).

Water withdrawals and return flows also show significant seasonal variation, with the largest withdrawals for public supply occurring in the late summer, and the lowest return flows from wastewater treatment plants typically occurring at the time of peak withdrawals; both water availability and excess availability have strong seasonal variations. Equations (1) and (2) can be applied at different time-scales to investigate seasonal availability. For example, periods of low streamflow and high water use are reflected through reduced natural baseflow occurring during the summer and fall.

The definition of excess availability given by equation (2) neglects changes in groundwater stored in a sub-basin over time. In general, when investigating summer availability, neglecting changes in groundwater storage results in a conservative estimate of water availability, as the volume of water stored in these periods is typically decreasing.

There are many hydrologic calculations required to evaluate water availability. Each component of the water-availability model is described in detail below, including a description of the data sources, the methods used, and the limiting assumptions. Appendix A provides water-budget analyses that supplement the description and evaluation of the hydrologic components presented below.

2 Components of Water Availability

The natural baseflow in each sub-basin is the driving quantity for assessing water availability in the Central Indiana region. The following sections provide details on how the Central Indiana region is divided into sub-basins, and how the natural baseflow is evaluated. Important data sources and limitations of the analysis are identified. An illustration of the components of the water availability assessment in a sub-basin is provided in Figure 2.1.

2.1 Definition of Sub-Basins

Three major drainage systems in the Central Indiana region are identified, by color, in Figure 2.2. From west to east, they include: tributaries of the Wabash River, the White River and tributaries, and tributaries to the East Fork White River. USGS stream gaging stations lie at the downstream end of each region. Three stations are shown in the tributaries of the Wabash

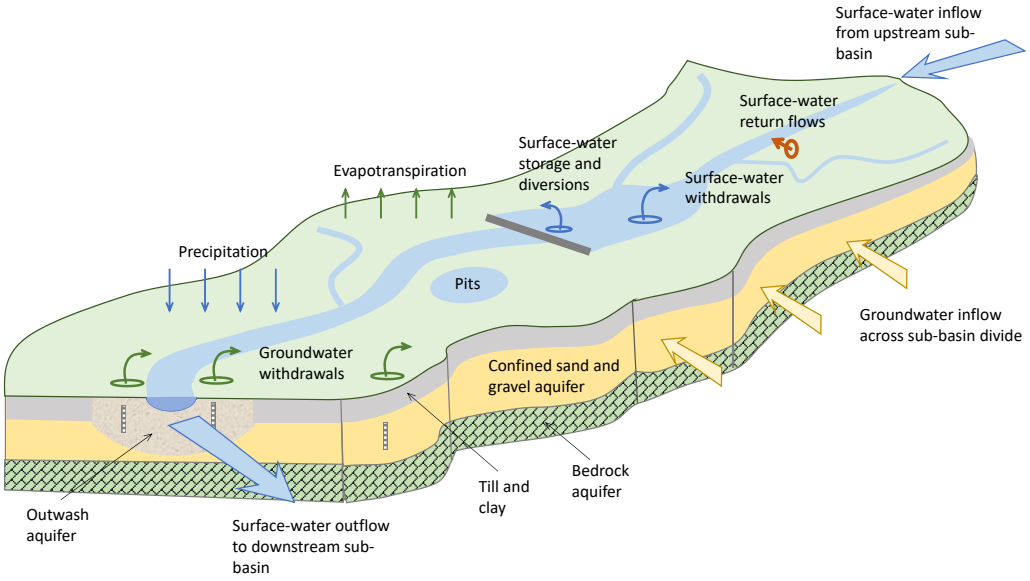

Figure 2.1: Conceptual sketch illustrating the components of water availability. *A sub-basin extends upstream from a USGS station to the watershed boundary or an upstream USGS station, and vertically to the lowest bedrock unit. Arrows indicate flow into or out of the sub-basin.*

River (03339500 Sugar Creek at Crawfordsville, 03340800 Big Raccoon Creek near Fincastle, and 03357330 Big Walnut Creek near Roachdale) while a single station lies at the downstream end of both the White River (03354000 White River near Centerton) and tributaries of the East Fork White River (03364000 East Fork White River at Columbus).

Each major drainage system is divided into sub-basins, identified in the figure by number, starting with 1 at the headwaters. Sub-basins are defined by the locations of USGS stations with daily flow records within each region. A USGS station represents the surface-water outlet for the entire upstream watershed. A single watershed often contains many other USGS stations, each of which represents the outlet of a smaller watershed lying within the larger one.

A USGS station is located at the downstream end of each sub-basin; sub-basins extend upstream from the station, terminating at a watershed divide or another USGS station. Sub-basin boundaries were developed from GAGES II data developed by the USGS (Falcone, 2011). Tables 2.1 through 2.3 identify the sub-basins in each major drainage system, the area of the sub-basin, the downstream USGS station, and the total watershed area contributing to the station. The period of record for each USGS station is also included in the tables. Schematics illustrating how the systems of sub-basins are connected are provided in Figures 2.3 and 2.4.

Figure 2.5 illustrates a single sub-basin within the White River drainage system. The location of USGS stations along the boundary of Sub-basin 5 are shown. The downstream station, where streamflow exits the sub-basin, is USGS 03351000 (White River near Nora). The two upstream stations, where streamflow enters the sub-basin, include USGS 03349510 (Cicero Creek at Arcadia) and 03349000 (White River at Noblesville).

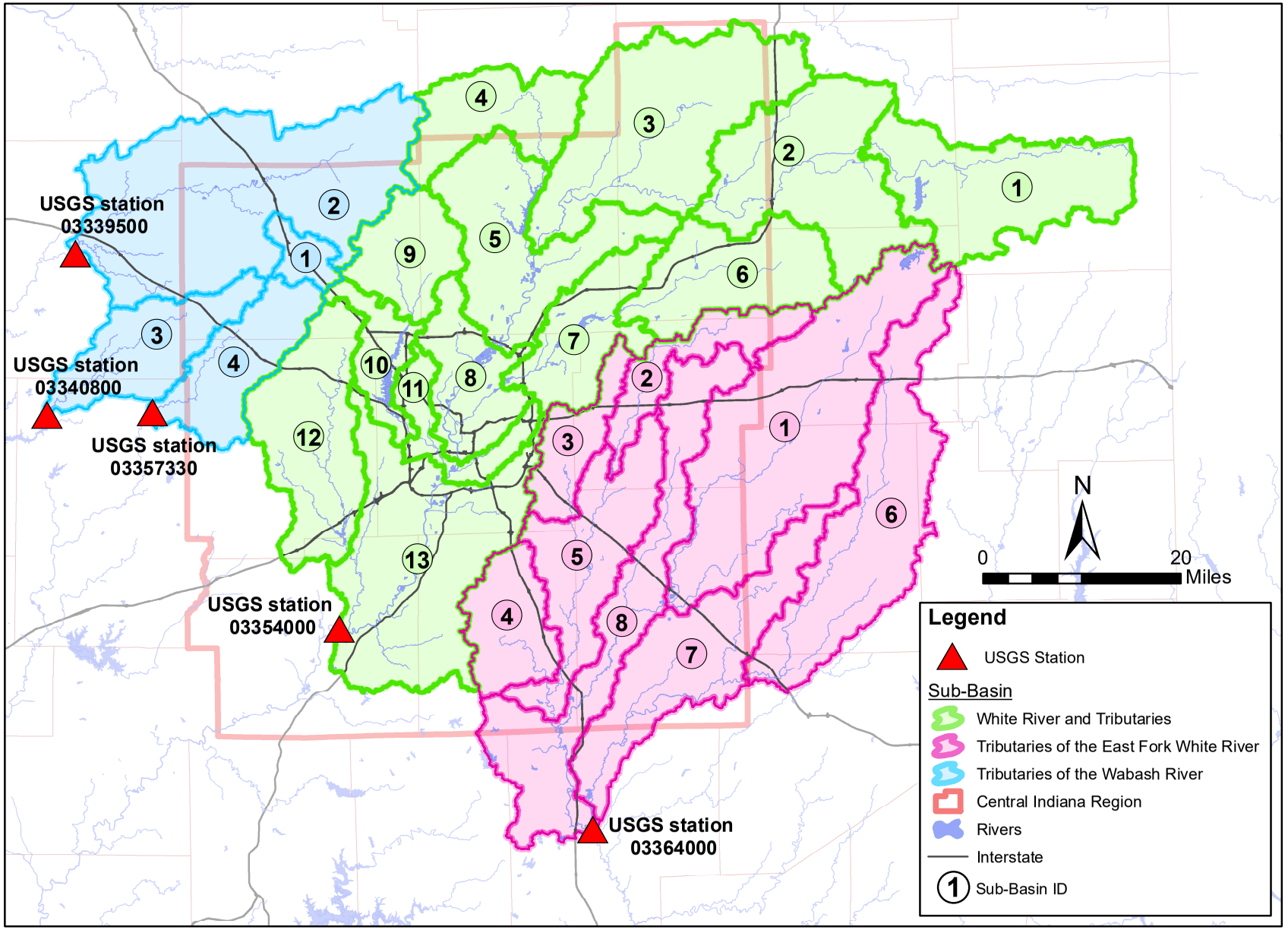

Figure 2.2: The Central Indiana region and three major drainage systems. *Each drainage system is divided into sub-basins, labeled with a number in the figure. Water availability is assessed in each sub-basin. Note that several sub-basins lie outside the Central Indiana region; they are included in the analysis as they impact the availability in the Central region.*

Table 2.1: Sub-basins in the White River drainage system.

Sub-Basin ID	USGS Station at outlet of Sub-Basin	Sub-Basin Area (mi^2)	Watershed Area (mi^2)	Period of USGS daily record
1	03347000 White River at Muncie, IN	242.1	241	1931 to present
2	03348130 White River at Raible Ave. at Anderson, IN	273.7	519	1999 to present
3	03349000 White River at Noblesville, IN	337.6	858	1946 to present
4	03349510 Cicero Creek at Arcadia, IN	131.0	131	2004 to present
5	03351000 White River near Nora, IN	231.1	1,219	1929 to present
6	03351500 Fall Creek near Fortville, IN	172.7	169	1941 to present
7	03352500 Fall Creek at Millersville, IN	129.7	298	1929 to present
8	03353000 White River at Indianapolis, IN	118.1	1,635	1904 to present
9	03353200 Eagle Creek at Zionsville, IN	105.7	106	1957 to present
10	03353500 Eagle Creek at Indianapolis, IN	68.3	174	1939 to present
11	03353611 White River at Stout Gen. Stn., Indianapolis, IN	64.5	1,898	1992 to present
12	03353800 White Lick Creek at Mooresville, IN	212.0	212	1957 to present
13	03354000 White River near Centerton, IN	355.1	2,444	1930 to present

Notes: mi^2= square miles.

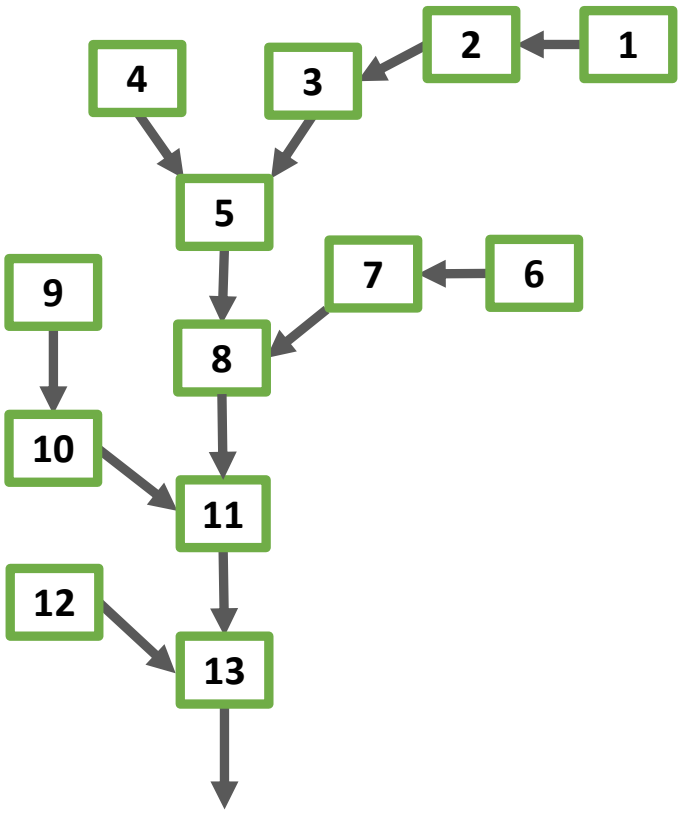

Figure 2.3: Schematic showing connections between sub-basins in the White River and tributaries drainage system.

Table 2.2: Sub-basins in the Wabash River drainage system.

Sub-Basin ID	USGS Station at outlet of Sub-Basin	Sub-Basin Area (mi^2)	Watershed Area (mi^2)	Period of USGS daily record
1	03339280 Prairie Creek near Lebanon, IN	33.3	33.2	1987 to present
2	03339500 Sugar Creek at Crawfordsville, IN	476.6	509	1938 to present
3	03340800 Big Raccoon Creek near Fincastle, IN	138.6	139	1957 to present
4	03357330 Big Walnut Creek near Roachdale, IN	131.2	131	2001 to present

Notes: mi^2= square miles.

Table 2.3: Sub-basins in the East Fork White River drainage system.

Sub-Basin ID	USGS Station at outlet of Sub-Basin	Sub-Basin Area (mi^2)	Watershed Area (mi^2)	Period of USGS daily record
1	03361500 Big Blue River at Shelbyville, IN	420.4	421	1943 to present
2	03361650 Sugar Creek at New Palestine, IN	91.4	93.9	1967 to present
3	03361850 Buck Creek at Acton, IN	78.7	78.8	1967 to present
4	03362000 Youngs Creek near Edinburgh, IN	107.2	107	1942 to present
5	03362500 Sugar Creek near Edinburgh, IN	194.2	474	1943 to present
6	03363500 Flatrock River at St. Paul, IN	300.7	303	1930 to present
7	03363900 Flatrock River at Columbus, IN	234.0	534	1967 to present
8	03364000 East Fork White River at Columbus, IN	278.7	1,707	1948 to present

Notes: mi^2= square miles.

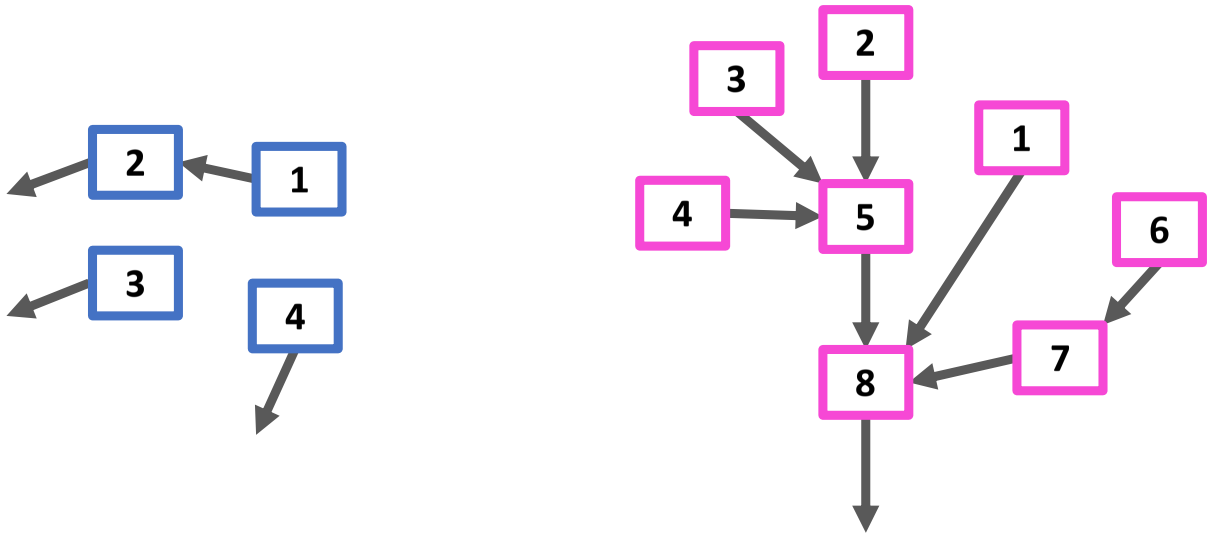

Figure 2.4: Schematic showing connections between sub-basins in the tributaries to the Wabash River *(left)* and the East Fork White River and tributaries (*right*) drainage system.

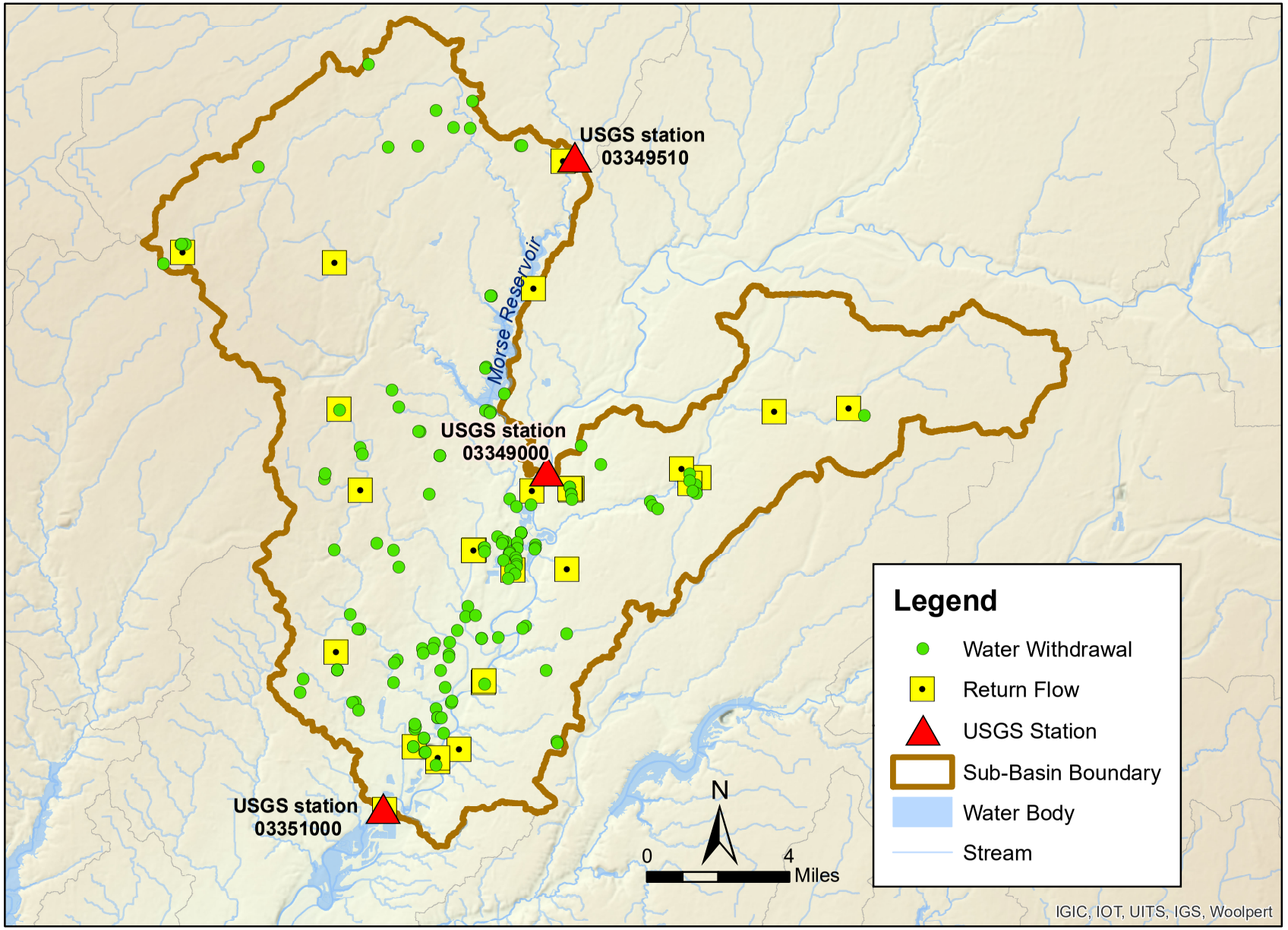

Figure 2.5: Sub-basin 5 in the White River drainage system. *The sub-basin includes downstream USGS station 03351000 (White River near Nora), and two upstream stations, 03349000 (White River at Noblesville) and 03349510 (Cicero Creek at Arcadia). Locations of water withdrawals and return flows are shown, along with Morse Reservoir.*

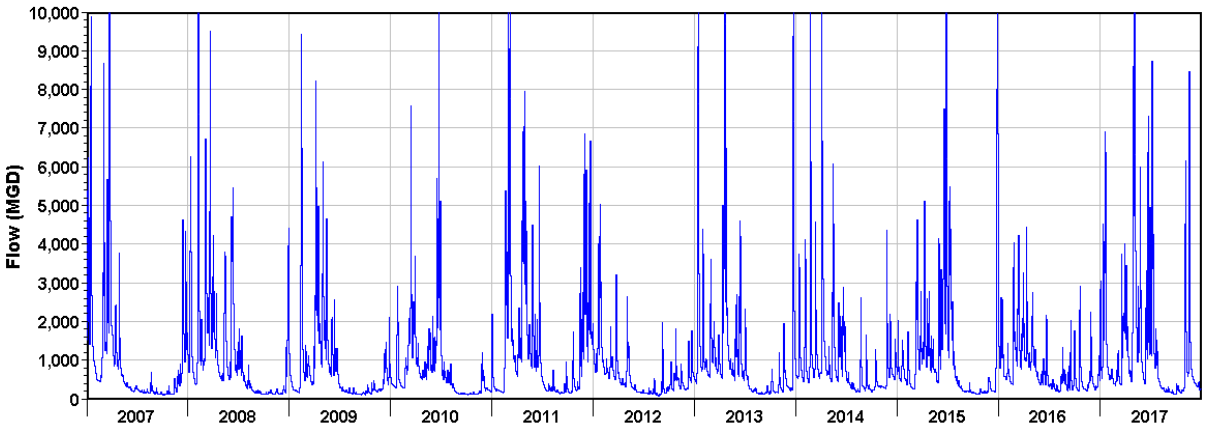

Figure 2.6: Daily flows, q_{usgs}, recorded at USGS station 03351000 (White River near Nora). *This station is the outlet for Sub-basin 5 of the White River drainage system, illustrated in Figure 2.5.*

2.2 USGS Daily Flow Records

Records of daily average streamflow at USGS stations quantify the total runoff from the upstream watershed, including surface runoff, baseflow, water withdrawals and return flows, and releases from reservoir storage. Surface runoff is comprised of overland flow that discharges to the stream directly from the land surface. Baseflow consists of groundwater discharge to the stream. The baseflow originates from the portion of precipitation that infiltrates into the ground, recharging the underlying aquifer. Return flows include, for example, effluent from wastewater treatment plants discharged to surface water. In the following analysis, the USGS daily flow record at a station is identified by the symbol q_{usgs}.

Figure 2.6 illustrates q_{usgs} for a portion of the daily flow record for the White River at USGS station 03351000 near Nora, which is the downstream station in Sub-basin 5. Daily flow records for all USGS stations used in this study were obtained from the National Water Information Service (USGS, 2020b).

2.3 Water Withdrawals

Historical water withdrawal data were obtained from the Indiana Department of Natural Resources (IDNR) Significant Water Withdrawal Facility (SWWF) database. The SWWF database contains reports, beginning in 1985, of total monthly withdrawals by water users capable of withdrawing greater than 100,000 gallons per day (gpd). Within the database, the water users are separated according to their water use category, which has an associated two-letter code. The six water use categories and associated codes within the database include: Agriculture/Irrigation (IR); Industry (IN); Public Supply (PS); Energy Production (EP); Rural Use (RU); and, Miscellaneous (MI).

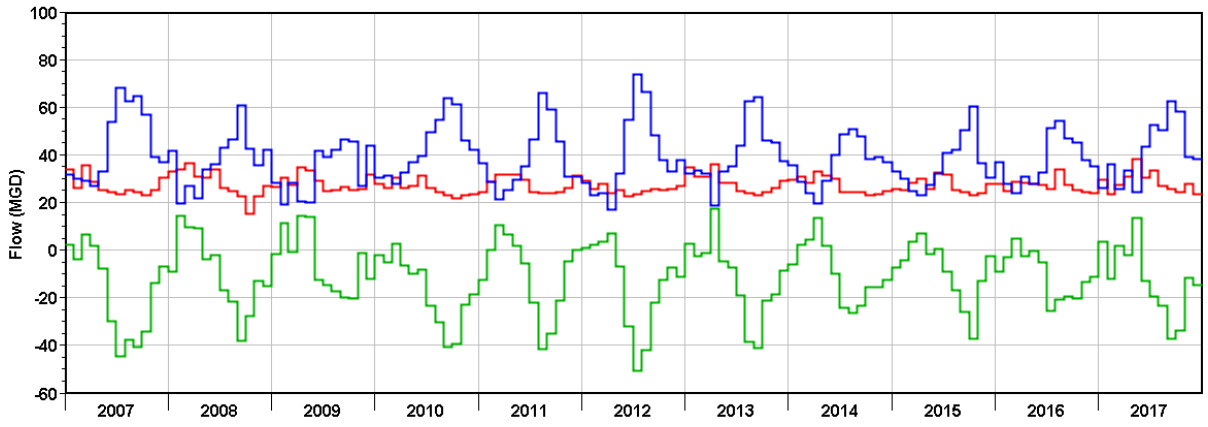

Figure 2.7: Total water withdrawals and return flows in Sub-basin 5 of the White River drainage system. *Total withdrawals (Q_{ww}) are shown in blue and total return flows (Q_{rf}) are shown in red. Net return flows ($Q_{rf} - Q_{ww}$) are shown in green. Locations of individual withdrawals and returns are shown in Figure 2.5.*

For use in the water availability assessment, the data was divided by sub-basin using the locations of the reported water withdrawals. In Equation (2), total water withdrawal in a sub-basin, Q_{ww} , is defined as the sum of all surface water and groundwater withdrawals, calculated as

$$\text{Sub-Basin:} \quad Q_{ww} = \sum q_{ww} = \sum (q_{gww} + q_{sww}) \tag{3}$$

where q_{ww} are individual water withdrawals, including both surface water (q_{sww}) and groundwater (q_{gww}) withdrawals, which are summed over the sub-basin. Locations of individual water withdrawals (q_{gww}, q_{sww}) in Sub-basin 5 of the White River drainage system are displayed in Figure 2.5. The sum of all individual withdrawals in the sub-basin, Q_{ww} , is illustrated in Figure 2.7.

2.4 Return Flows

Records of historical return flows in each sub-basin were obtained from the EPA ECHO database (EPA, 2020). Records maintained in the database include discharge monitoring reports regulated under the NPDES (National Pollutant Discharge Elimination System) program. In Indiana, the NPDES permit program is administered by IDEM on behalf of the EPA. All discharge data used in this study was obtained from the EPA ECHO database. Major return flows in the Central Indiana region include wastewater treatment plant effluent, cooling water discharge from energy producers, and dewatering discharge from mines. Data retrieved from ECHO includes monthly, quarterly, or annual average discharges from regulated facilities for

the period 2007-2017. Discharge data was unavailable for years prior to 2007.

The NPDES data was divided by sub-basin using outfall locations reported in the database. In Equation (2), the total return flow in a sub-basin, Q_{rf} , is defined as the sum of all surface water discharges occurring in the sub-basin, calculated as

$$\text{Sub-Basin:} \quad Q_{rf} = \sum q_{rf} \tag{4}$$

where q_{rf} are return flows from individual facilities, which are summed over the sub-basin area.

Figure 2.7 illustrates both the total water withdrawals, Q_{ww} , and total return flows, Q_{rf}, in Sub-basin 5 of the White River drainage system for the period 2007-2017. Locations of individual return flows (q_{rf}) in Sub-basin 5 are displayed in Figure 2.5.

2.5 Reservoir Storage

There are three major surface-water reservoirs in the Central Indiana region, all within the White River drainage system: Morse Reservoir in Sub-basin 5, Geist Reservoir in Sub-basin 6, and Eagle Creek Reservoir in Sub-basin 10. In addition, two reservoirs lie outside of the Central Indiana region but within the major drainage systems included in this study: Prairie Creek Reservoir is located at the headwaters of the White River drainage system in Sub-basin 1, and Summit Lake Reservoir is located at the headwaters the East Fork White River drainage system in Sub-basin 1.

Four of the reservoirs are operated for water supply by supplementing downstream flows to be captured by groundwater wells or surface water intakes. Prairie Creek Reservoir is operated by Indiana American Water to provide low flows to its Muncie well field. Morse Reservoir on Cicero Creek and Geist Reservoir on Fall Creek are owned and operated by Citizens Water. Water is released from the reservoirs during low flow conditions to supplement streamflow for downstream withdrawal. Eagle Creek Reservoir on Eagle Creek is owned by the City of Indianapolis and operated by the Army Corps of Engineers. This reservoir is operated primarily for flood control, but low flows are released to maintain an adequate source for water supply wells operated by the Town of Speedway. Summit Lake Reservoir is operated by the DNR to provide flood control.

Reservoirs represent significant anthropogenic changes that regulate the natural streamflow in a sub-basin. This study focuses on releases made during low flow periods and the subsequent recovery of reservoir levels. Flood control operations at reservoirs only affects the natural streamflow during high-flow conditions. Reservoir operation records for the Morse and Geist Reservoirs were provided by Citizens Water for use in this study. Data and information in Citizens Water Drought Management Plan (Citizens, 2013), was used to estimate the daily change in reservoir storage, q_{stor}, due to low-flow releases and the subsequent recovery of reservoir levels. Figure 2.8 illustrates operation of the Morse Reservoir in 2012. Positive values of q_{stor} indicate that water is being released from the reservoir and reservoir levels are falling, while

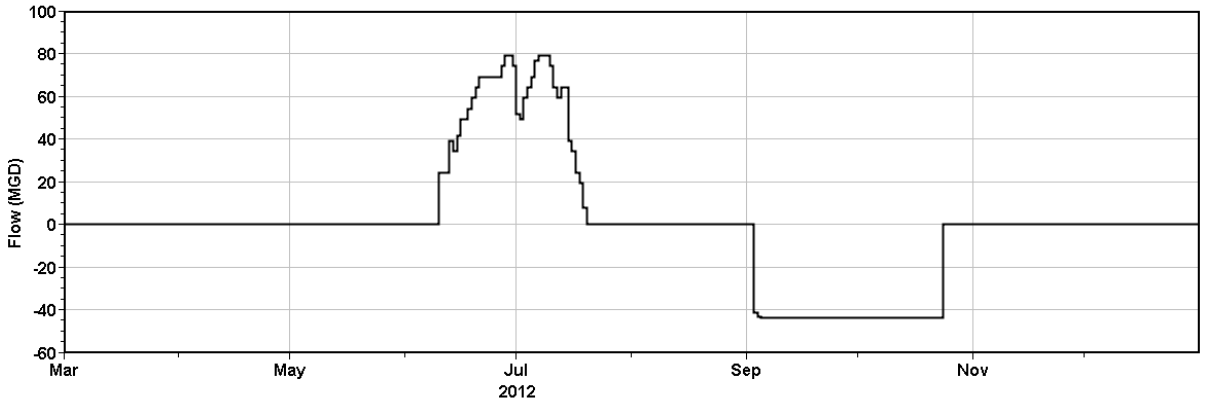

Figure 2.8: Estimated changes in storage, Q_{stor}, in Morse Reservoir in 2012. *Net releases from the reservoir in Sub-basin 5 of the White River drainage system occur in June and July, and refilling of the reservoir occurs in September and October.*

negative values indicate that the reservoir is filling, as defined in equation (5)

$$\text{Reservoir:} \quad \frac{dV}{dt} = -q_{stor} \tag{5}$$

where dV/dt represents the change in water volume stored in the reservoir over time.

Reservoir storage released in a sub-basin is given by

$$\text{Sub-Basin:} \quad Q_{stor} = \sum q_{stor} \tag{6}$$

where the summation includes releases from all reservoirs in a sub-basin. In the study area, there is never more than a single reservoir in a sub-basin; therefore, within a sub-basin that includes a reservoir,

$$\text{Sub-Basin:} \quad Q_{stor} = q_{stor} \tag{7}$$

2.6 Aquifer Storage

A large volume of water lies in storage in the saturated and unsaturated formations underlying the Central Indiana region, including the till, outwash, alluvium, buried sand and gravel, and bedrock. The volume of water stored changes in response both to seasonal variations in recharge from excess precipitation and pumping from groundwater wells. Increasing volume stored in an aquifer is observed as an increase in the water level in observation wells screened within the aquifer, while periods of decreasing storage are observed as decreasing water levels in wells. Figure 2.9 illustrates the annual variation in water levels in two USGS observation wells screened in outwash. In general, water levels rise in the first half of the year when recharge is largest, and decline in the second half of the year when recharge is smallest. Seasonal variations in

recharge result in seasonal changes in aquifer storage, which in turn lead to seasonal variations in groundwater discharge to surface waters. We address seasonal changes in aquifer storage by using natural baseflow (groundwater discharge to streams) in our definition of water availability (1), as described in Appendix A.

Groundwater storage also changes in response to operation of pumping wells. This is inherently a transient process, with groundwater initially taken out of storage near the well when it is pumped, and over time the source of the pumped water shifts to induced leakage from surface waters through a process called stream depletion. The change in aquifer storage related to stream depletion is neglected in our definitions of the natural streamflow and natural baseflow. The approximation is discussed in Appendix A.

It is possible, but unsustainable, to increase water availability under low-flow conditions by pumping water from groundwater storage; this becomes ineffective when the source of pumped water shifts from storage to stream depletion. Also, the large volume of water stored in the ground is only accessible at large flow rates in formations with high transmissivities. In general, within the study area, groundwater is accessible at significant flow rates from outwash deposits, alluvial deposits, and buried sand and gravel lenses. The bedrock within the study area generally transmits much less groundwater, and the till transmits very little. This effectively limits large withdrawals to the outwash and alluvium adjacent to streams. Unfortunately, the closer to the stream, and the more transmissive the aquifer, the less water can be removed from storage prior to stream depletion. We neglect groundwater storage as a short-term source of excess availability in equation (2).

2.7 Natural Streamflow

Evaluation of the natural streamflow at each USGS station, and separation of natural streamflow into natural baseflow and natural stormflow, is the basis of the water availability modeling presented here. Natural streamflow is defined as the daily flow at a USGS station that would occur if their were no anthropogenic effects of water withdrawals, return flows, and changes in reservoir storage occurring in the watershed. The natural streamflow generated in a ***watershed*** is estimated here as:

$$\text{Watershed:} \quad q_{nsf} = q_{usgs} - \sum(q_{rf} - q_{ww}) - \sum q_{stor} \tag{8}$$

where q_{usgs} is the daily flow record at the USGS station, with individual return flows and withdrawals summed over the entire watershed upstream of the USGS station. Note that we are combining monthly average flow values, q_{ww} and q_{rf}, with daily values, q_{usgs} and q_{stor}, to estimate natural daily values, q_{nsf}, and that the summation is over the entire upstream watershed rather than an individual sub-basin.

This expression for natural streamflow is derived from a water budget analyses presented in Appendix A. The analysis identifies the approximations made in developing the relationship.

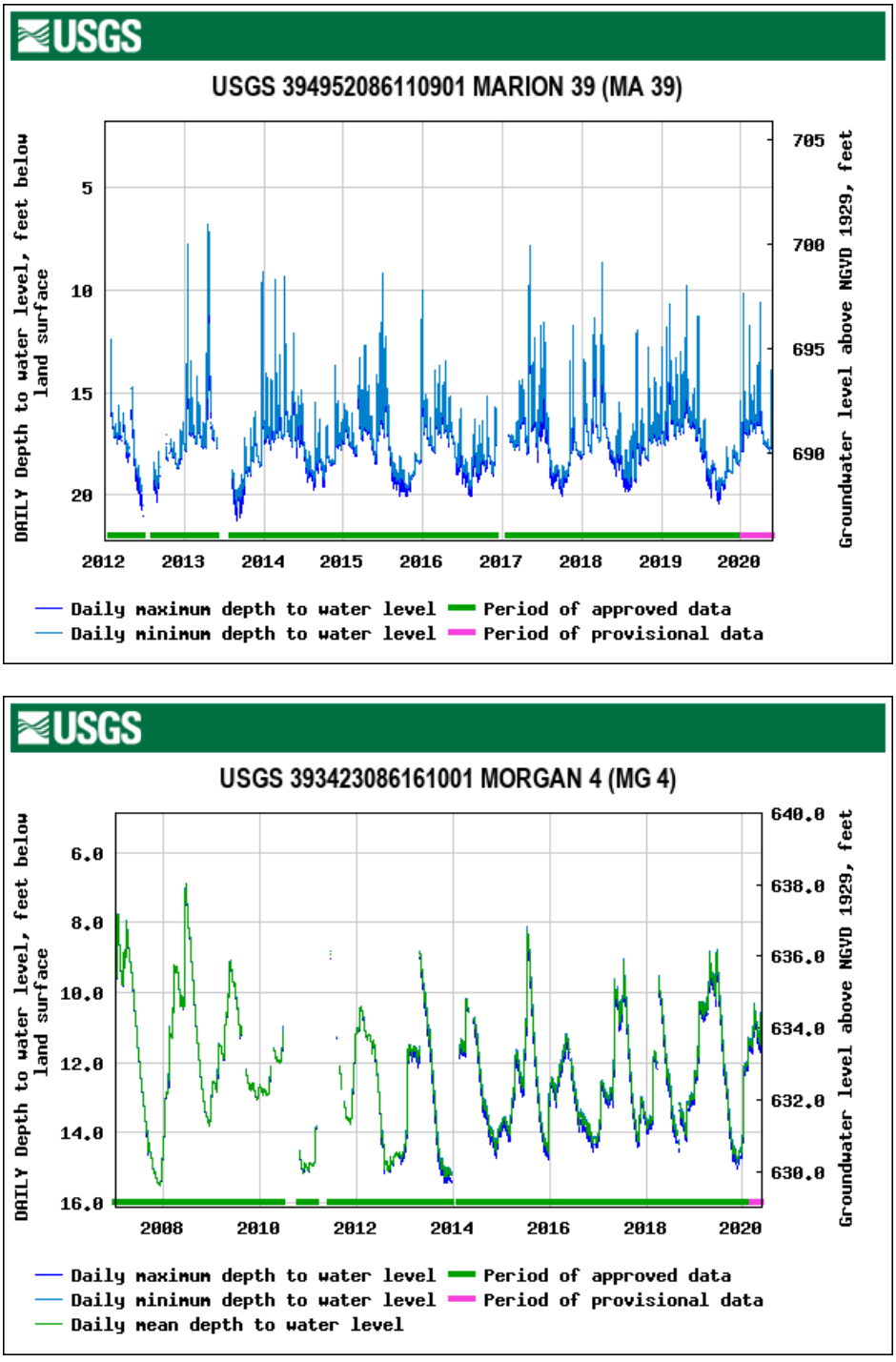

Figure 2.9: Annual changes in groundwater level in the outwash aquifer (USGS, 2020b): Marion County (*top*), and Morgan County (*bottom).*

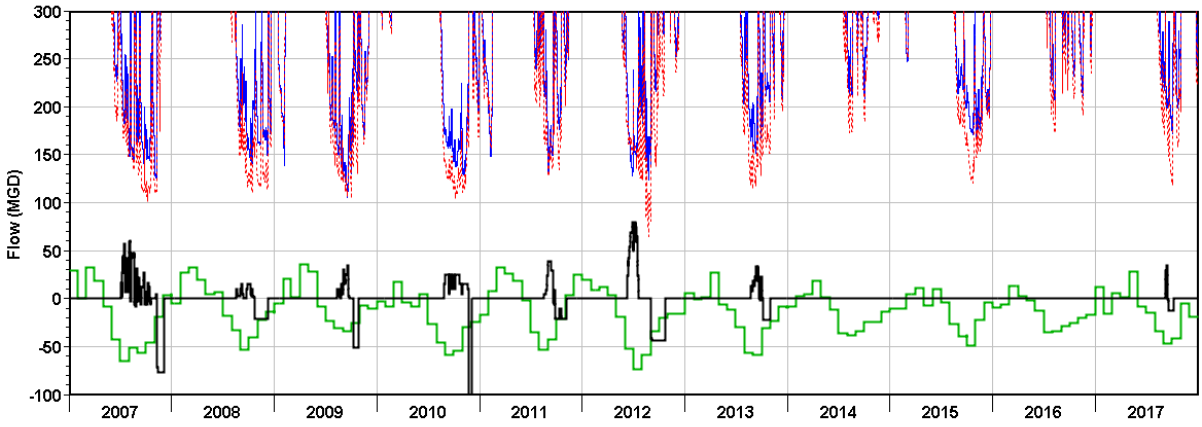

Figure 2.10: Reconstruction of natural streamflow, at USGS station 03351000 (White River near Nora). *The reconstruction, q_{nsf} (blue), is based on USGS daily flow records, q_{usgs} (red), net return flows in the watershed, $\sum(q_{rf} - q_{ww})$ (green), and reservoir releases, $\sum q_{stor}$ (black).*

In developing equation (8), the primary approximation is that stream depletion, caused by fluctuations in groundwater withdrawals, occurs instantaneously. While this is not true, it is a reasonable approximation for this setting, as the major groundwater withdrawals in this region occur within the outwash and alluvial deposits immediately adjacent to rivers. Further, only fluctuations in groundwater withdrawals create a stream depletion lag time; the average annual groundwater withdrawals are reflected as a direct reduction in streamflow.

Figure 2.10 illustrates the components of reconstructed natural flow at USGS station 03351000, Whiter River near Nora, for the period 2007-2017. Figure 2.11 provides a more detailed illustration of the natural streamflow reconstruction for the period March through December, 2012.

2.8 Natural Baseflow

Baseflow estimates for a watershed are obtained from streamflow records by a method called baseflow separation. Baseflow separation partitions streamflow into a baseflow component and a stormflow component. The separation is somewhat subjective, but there are standardized approaches. The USGS computer program PART (Rutledge, 1998, 2007) is used in this study to separate baseflow from daily streamflow measurements.

Natural baseflow is evaluated by applying baseflow separation to the reconstructed natural streamflow record. This provides an estimate of the natural groundwater discharge to the stream that would occur in the watershed in the absence of groundwater withdrawals and return flows. As such, it is a baseline estimate of the total available groundwater supply.

The natural baseflow, q_{nbf}, was evaluated for each USGS station. The natural baseflow generated within a sub-basin, Q_{nbf}, is then calculated as

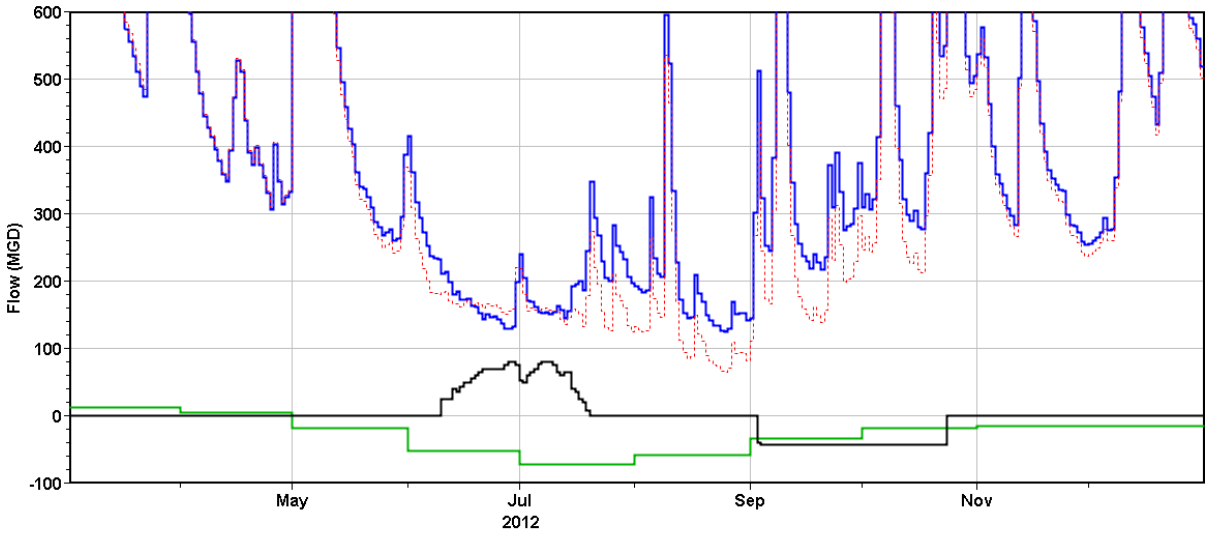

Figure 2.11: Reconstruction of natural streamflow at USGS station 03351000 (White River near Nora) for 2012. *The reconstruction, q_{nsf} (blue), is based on USGS daily flow records, q_{usgs} (red), net return flows in the watershed, $\sum(q_{rf} - q_{ww})$ (green), and reservoir releases, Q_{stor} (black).*

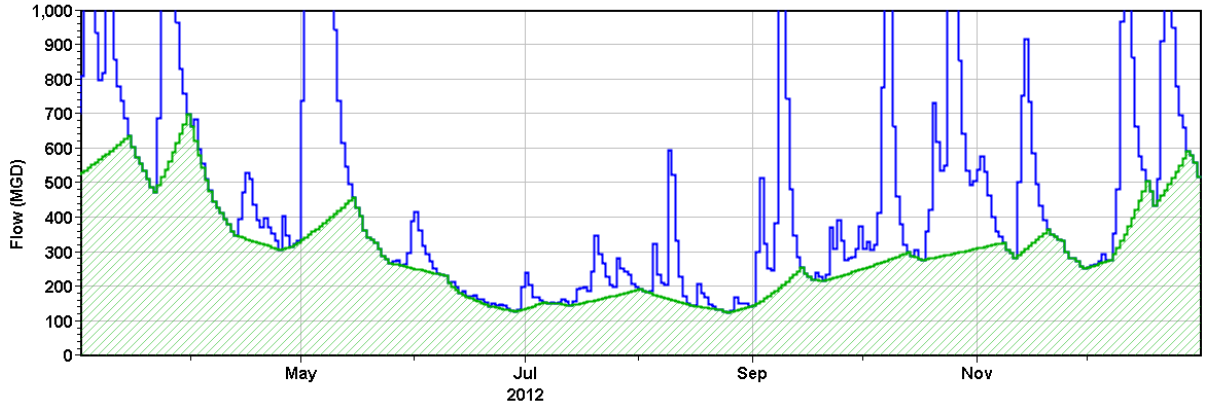

Figure 2.12: Example: Separation of natural baseflow from natural streamflow at USGS station 03351000 (White River near Nora). *Natural baseflow, q_{nbf}, is shown in green and natural streamflow, q_{nsf}, is shown in blue.*

$$\text{Sub-Basin:} \quad Q_{nbf} = \sum q_{nbf} \tag{9}$$

where the right-hand side is the sum of natural baseflows, q_{nbf}, crossing the sub-basin boundary. q_{nbf} is positive for outflow from the sub-basin and negative for inflows: the natural baseflows computed for USGS stations along the upstream sub-basin boundary are subtracted from the natural baseflow at the downstream USGS station to evaluate the natural baseflow generated within the sub-basin.

All aquifers in the region–including outwash, till, buried sand and gravel, and bedrock–are hydraulically connected to surface waters. In a natural system, aquifer recharge eventually discharges to a stream regardless of where the recharge occurs. Natural baseflow is the total groundwater output from the aquifer system in response to an input of recharge and is therefore a measure of total groundwater availability.

2.9 Instream Flows

Ecological protection is understood to be one of the recognized beneficial uses of water in the State of Indiana (IDNR, 2015). Instream flow is commonly defined as a minimum flow that is retained in the stream to protect ecological health, recreational use, and water quality. Instream flow is often referred to as an environmental flow. Recommendations for instream flow limits in Indiana are presented by the IDNR in the document titled Indiana's Water Shortage Plan (IDNR, 2015). The plan identifies the 80 percent exceedance flow for the months of May through October to be used as a trigger to initiate a process to protect aquatic and riparian habitat during a surface water shortage. To maintain water quality in Indiana streams, the IDNR suggests reductions in water use to maintain the $Q_{7,10}$ flow in all streams where possible. The $Q_{7,10}$ is defined as the 7-day low flow in a stream that occurs on average once every 10 years.

In the absence of regulated instream flow requirements, the annual 90% exceedance flow (annual Q_{90}) is often used as a presumptive standard for environmental flow protection (Gleeson and Richter, 2017; Richter et al., 2011). As default values, we specify the annual Q_{90} as the instream flow for January through June (Quarters 1 and 2), when surface water is abundant, and $Q_{7,10}$ from July to December (Quarters 3 and 4), when low flows typically occur. In our analysis, these values can be considered ***place-holders*** until instream flow limits are defined and regulated in the State of Indiana.

Instream flow values for each USGS station used in the analysis were obtained from Fowler and Wilson (2015). Tables 2.4 through 2.6 summarize the low-flow trigger (May through October Q_{80}), the annual Q_{90} , and the $Q_{7,10}$ at the outlets of each sub-basin. The low-flow trigger was obtained from a frequency analysis of the USGS daily flow data. These flow quantiles are based on the USGS daily flow records, uncorrected for withdrawals and return flows, and are therefore dependent on how withdrawals and returns have occurred in the past. To be consistent with Fowler and Wilson (2015), the values are reported in cubic feet per second

(cfs).

The portion of the instream flow requirement generated within a sub-basin, Q_{if} , is calculated as

$$\text{Sub-Basin:} \quad Q_{if} = \sum q_{if} \tag{10}$$

where the right hand side is the sum of instream flows, q_{if}, crossing the sub-basin boundary. q_{if} is the instream flow computed at a USGS station, and is positive for instream flows leaving the sub-basin (at downstream end) and negative for flows entering the sub-basin (upstream end). Values of Q_{if} specified for each sub-basin in the availability model are summarized in Tables 2.7 through 3.3. The values are reported in units of million gallons per day (MGD) to be consistent with the water-availability model. The same information for Quarters 3 and 4 is displayed on a map of the sub-basins in Figure 2.13.

2.10 Comments on Data and Quality Control

As discussed previously, we make use of the Indiana SWWF database as a source for water withdrawal data, and the EPA ECHO database as the source for return flows. The purpose of the SWWF database is to track water use, and the EPA database is intended to track water-quality compliance. The two databases are organized and managed in disparate ways which make it challenging to extract and collate data in the form of time series. As data was assembled from primary sources, some informal quality control was performed with changes made to the data in the 2007-2017 period, including the following:

- Individual withdrawals in the SWWF database had to be matched with facilities. Often the reported well or intake identifier varies subtly from year to year. For example, a well identifier may be given as "W1" one year and "W-1". These cases were individually sorted with changes made on a case-by-case basis.

- When return flows show unexplained spikes, large enough to have an impact on hydrologic calculations, daily flows at the nearest downstream USGS station were checked. If no evidence of a corresponding spike in streamflow was found, the spike in return flows was removed or reduced to adjacent values in the time series. Numerous isolated spikes were removed from NPDES data before processing. We believe most isolated spikes represent reporting errors.

- The locations of some SWWF withdrawals and NPDES outfalls were erroneous, or inconsistent with other facility data regarding location. When these problems were identified, facility locations were verified on aerial photography and the coordinates of withdrawals or outfalls were changed. One example of this type of error includes surface water intakes for the Indiana Power and Light Eagle Valley generating station. The SWWF database

Table 2.4: Low-flow triggers and default instream flows in the White River drainage system.

Sub-Basin ID	USGS station at outlet of Sub-Basin	Watershed Area (mi^2)	May-Oct Q_{80} (cfs)	Annual Q_{90}* (cfs)	Annual $Q_{7,10}$* (cfs)
1	03347000 White River at Muncie, IN	241	17	14	2.9
2	03348130 White River at Raible Ave. at Anderson, IN	519	131	114	72
3	03349000 White River at Noblesville, IN	858	161	142	82
4	03349510 Cicero Creek at Arcadia, IN	131	5.2	4.5	1.0
5	03351000 White River near Nora, IN	1,219	199	191	123
6	03351500 Fall Creek near Fortville, IN	169	36	33	16
7	03352500 Fall Creek at Millersville, IN	298	60	55	36
8	03353000 White River at Indianapolis, IN	1,635	198	160	73
9	03353200 Eagle Creek at Zionsville, IN	106	2.6	1.7	0.0
10	03353500 Eagle Creek at Indianapolis, IN	174	9.5	9.7	3.9
11	03353611 White River at Stout Gen. Stn., Indianapolis, IN	1,898	389	318	171
12	03353800 White Lick Creek at Mooresville, IN	212	20	15	3.9
13	03354000 White River near Centerton, IN	2,444	517	427	274

Notes: mi^2= square miles. cfs = cubic feet per second.

* Q_{90} and $Q_{7,10}$ flows obtained from Fowler and Wilson (2015).

Table 2.5: Low-flow triggers and default instream flows in the Wabash River drainage system.

Sub-Basin ID	USGS station at outlet of Sub-Basin	Watershed Area (mi^2)	May-Oct Q_{80} (cfs)	Annual Q_{90}* (cfs)	Annual $Q_{7,10}$* (cfs)
1	03339280 Prairie Creek near Lebanon, IN	33.2	3.4	3.0	0.5
2	03339500 Sugar Creek at Crawfordsville, IN	509	35	30	8.9
3	03340800 Big Raccoon Creek near Fincastle, IN	139	8.0	6.2	1.9
4	03357330 Big Walnut Creek near Roachdale, IN	131	11	7.7	1.4

Notes: mi^2= square miles. cfs = cubic feet per second.

* Q_{90} and $Q_{7,10}$ flows obtained from Fowler and Wilson (2015).

Table 2.6: Low-flow triggers and default instream flows in the East Fork White River drainage system.

Sub-Basin ID	USGS station at outlet of Sub-basin	Watershed Area (mi^2)	May-Oct Q_{80} (cfs)	Annual Q_{90}* (cfs)	Annual $Q_{7,10}$* (cfs)
1	03361500 Big Blue River at Shelbyville, IN	421	88	77	43
2	03361650 Sugar Creek at New Palestine, IN	93.9	9.9	8.4	2.3
3	03361850 Buck Creek at Acton, IN	78.8	7.1	5.9	1.4
4	03362000 Youngs Creek near Edinburgh, IN	107	6.2	5.1	1.7
5	03362500 Sugar Creek near Edinburgh, IN	474	58	48	20
6	03363500 Flatrock River at St. Paul, IN	303	19	16	2.5
7	03363900 Flatrock River at Columbus, IN	534	73	60	29
8	03364000 East Fork White River at Columbus, IN	1,707	307	261	134

Notes: mi^2= square miles. cfs = cubic feet per second.

* Q_{90} and $Q_{7,10}$ flows obtained from Fowler and Wilson (2015).

Table 2.7: Instream flow requirements, Q_{if}, specified in the availability model for each sub-basin in the White River drainage system.

Sub-Basin ID	USGS station at outlet of Sub-Basin	Sub-Basin Area (mi^2)	Q1 and Q2 Q_{if}* (MGD)	Q3 and Q4 Q_{if}** (MGD)
1	03347000 White River at Muncie, IN	242.1	9	1.9
2	03348130 White River at Raible Ave. at Anderson, IN	273.7	65	44
3	03349000 White River at Noblesville, IN	337.6	18	7
4	03349510 Cicero Creek at Arcadia, IN	131.0	2.9	0.65
5	03351000 White River near Nora, IN	231.1	28	25
6	03351500 Fall Creek near Fortville, IN	172.7	21	10
7	03352500 Fall Creek at Millersville, IN	129.7	15	13
8	03353000 White River at Indianapolis, IN	118.1	-56	-55
9	03353200 Eagle Creek at Zionsville, IN	105.7	1.1	0.0
10	03353500 Eagle Creek at Indianapolis, IN	68.3	5.2	2.5
11	03353611 White River at Stout Gen. Stn., Indianapolis, IN	64.5	96	60
12	03353800 White Lick Creek at Mooresville, IN	212.0	10	2.5
13	03354000 White River near Centerton, IN	355.1	60	64

Notes: mi^2= square miles. MGD = million gallons per day.

* Quarter 1 and 2 instream flow requirements based on the annual Q_{90}.

** Quarter 3 and 4 instream flow requirements based on the $Q_{7,10}$.

Table 2.8: Instream flow requirements, Q_{if}, specified in the availability model for each sub-basin in the Wabash River drainage system.

Sub-Basin ID	USGS station at outlet of Sub-Basin	Sub-Basin Area (mi^2)	Q1 and Q2 Q_{if}* (MGD)	Q3 and Q4 Q_{if}** (MGD)
1	03339280 Prairie Creek near Lebanon, IN	33.3	1.9	0.32
2	03339500 Sugar Creek at Crawfordsville, IN	476.6	17	5.4
3	03340800 Big Raccoon Creek near Fincastle, IN	138.6	4.0	1.2
4	03357330 Big Walnut Creek near Roachdale, IN	131.2	5.0	0.90

Notes: mi^2= square miles. MGD = million gallons per day.

* Quarter 1 and 2 instream flow requirements based on the annual Q_{90}.

** Quarter 3 and 4 instream flow requirements based on the $Q_{7,10}$.

Table 2.9: Instream flow requirements, Q_{if}, specified in the availability model for each sub-basin in the East Fork White River drainage system.

Sub-Basin ID	USGS station at outlet of Sub-basin	Sub-Basin Area (mi^2)	Q1 and Q2 Q_{if}* (MGD)	Q3 and Q4 Q_{if}** (MGD)
1	03361500 Big Blue River at Shelbyville, IN	420.4	50	28
2	03361650 Sugar Creek at New Palestine, IN	91.4	5.4	1.5
3	03361850 Buck Creek at Acton, IN	78.7	3.8	0.90
4	03362000 Youngs Creek near Edinburgh, IN	107.2	3.3	1.1
5	03362500 Sugar Creek near Edinburgh, IN	194.2	18	9.4
6	03363500 Flatrock River at St. Paul, IN	300.7	10	1.6
7	03363900 Flatrock River at Columbus, IN	234.0	28	17
8	03364000 East Fork White River at Columbus, IN	278.7	49	27

Notes: mi^2= square miles. MGD = million gallons per day.

* Quarter 1 and 2 instream flow requirements based on the annual Q_{90}.

** Quarter 3 and 4 instream flow requirements based on the $Q_{7,10}$.

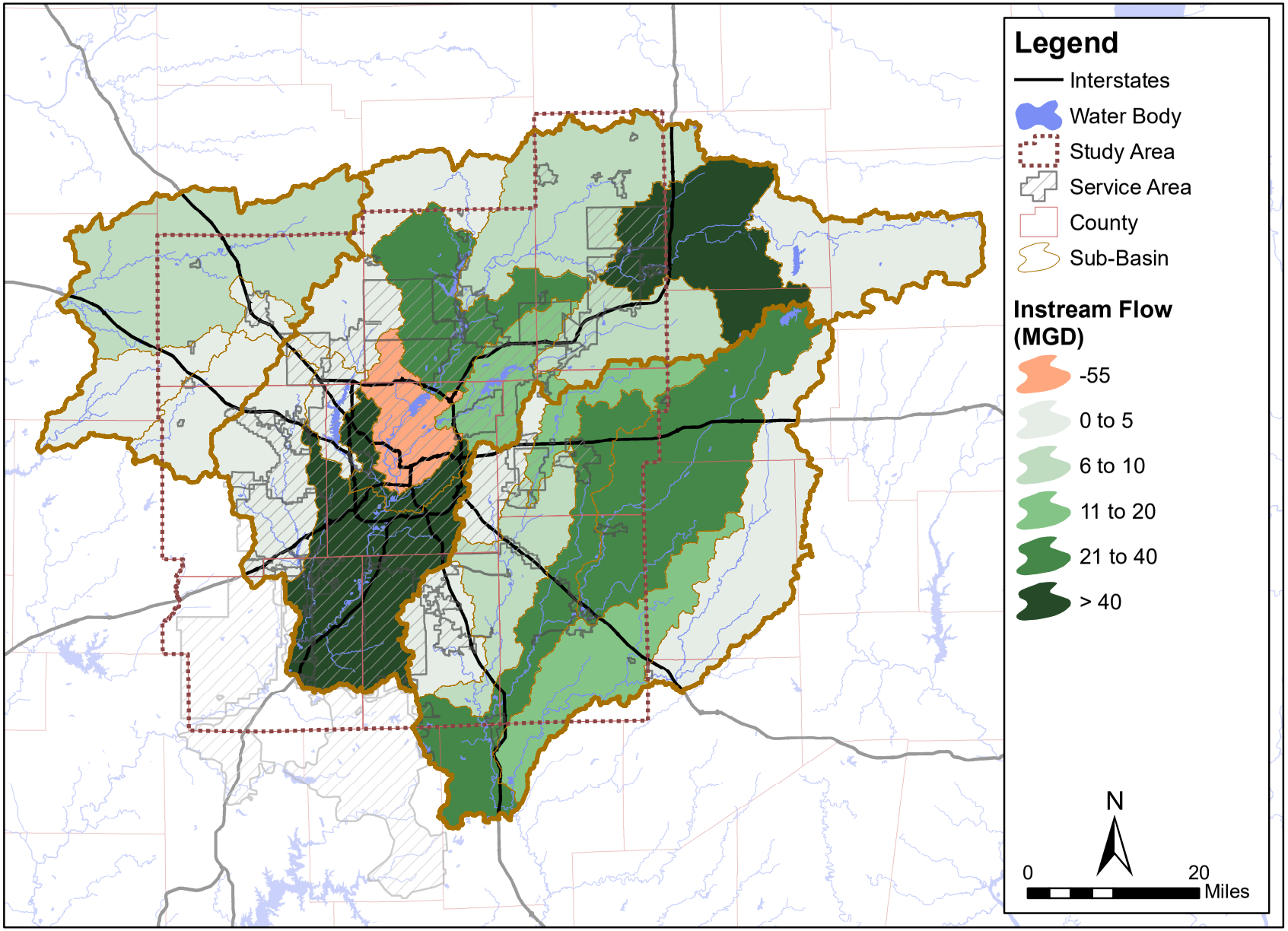

Figure 2.13: Instream flow generated within each sub-basin, Q_{if}, in Quarters 3 and 4. *Note that negative values indicate that upstream instream flow requirements are greater than downstream requirements. Although colors are applied to an entire sub-basin, cumulative excess availability is computed at the downstream end of each sub-basin.*

identifies two major intakes located in Sub-Basin 13. An investigation of aerial photos and facility data suggests that the intakes are located downstream of Sub-basin 13.

When making hydrologic calculations based on the withdrawal and return records, some data modifications were necessary to realistically constrain results. These changes include the following:

- When reconstructing natural streamflow, some short periods of negative streamflow occurred at some locations. When evaluating natural baseflow from the natural streamflow record, any negative values of natural streamflow were changed to zeros.

- When assessing sub-basin excess availability, negative values of net baseflow generated in the basins occurred in sub-basins 8, 10, 11, and 13 of the White River drainage system, and Sub-basins 6 and 8 of the East Fork White River system. When calculating sub-basin availability, the negative values were replaced with zeros.

- In calculating the natural streamflows, withdrawals at the three major Martin Marietta quarries were assumed equal to return flows. This was necessary to produce hydrologically feasible recharge values for the two sub-basins that the facilities occur in. When making availability calculations for sub-basin 5 of the White River drainage system, two estimates were made. First, withdrawals and returns from Martin Marietta facilities were included as reported in the SWWF and ECHO databases; second, returns at Martin Marietta facilities were assumed to equal withdrawals.

While the overall quality of the data contained in the two databases is unclear, there is much anecdotal evidence produced in this study that suggests the data is valuable for assessing regional hydrologic conditions. The correlation of water withdrawals and return flows for individual facilities or water use sectors is discussed in Section 4, with further discussion of quality control for large facilities. Ultimately, an assessment of the results of individual hydrologic calculations based on the data sets was made, and unrealistic results were investigated. Often this led to the identification of suspect data for major water use or return flows, which were investigated further. Overall, the two databases appear to be consistent with each other, and lead to realistic and reproducible hydrologic results.

2.11 Summary

All components of equations (1) and (2) are computed and summarized for each sub-basin in the Central Indiana region, as described in the previous sections. Results of the analysis are presented in Section 3. Here we provide graphical summaries of the steps taken in computing sub-basin water availability and excess availability, to clarify the process described above. Figure 2.14 presents the division of the Central Indiana region into smaller hyrdologic regions. The region is first divided into three major drainage systems which are then sub-divided into

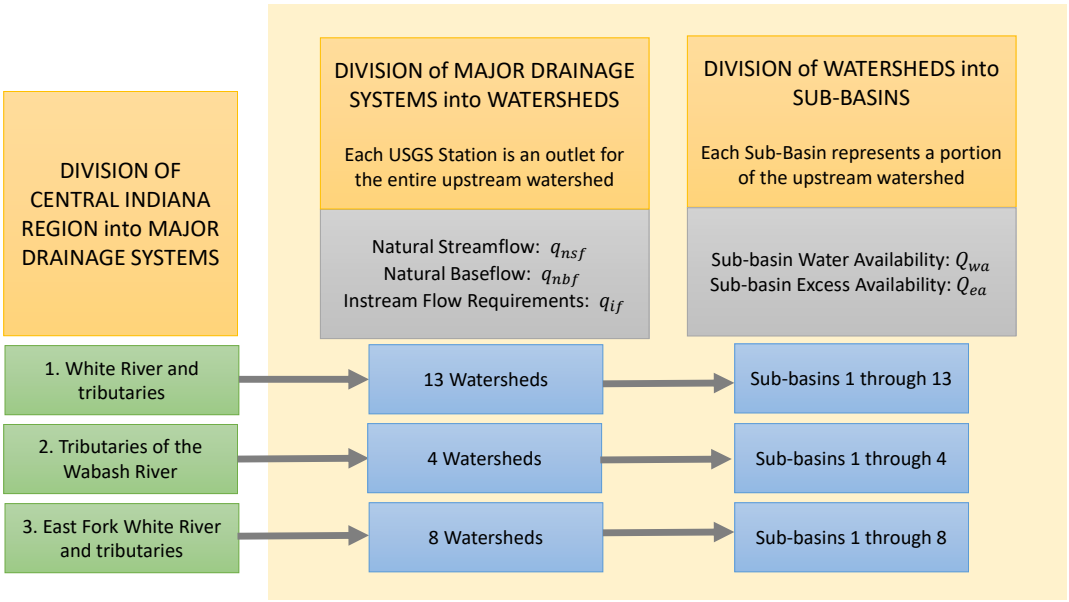

Figure 2.14: The process of subdividing the Central Indiana region, from major drainage systems to sub-basins.

watershed units. Finally each watershed is sub-divided into sub-basins. Separate hydrologic calculations are required at the watershed scale and the sub-basin scale.

Illustrations of the flow of data from primary data sources to sub-basin availability are presented in Figures 2.15 and 2.16. Figure 2.15 illustrates the progression from primary data sources to calculations of instream flow requirements and natural baseflow made for the entire watershed upstream of each USGS station. Figure 2.16 illustrates the translation from watershed properties to sub-basin properties, and the calculation of water availability and excess availability.

The hydrologic calculations identified in the figures and explained in Section 2 above provide all data needed to evaluate water availability (equation 1) and excess water availability (equation 2) for each sub-basin in the Central Indiana region.

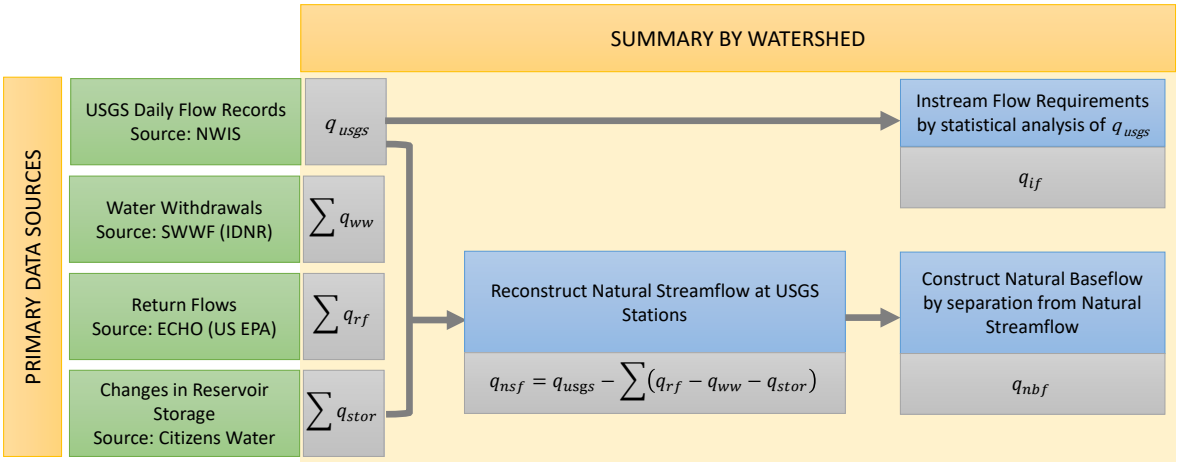

Figure 2.15: The process of computing natural baseflow for a watershed from primary data sources.

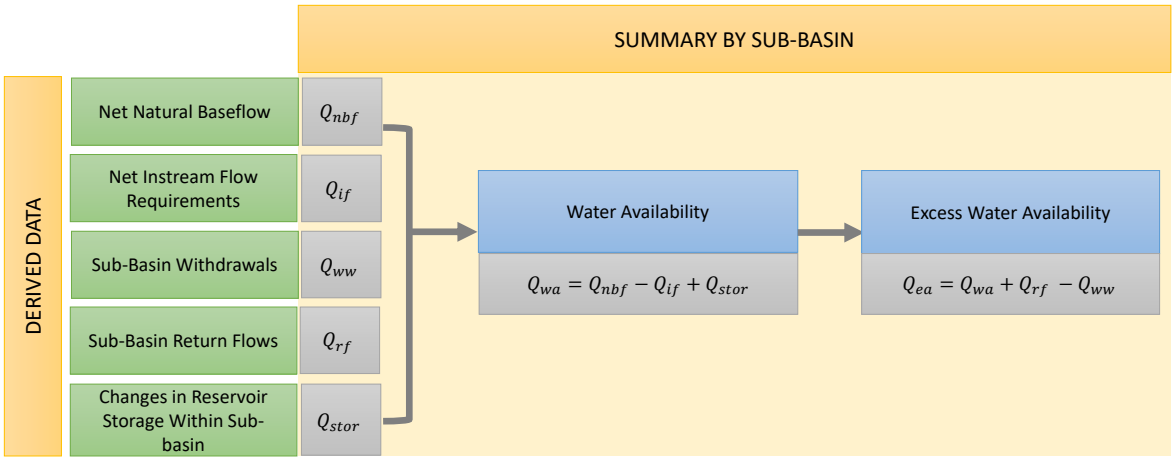

Figure 2.16: The process of computing excess availability for a sub-basin.

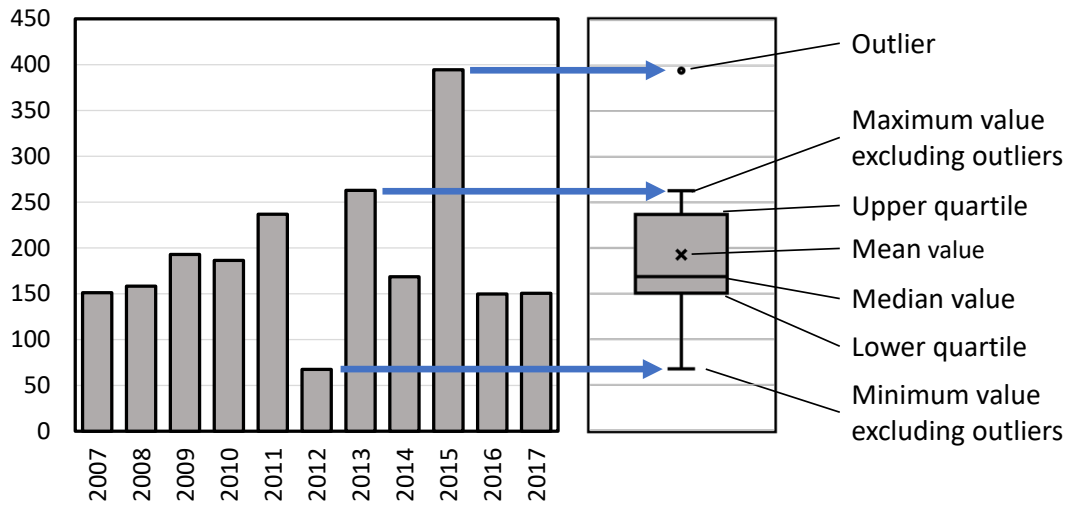

Figure 3.1: Description of box and whisker plots. *The annual time series on the left is represented as a single box and whisker plot illustrating outliers, minimum and maximum values, and quartile values.*

3 Water-Availability Assessment, 2007-2017

Assessments of excess water availability are made based on three-month averages, representing calendar-year quarters: Quarter 1 (January through March), Quarter 2 (April through June), Quarter 3 (July through September), and Quarter 4 (October through December). This temporal discretization was chosen to represent both seasonal variation in the hydrologic system and quarterly variation in water use. In most cases, Quarters 3 and 4 represent the lower limits on water availability in each sub-basin, with Quarter 3 being defined as the critical quarter here.

We present in Figures 3.2 and 3.3 examples of the assessments conducted for Sub-basin 5 in the White River drainage system. The figures present the data as box and whisker plots, which illustrate the range of the data and quartile values for the years 2007 through 2017. Figure 3.1 provides an explanation of this box and whisker plot, used here to summarize time-series data.

Figure 3.2 shows the components of excess availability during Quarter 3 for the years 2007 through 2017. Note that the anthropogenic effects of water withdrawal, return flows, and reservoir storage have relatively narrow ranges. This illustrates that the variability in excess water availability is due to the variability in natural baseflow.

Figure 3.3 (*top*) presents the average excess water availability in the sub-basin on an annual and quarterly basis, clearly illustrating the seasonal variability for the period 2007-2017. Figure 3.3 (*bottom*) illustrates the cumulative excess water availability in Sub-basin 5, which is the sum of excess availability in Sub-basin 5 and all connected, upstream sub-basins:

$$Q_{cea} = \sum_{n=1}^{5} (Q_{ea})_n \tag{11}$$

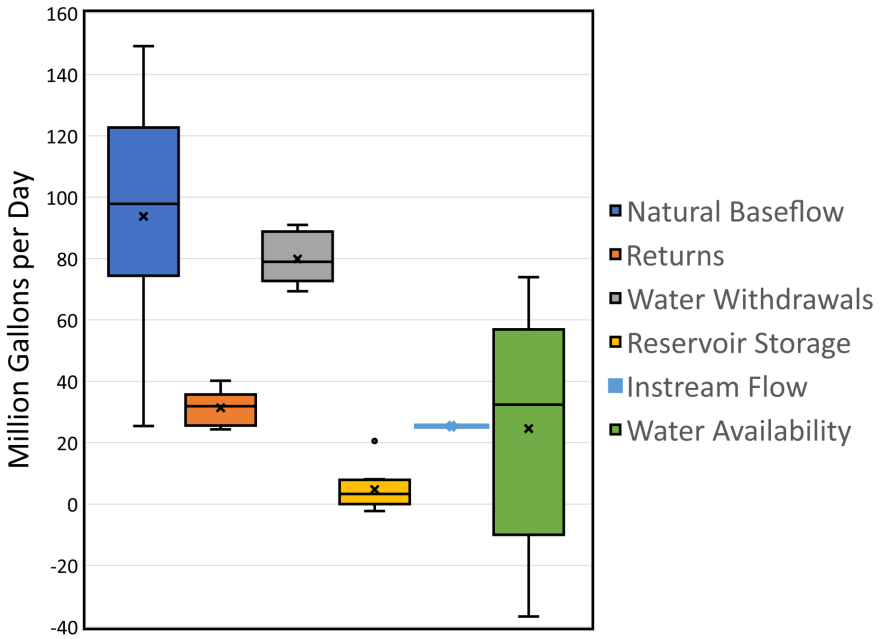

Figure 3.2: Components of excess water availability for Quarter 3 in Sub-basin 5 of the White River drainage system, 2007-2017. *Note that the variability in excess water availability is driven by the variability in natural baseflow, rather than anthropegenic components of withdrawals, returns, and reservoir storage.*

where Q_{cea} is the cumulative excess availability in Sub-basin 5, and $(Q_{ea})_n$ is the excess water availability in each of the n upstream sub-basins. Note that while the top figure shows that excess availability in Sub-basin 5 may be negative, the cumulative availability is always positive for the period 2007-2017. This indicates that years of net water deficit in the sub-basin have been adequately supplemented by excess water availability from upstream during that time period.

3.1 Assessment Based on Historic Use of Reservoir Storage

Tables 3.1 through 3.6 summarize the results of the water availability assessment for the period 2007-2017, including excess availability and cumulative excess availability for the sub-basins in each of the three major drainage systems. The tables include values from the box and whisker plots including the minimum availability, the lower quartile, and the median availability. In addition, the year of occurrence of the minimum availability is provided. Maps illustrating the minimum Quarter 3 excess water availability and cumulative excess availability are presented in Figures 3.4 and 3.5. More complete details for each sub-basin are presented in Appendix B as graphs of Quarter 3 excess availability, annual and quarterly excess availability, and annual and quarterly cumulative excess availability for each sub-basin.

Table 3.1 presents two values for excess water availability in Sub-basin 5 (White River

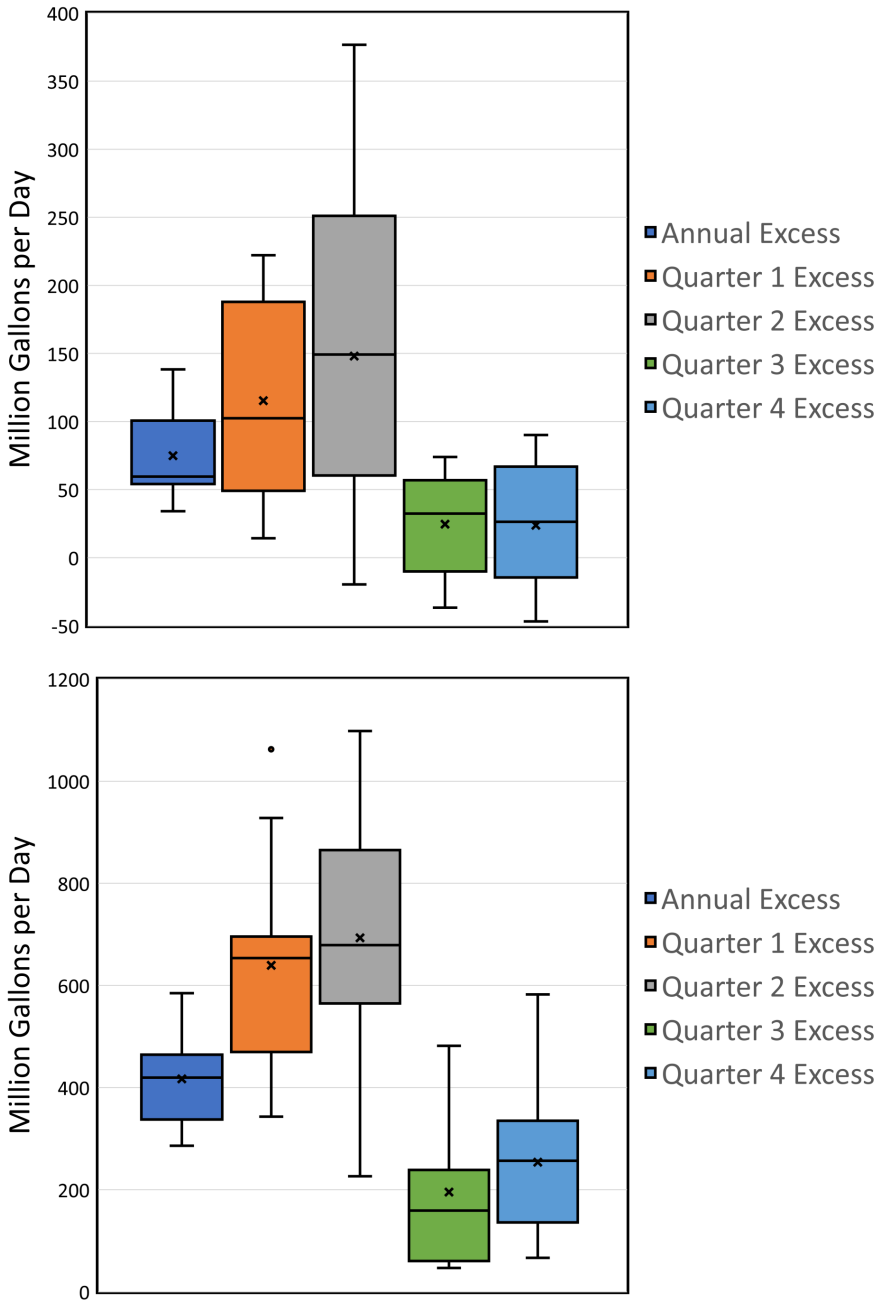

Figure 3.3: Sub-basin 5 excess water availability by season, 2007-2017. *Sub-basin excess (top) and cumulative excess (bottom). Note that the negative values of sub-basin excess availability in the top figure are offset by outflows from the upstream sub-basin, when computing cumulative excess availability, with results shown in the bottom figure.*

from Nobelsville to Nora). The two values are based on two different assumptions about water withdrawals and returns at the Martin Marietta quarries in the sub-basin. The first values includes withdrawals and returns as reported by Martin Marietta, while the second values assume that withdrawals and returns are equal. The results provide insight on the significance of the unknown hydrologic conditions at the quarries. This information is only provided in the tables of excess water availability: tables of cumulative excess (Table 3.4) and figures of both excess and cumulative excess water availability (Figures 3.4 and 3.5) present results based on reported withdrawals and returns.

Historic reservoir releases from Morse and Geist Reservoirs are included in the assessment of water availability for the 2007-2017 period. During 2007-2017, the total available reservoir storage was not depleted in either reservoir. The lowest reservoir levels occurred in 2012. At that time, Morse Reservoir had approximately 1.8 billion gallons remaining in storage and Geist Reservoir retained approximately 2.9 billion gallons of water (Citizens, 2013). In this analysis of excess and cumulative excess water availability, the unused storage is considered to be an emergency supply that would be used during droughts more severe than the 2012 drought.

Table 3.1: Excess water availability in each sub-basin of the White River drainage system during Quarter 3. *Assessment based on historic use of storage in Morse and Geist Reservoirs.*

Sub-Basin ID	USGS station at outlet of Sub-Basin	Year of Minimum	Minimum (MGD)	Lower Quartile (MGD)	Median (MGD)
1	03347000 White River at Muncie, IN	2007	10	14	27
2	03348130 White River at Raible Ave. at Anderson, IN	2009	21	35	59
3	03349000 White River at Noblesville, IN	2007	15	20	60
4	03349510 Cicero Creek at Arcadia, IN	2012	3	4	8
5	03351000 White River near Nora, IN*	2009	-37	-14	32
5	03351000 White River near Nora, IN **	2009	-10	10	48
6	03351500 Fall Creek near Fortville, IN	2012	14	19	43
7	03352500 Fall Creek at Millersville, IN	2007	-9	-3	3
8	03353000 White River at Indianapolis, IN	2017	-54	–42	-8
9	03353200 Eagle Creek at Zionsville, IN	2012	2	7	9
10	03353500 Eagle Creek at Indianapolis, IN	2010	-3	-1	4
11	03353611 White River at Stout Gen. Stn., Indianapolis, IN	2010	12	24	35
12	03353800 White Lick Creek at Mooresville, IN	2012	10	15	45
13	03354000 White River near Centerton, IN	2014	-4	39	65

Notes: MGD = million gallons per day.

* Availability includes withdrawals and returns as reported by Martin Marietta.

** Availability assumes returns and withdrawals by Martin Marietta are equal.

Table 3.2: Excess water availability in each sub-basin of the Wabash River drainage system during Quarter 3.

Sub-Basin ID	USGS station at outlet of Sub-Basin	Year of Minimum	Minimum (MGD)	Lower Quartile (MGD)	Median (MGD)
1	03339280 Prairie Creek near Lebanon, IN	2007	0.7	1	3
2	03339500 Sugar Creek at Crawfordsville, IN	2012	6	22	46
3	03340800 Big Raccoon Creek near Fincastle, IN	2012	0.1	5	12
4	03357330 Big Walnut Creek near Roachdale, IN	2012	0.9	8	13

Notes: MGD = million gallons per day.

Table 3.3: Excess water availability in each sub-basin of the East Fork White River drainage system during Quarter 3.

Sub-Basin ID	USGS station at outlet of Sub-Basin	Year of Minimum	Minimum (MGD)	Lower Quartile (MGD)	Median (MGD)
1	03361500 Big Blue River at Shelbyville, IN	2012	14	37	79
2	03361650 Sugar Creek at New Palestine, IN	2012	2	3	8
3	03361850 Buck Creek at Acton, IN	2007	1	7	13
4	03362000 Youngs Creek near Edinburgh, IN	2007	3	10	21
5	03362500 Sugar Creek near Edinburgh, IN	2015	-15	4	26
6	03363500 Flatrock River at St. Paul, IN	2012	3	21	40
7	03363900 Flatrock River at Columbus, IN	2012	-3	11	39
8	03364000 East Fork White River at Columbus, IN	2015	-28	15	91

Notes: MGD = million gallons per day.

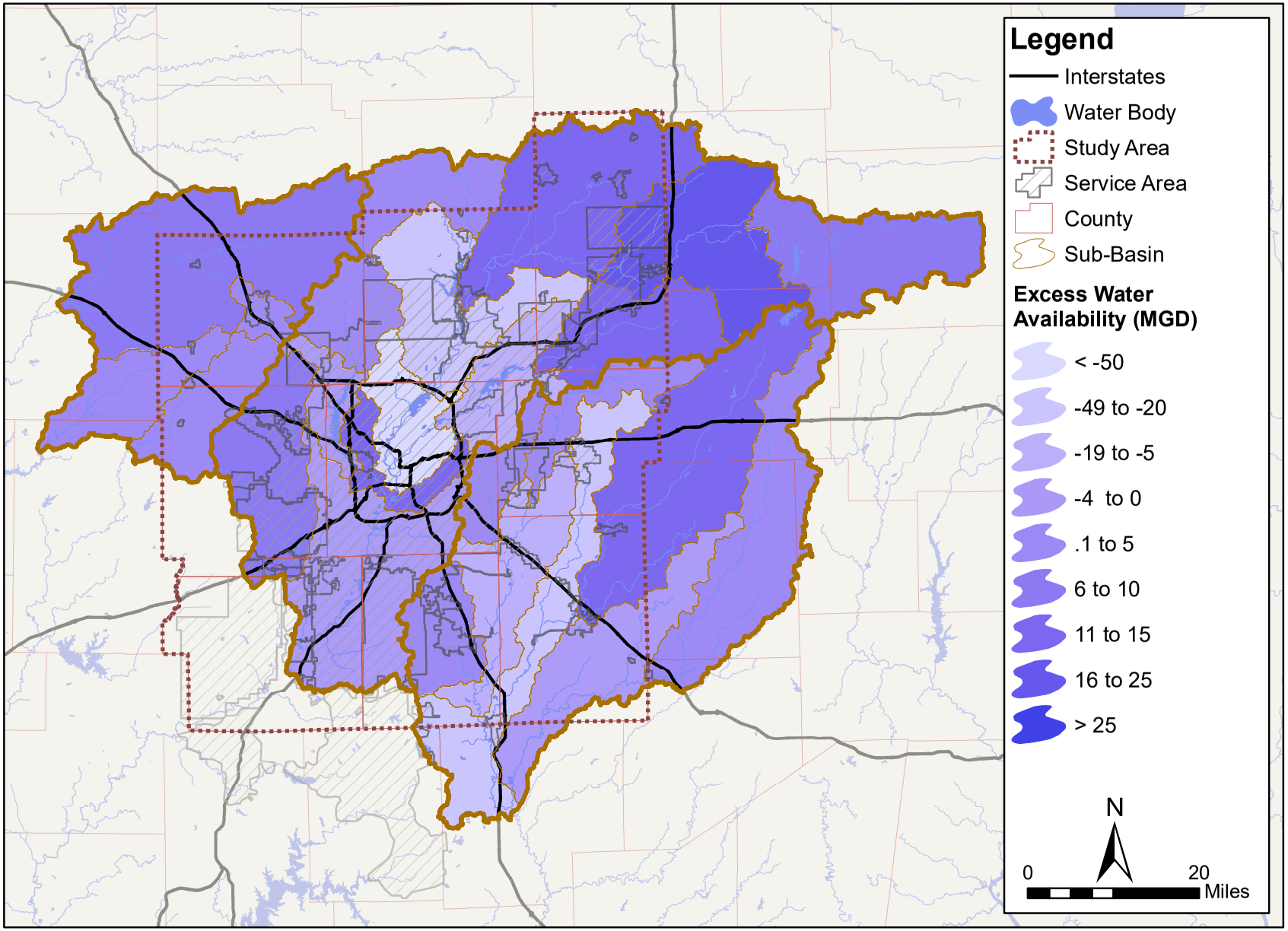

Figure 3.4: Minimum, Quarter 3, excess water availability by sub-basin, 2007-2017. *Note that negative values indicate insufficient water availability generated within the sub-basin to support current water withdrawals. Although colors are applied to an entire sub-basin, excess availability is computed at the downstream end of each sub-basin. Assessment based on historic use of storage in Morse and Geist Reservoirs.*

Table 3.4: Cumulative excess water availability in the White River drainage system during Quarter 3. *Assessment based on historic use of storage in Morse and Geist Reservoirs.*

Sub-Basin ID	USGS station at outlet of Sub-Basin	Year of Minimum	Minimum (MGD)	Lower Quartile (MGD)	Median (MGD)
1	03347000 White River at Muncie, IN	2007	10	14	27
2	03348130 White River at Raible Ave. at Anderson, IN	2009	32	45	86
3	03349000 White River at Noblesville, IN	2012	54	92	113
4	03349510 Cicero Creek at Arcadia, IN	2012	3	4	8
5	03351000 White River near Nora, IN*	2012	46	60	159
6	03351500 Fall Creek near Fortville, IN	2012	14	19	43
7	03352500 Fall Creek at Millersville, IN	2007, 2012	7	22	49
8	03353000 White River at Indianapolis, IN	2007, 2012	33	150	249
9	03353200 Eagle Creek at Zionsville, IN	2012	2	7	9
10	03353500 Eagle Creek at Indianapolis, IN	2012	6	6	15
11	03353611 White River at Stout Gen. Stn., Indianapolis, IN	2012	56	197	312
12	03353800 White Lick Creek at Mooresville, IN	2012	10	15	45
13	03354000 White River near Centerton, IN	2012	131	269	421

Notes: MGD = million gallons per day.

* Availability includes withdrawals and returns as reported by Martin Marietta .

Table 3.5: Cumulative excess water availability in the Wabash River drainage system during Quarter 3.

Sub-Basin ID	USGS station at outlet of Sub-Basin	Year of Minimum	Minimum (MGD)	Lower Quartile (MGD)	Median (MGD)
1	03339280 Prairie Creek near Lebanon, IN	2007	0.7	1	3
2	03339500 Sugar Creek at Crawfordsville, IN	2012	7	26	48
3	03340800 Big Raccoon Creek near Fincastle, IN	2012	0.1	5	12
4	03357330 Big Walnut Creek near Roachdale, IN	2012	0.9	8	13

Notes: MGD = million gallons per day.

Table 3.6: Cumulative excess water availability in the East Fork White River drainage system during Quarter 3.

Sub-Basin ID	USGS station at outlet of Sub-Basin	Year of Minimum	Minimum (MGD)	Lower Quartile (MGD)	Median (MGD)
1	03361500 Big Blue River at Shelbyville, IN	2012	14	37	79
2	03361650 Sugar Creek at New Palestine, IN	2012	2	3	8
3	03361850 Buck Creek at Acton, IN	2007	1	7	13
4	03362000 Youngs Creek near Edinburgh, IN	2007	3	10	21
5	03362500 Sugar Creek near Edinburgh, IN	2012	11	42	99
6	03363500 Flatrock River at St. Paul, IN	2012	3	21	40
7	03363900 Flatrock River at Columbus, IN	2012	0.2	31	77
8	03364000 East Fork White River at Columbus, IN	2012	45	120	395

Notes: MGD = million gallons per day.

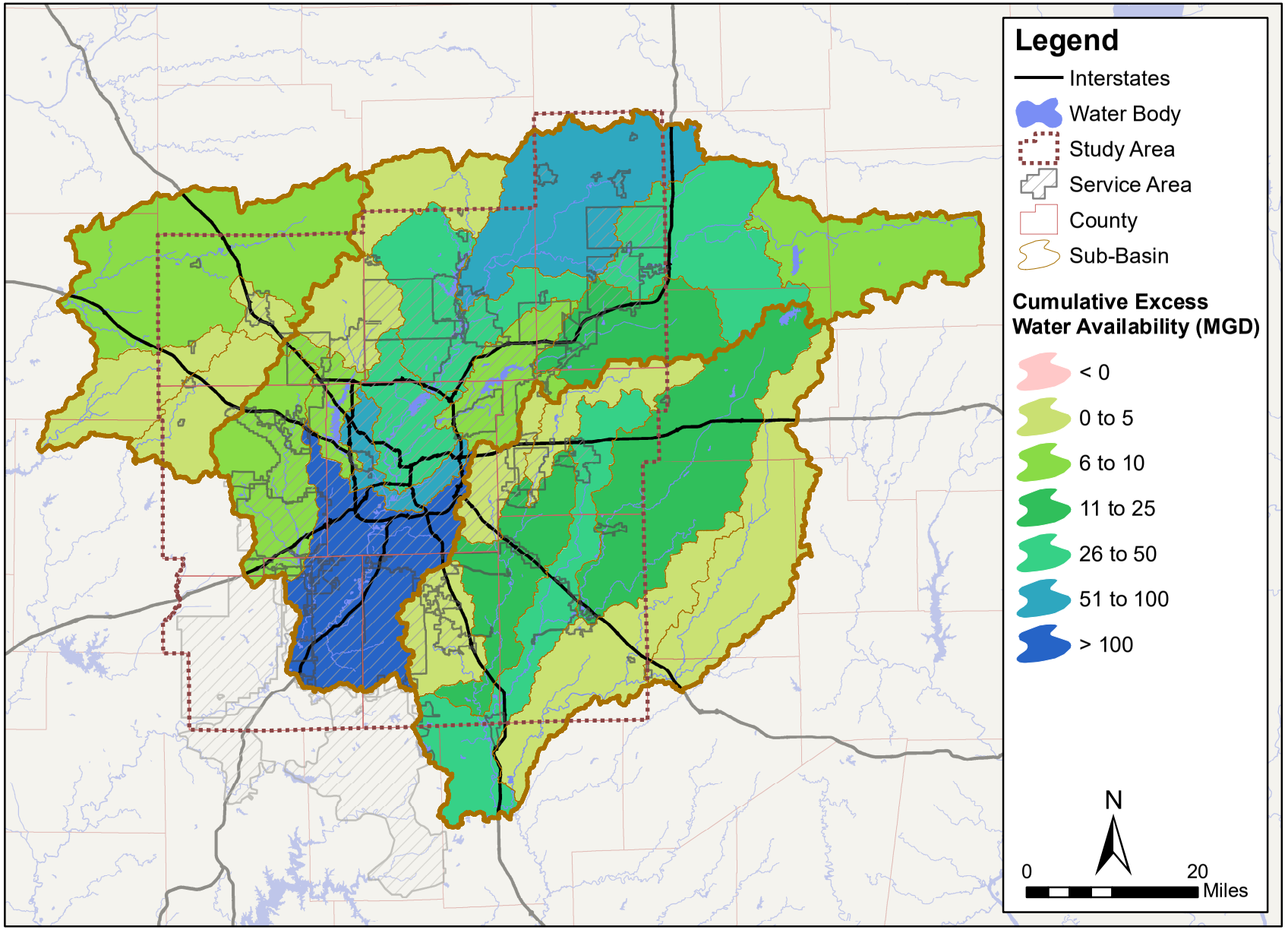

Figure 3.5: Minimum, Quarter 3, cumulative excess water availability, 2007-2017. *Excess water from upstream sub-basins is used in downstream sub-basins with negative excess availability. Note that there are no negative cumulative values. Although colors are applied to an entire sub-basin, cumulative excess availability is computed at the downstream end of each sub-basin. Assessment based on historic use of storage in Morse and Geist Reservoirs.*

3.2 Assessment Based on Full Use of Reservoir Storage

Here the assessment of excess and cumulative excess availability includes an accounting of the unused storage in Morse and Geist Reservoirs during the 2007-2017 period. Since 2012, Citizens Water has expanded the capacity of their surface water intakes downstream from both reservoirs, and water released from their reservoirs is now accessible to them. In the future more water is likely to be released from the two reservoirs, as Citizens is now able to capture the released water. In the availability model results presented here, the 1.8 billion gallons of unused storage in Morse Reservoir and 2.9 billion gallons in Geist reservoir in 2012 is released at a constant rate, in addition to the historic releases, throughout Quarters 3 and 4. The additional release occurs at at rate of 10 MGD from Morse Reservoir and 16 MGD from Geist Reservoir. This change affects only the sub-basins in the White River drainage system, and those results are presented in Tables 3.7 and 3.8. Figures 3.6 and 3.7 present results for all three drainage systems.

Table 3.7: Excess water availability in each sub-basin of the White River drainage system during Quarter 3. *Assessment based on full use of storage in Morse and Geist Reservoirs.*

Sub-Basin ID	USGS station at outlet of Sub-Basin	Year of Minimum	Minimum (MGD)	Lower Quartile (MGD)	Median (MGD)
1	03347000 White River at Muncie, IN	2007	10	14	27
2	03348130 White River at Raible Ave. at Anderson, IN	2009	21	35	59
3	03349000 White River at Noblesville, IN	2007	15	20	60
4	03349510 Cicero Creek at Arcadia, IN	2012	3	4	8
5	03351000 White River near Nora, IN*	2009	-27	-4	42
5	03351000 White River near Nora, IN **	2009	0	20	58
6	03351500 Fall Creek near Fortville, IN	2012	14	19	43
7	03352500 Fall Creek at Millersville, IN	2007	7	13	19
8	03353000 White River at Indianapolis, IN	2017	-54	–42	-8
9	03353200 Eagle Creek at Zionsville, IN	2012	2	7	9
10	03353500 Eagle Creek at Indianapolis, IN	2010	-3	-1	4
11	03353611 White River at Stout Gen. Stn., Indianapolis, IN	2010	12	24	35
12	03353800 White Lick Creek at Mooresville, IN	2012	10	15	45
13	03354000 White River near Centerton, IN	2014	-4	39	65

Notes: MGD = million gallons per day.

* Availability includes withdrawals and returns as reported by Martin Marietta.

** Availability assumes returns and withdrawals by Martin Marietta are equal.

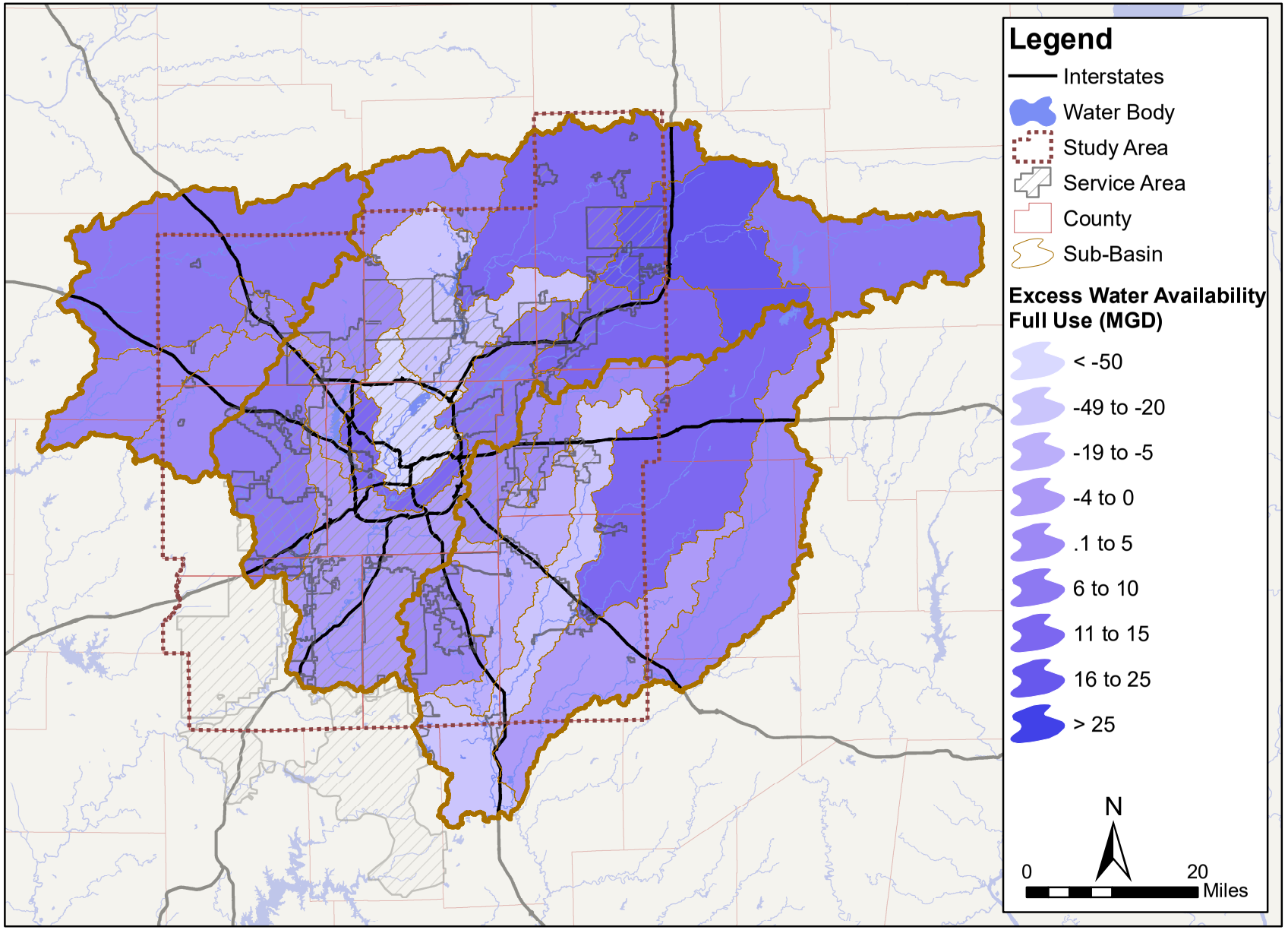

Figure 3.6: Minimum, Quarter 3, excess water availability by sub-basin, 2007-2017. *Note that negative values indicate insufficient water availability generated within the sub-basin to support current water withdrawals. Although colors are applied to an entire sub-basin, excess availability is computed at the downstream end of each sub-basin. Assessment based on full use of storage in Morse and Geist Reservoirs.*

Table 3.8: Cumulative excess water availability in the White River drainage system during Quarter 3. *Assessment based on full use of storage in Morse and Geist Reservoirs.*

Sub-Basin ID	USGS station at outlet of Sub-Basin	Year of Minimum	Minimum (MGD)	Lower Quartile (MGD)	Median (MGD)
1	03347000 White River at Muncie, IN	2007	10	14	27
2	03348130 White River at Raible Ave. at Anderson, IN	2009	32	45	86
3	03349000 White River at Noblesville, IN	2012	54	92	113
4	03349510 Cicero Creek at Arcadia, IN	2012	3	4	8
5	03351000 White River near Nora, IN*	2012	56	70	169
6	03351500 Fall Creek near Fortville, IN	2012	14	19	43
7	03352500 Fall Creek at Millersville, IN	2007, 2012	23	38	65
8	03353000 White River at Indianapolis, IN	2007, 2012	59	176	275
9	03353200 Eagle Creek at Zionsville, IN	2012	2	7	9
10	03353500 Eagle Creek at Indianapolis, IN	2012	6	6	15
11	03353611 White River at Stout Gen. Stn., Indianapolis, IN	2012	82	223	338
12	03353800 White Lick Creek at Mooresville, IN	2012	10	15	45
13	03354000 White River near Centerton, IN	2012	157	298	447

Notes: MGD = million gallons per day.

* Availability includes withdrawals and returns as reported by Martin Marietta .

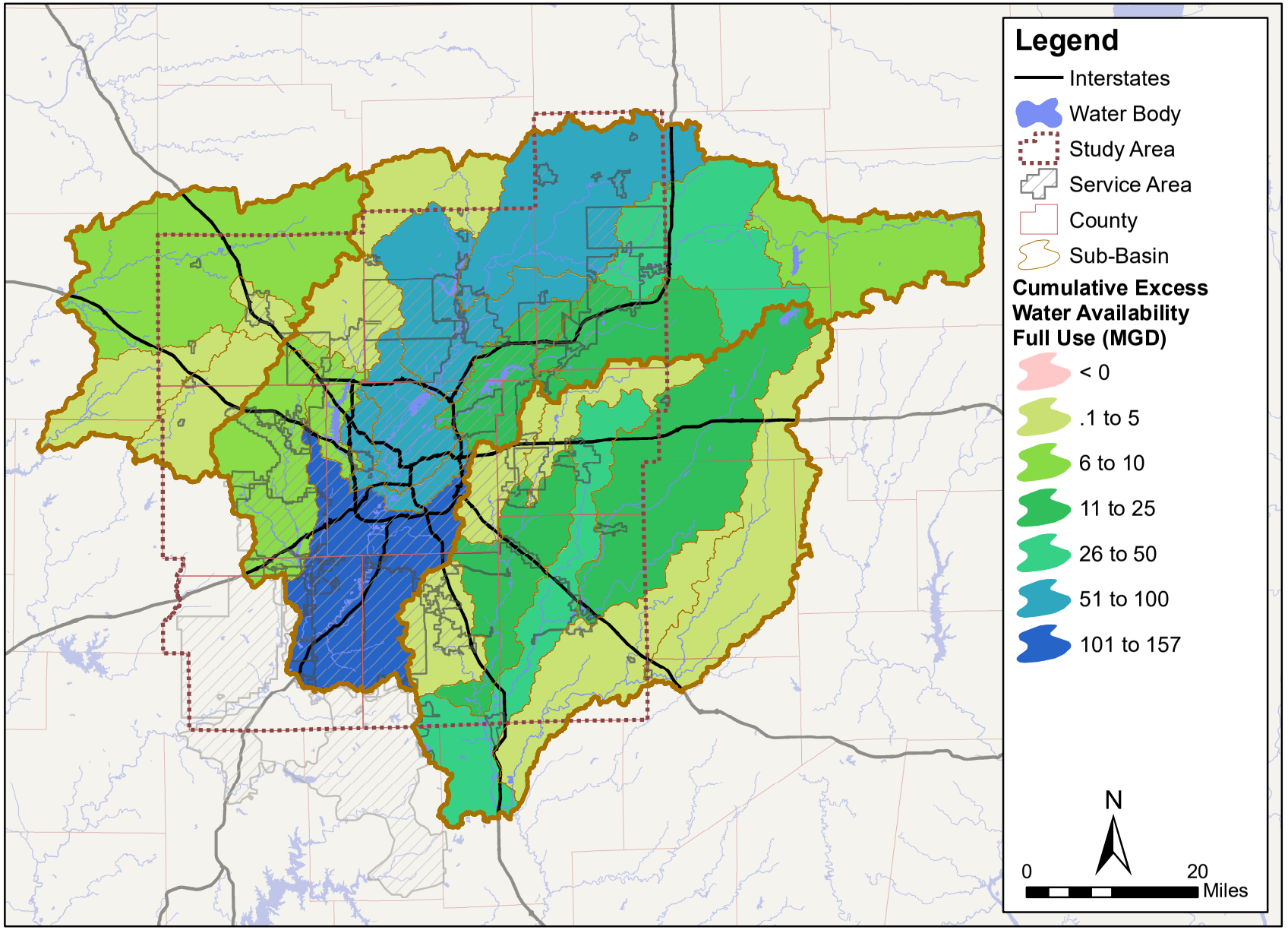

Figure 3.7: Minimum, Quarter 3, cumulative excess water availability, 2007-2017. *Excess water from upstream sub-basins is used in downstream sub-basins with negative excess availability. Note that there are no negative cumulative values. Although colors are applied to an entire sub-basin, cumulative excess availability is computed at the downstream end of each sub-basin. Assessment based on full use of storage in Morse and Geist Reservoirs.*

3.3 Cumulative Availability along the White River, 2012

A graphical summary of results may be made by plotting cumulative values versus river mile, from upstream to downstream, along major rivers and tributaries in the water availability model. Here, we present results for the White River. This alternate method of visualizing results highlights features of the sub-basins with the largest water withdrawals and return flows in the Central Indiana region.

Figure 3.8 presents the components of cumulative water availability along the White River, from Sub-basin 2 through 13. The results correspond to Quarter 3, 2012, with full use of storage in Morse and Geist Reservoirs. Water availability in a sub-basin is expressed by equation (1), repeated here

$$\text{Sub-Basin:} \quad Q_{wa} = Q_{nbf} - Q_{if} + Q_{stor} \tag{12}$$

The cumulative water availability at the outlet of a sub-basin (Q_{cwa}) is obtained by summing the values of all upstream sub-basins

$$(Q_{cwa})_m = \sum_{n=1}^{m} (Q_{wa})_n = \sum_{n=1}^{m} (Q_{nbf} - Q_{if} + Q_{stor})_n \tag{13}$$

where m is the downstream sub-basin where the cumulative values are being evaluated and n includes all connected upstream sub-basins contributing to water availability.

As illustrated in Figure 3.8, the cumulative natural baseflow increases steadily moving downstream along the White River. The cumulative instream flow, which in Quarter 3 is defined as the $Q_{7,10}$, also rises steadily through Sub-basin 5. Current and historic large withdrawals for public supply result in lower values of the $Q_{7,10}$ in Sub-basin 8. The $Q_{7,10}$ increases abruptly at the outlet of Sub-basin 11, where large return flows from the Belmont Advanced Wastewater Treatment Plant occur. The cumulative reservoir storage appears as horizontal lines with abrupt increases where Cicero Creek and Fall Creek join the White River, due to contributions from Morse and Geist Reservoirs, respectively.

Figure 3.9 presents cumulative water availability and cumulative net withdrawals by river mile. The cumulative net withdrawals are equal to the sum of all upstream water withdrawals minus the sum of all upstream return flows. Cumulative water availability grows steadily through Sub-Basin 3, while cumulative net withdrawals remain fairly constant. This indicates that withdrawals are largely equal to return flows through Sub-basin 3.

The difference between the ***cumulative water availability*** and the ***cumulative net withdrawal*** curves at any location along the river is equal to the ***cumulative excess water availability*** at that location. The cumulative excess water availability grows at a near-constant rate through Sub-basin 3. The slope of the cumulative water availability curve increases sharply downstream of Sub-basin 3. This break in slope is caused by the decrease in the $Q_{7,10}$ across Sub-basin 8, illustrated in Figure 3.8. The slope of the cumulative net withdrawals also increases sharply across Sub-basins 5 through 8, due to large withdrawals relative to return flows for

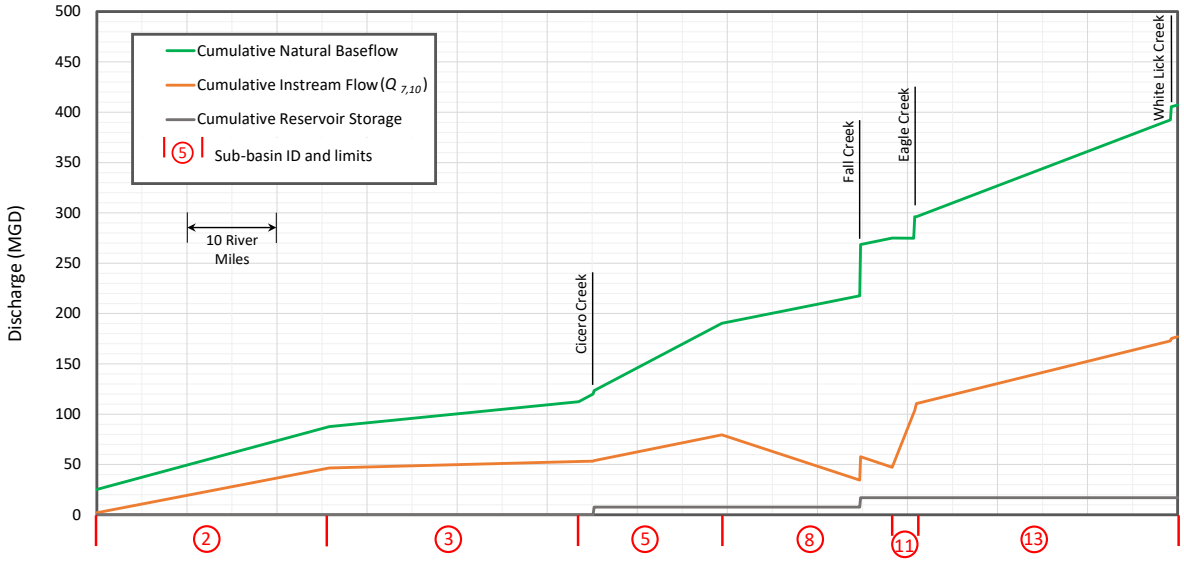

Figure 3.8: Components of cumulative water availability by river mile along the White River in Quarter 3, 2012. *Each component is assumed to vary linearly between sub-basin boundaries, except at junctures with major tributaries, where each component increases abruptly. Assessment based on full use of storage in Morse and Geist Reservoirs.*

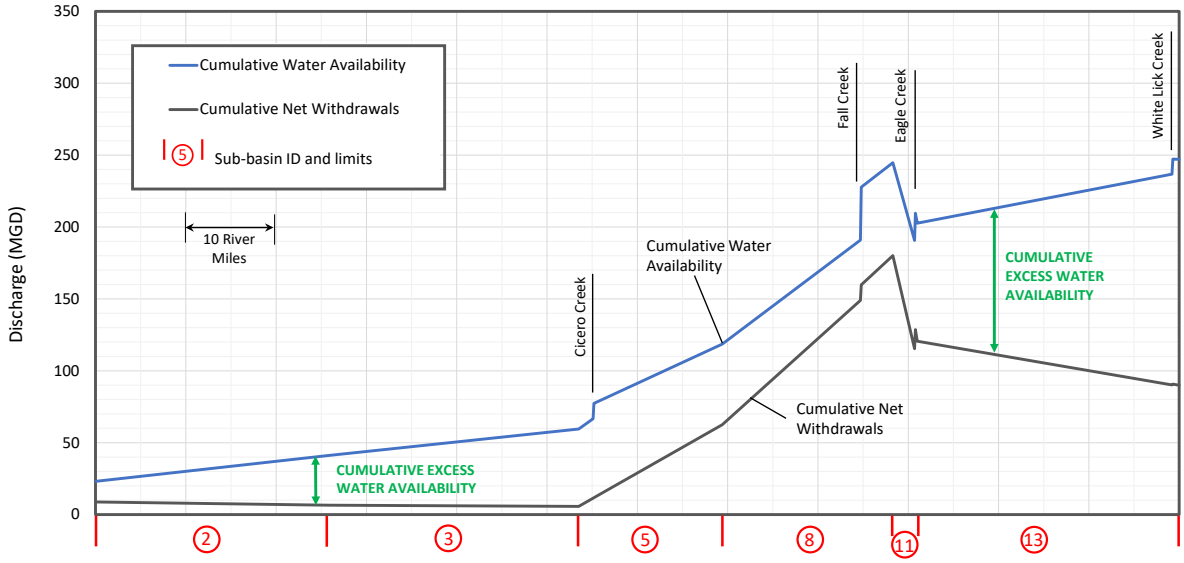

Figure 3.9: Cumulative water availability, net withdrawals, and excess water availability by river mile along the White River in Quarter 3, 2012. *Net withdrawals includes all upstream water withdrawals minus all return flows. Each component is assumed to vary linearly between sub-basin boundaries, except at junctures with major tributaries, where each component increases abruptly. Assessment based on full use of storage in Morse and Geist Reservoirs.*

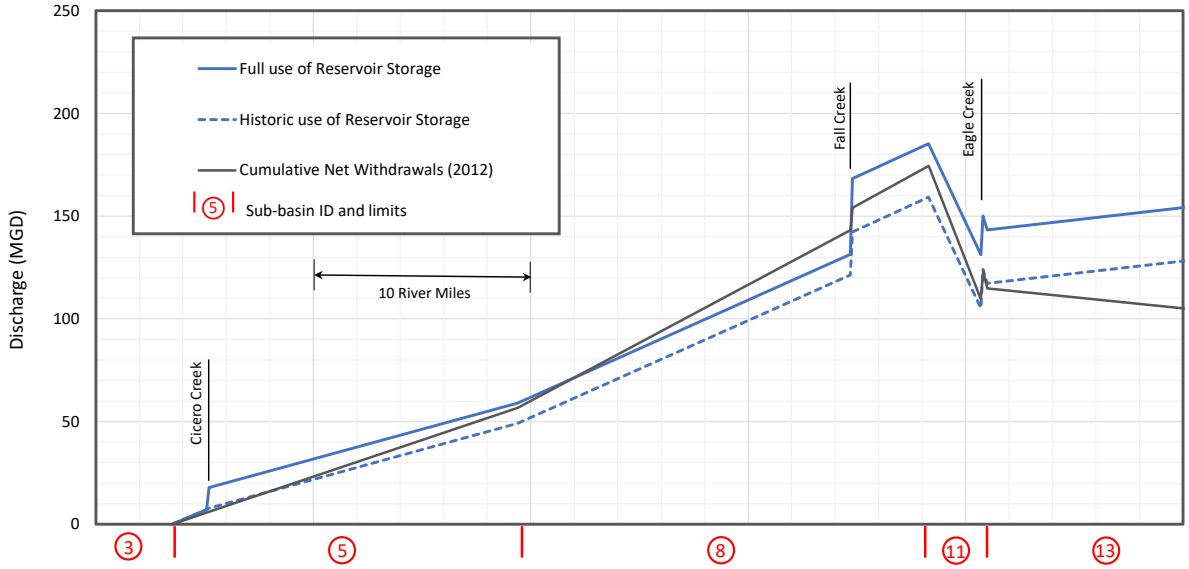

Figure 3.10: Cumulative water availability (*blue lines*) and net withdrawals, relative to the upstream boundary of Sub-basin 5, along the White River in Quarter 3, 2012. *The figure illustrates the reliance of Hamilton and Marion Counties on excess water availability from upstream. Net withdrawals includes all upstream water withdrawals minus all return flows. Each component is assumed to vary linearly between sub-basin boundaries, except at junctures with major tributaries, where each component increases abruptly.*

both mining and water supply by multiple utilities in Sub-basin 5, and large withdrawals by Citizens Water in Sub-basin 8 with no major return flows. In this region the cumulative excess water availability gradually decreases when moving downstream. Sub-basin 11 contains minor withdrawals and major return flows at the Belmont Advanced Wastewater Treatment Plant. From Sub-Basin 11 through 13, there is a much larger cumulative excess water availability than upstream.

Figure 3.10 illustrates the reliance of Hamilton and Marion County water supplies on excess water availability from upstream sub-basins in Quarter 3 of 2012. In the Figure, cumulative water availability and cumulative net withdrawals are calculated starting at the upstream boundary of Sub-basin 5. In this way, excess water availability from Sub-basins 1 through 3 are eliminated from the cumulative values. Cumulative availability based both on historic use of reservoirs and full use of reservoirs are shown. Both availability curves fall below the cumulative net withdrawals curve between Sub-basins 5 and 8, indicating a deficit in cumulative excess water availability across Hamilton and Marion Counties. Apparently, in 2012, water demands in those counties were met through use of excess water availability from upstream sub-basins.

3.4 Summary

Results of the water-availability assessment provide insight into the spatial and temporal distribution of water withdrawals, return flows, natural baseflow, reservoir releases and instream flow requirements throughout the Central Indiana region. Water availability is limited by seasonal low flows that usually occur in the late summer and fall. The natural hydrologic conditions are characterized by lower baseflow in Quarters 3 (July through September) and 4 (October through December); Quarters 1 (January through March) and 2 (April through June) are characterized by relatively large natural baseflow in streams, with net excess availability in most sub-basins. Temporal variations in water demand and returns at wastewater treatment plants are also characterized by relatively large withdrawals and relatively low returns during Quarter 3. Therefore, throughout this report, Quarter 3 is defined as the critical period for evaluating excess water availability. For the period of record (2007-2017), the critical year for excess water availability varies by sub-basin, with 2007, 2009 and 2012 being the most frequent critical years. 2012 represents the critical year for cumulative excess availability in the region.

Throughout the region, excess water availability in the driest months depends upon the discharges from permitted wastewater treatment plants upstream. The public water supply in Central Indiana relies on ***indirect water reuse***. Discharge from wastewater treatment plants is as important to maintaining availability as is the natural baseflow. This conclusion is consistent with recent studies of water re-use in the Wabash River watershed (Wiener et al., 2016, 2020), and has implications for projecting water availability into the future (Section 6): increases in future demand in the Public Supply sector are largely offset by increases in discharge from wastewater treatment plants.

Finally, availability of water in the state is not limited by any current regulation of instream flow levels. The IDNR recommends a minimum instream flow equal to the $Q_{7,10}$. In the White River drainage system, with large anthropogenic effects on streamflow, the $Q_{7,10}$ is more a reflection of past water withdrawal and returns than it is a measure of ecological health of the River. In this study, the annual Q_{90} is used as a default value for instream flow in Quarters 1 and 2, and the $Q_{7,10}$ is used in the critical Quarters 3 and 4. Increasing the instream flow requirements will directly decrease excess water availability.

Variations in excess water availability occur in the three major drainage systems in the region. Characteristics of each drainage system are described below.

White River and tributaries The White River and tributaries drainage system is characterized by locally large water withdrawals for public supply and power generation, focused in Marion and Hamilton Counties. Similarly large return flows occur at major wastewater treatment plants, with large withdrawals and returns typically occurring in adjacent basins. Sub-basins with deficits in Quarter 3 excess availability include Sub-basin 5 (Noblesville through Nora region), Sub-Basin 7 (Geist Reservoir and downstream reaches of Fall Creek), Sub-basin 8 (Indianapolis region), Sub-basin 10 (Eagle Creek from the reservoir through Speedway) and

Sub-basin 13 (South Indianapolis through Centerton).

Sub-basin 5 in Hamilton County has a deficit in excess availability, due primarily to extreme summer demands for public supply, low summer return flows at wastewater treatment plants, and dewatering of two quarries operated by Martin Marietta. Sub-Basin 8 in Marion County includes large withdrawals by Citizens Water for public supply; major return flows from the Belmont Advanced Wastewater Treatment Plant occur in the adjacent downstream sub-basin (11), which is characterized by large excess availability.

Results show that when full use of the available storage in Morse and Geist Reservoirs is made, deficits in Sub-basins 5 and 7 are greatly reduced, or eliminated.

Tributaries of the Wabash River The tributaries of the Wabash River drainage system is characterized by small water withdrawals, small return flows, and large variation in natural baseflow. In the period 2007-2017, excess water availability has been very low in each sub-basin, but has not been negative. However, there is little room for increasing the water supply in this region due to frequent periods of low baseflow.

East Fork White River and tributaries The East Fork of the White River and tributaries drainage system is also characterized by small water withdrawals, small return flows, and large variation in natural baseflow. In the period 2007-2017, excess water availability has been very low in each sub-basin, and has become negative in two downstream sub-basins. The negative values are due to periods of extremely low to zero natural baseflow, rather than excessive anthropogenic effects (withdrawals and returns). Sub-basins 5 and 8 (Greenfield through Columbus) in Shelby and Franklin Counties have negative excess availability, due primarily to the operation of irrigation wells in the downstream reaches of each basin. In both cases, most withdrawals for public supply occur upstream in the basins.

Cumulative Excess Availability Despite several sub-basins with deficits in excess availability, minimum Quarter 3 cumulative excess availability has been positive for the period of record, 2007-2017, in the entire Central Indiana region. This highlights the fact that informal transfers of excess water between sub-basins is an important feature of the regional water supply system, as it exists today. The water supply for both Hamilton and Marion Counties depends, in part, on excess water availability in upstream sub-basins.

4 Major Changes in Water Use and Returns, 2007-2017 and Beyond

Understanding current water availability and predicting future conditions requires an investigation of the relationship between water use and water returns for the major water-use sectors, as well as an evaluation of any recent major changes to the system. Here we consider the following major changes from the last decade that impact current and future water availability in the Central Indiana region:

- Regional relationships between withdrawals for public supply and the corresponding return flows at wastewater treatment plants
- Projected impacts to wastewater treatment plant discharge and stream baseflow due to the DigIndy Deep Tunnel Interceptor Project
- Significant changes in water demand in the Energy Sector
- Impacts of the Mining Sector on water availability
- Impact of Citizens improvements to water-supply infrastructure on water accessibility and availability
- Impact of the new Citizen Reservoir on future water availability

4.1 Public Supply Withdrawals and WWTP Returns

In general, the relationship between withdrawals for public supply and returns from wastewater treatment plants will vary from system to system depending on the characteristics of both the water-supply service area and the service area for the sanitary district collecting and treating wastewater. Some conclusions can be drawn, however, by investigating larger regions. In the Central Indiana region, we separate regions by two categories: those whose sanitary systems include combined sewer overflows (CSOs) and those that do not.

Figure 4.1 (*top*) illustrates the relationship between total public supply withdrawals and total wastewater treatment plant returns for the White River from the headwaters through the Nobleseville Wastewater Treatment Plant (Sub-basins 1, 2, and 3). This is a region that is serviced by CSOs and we see peak water withdrawals occurring in Quarters 3 and 4, with peak returns flows occurring in Quarters 1 and 2. During Quarter 3, we observe that the withdrawals and return flows become approximately equal. On an annual average, more treated wastewater is returned to the White River than is withdrawn for public supply, due primarily to the combined sewer system delivering storm water to the treatment plants, and infiltration and inflow to the sanitary system.

In contrast, Figure 4.1 (*middle*) illustrates the relationship for the region downstream from the Noblesville wastewater treatment plant to the Carmel treatment plant with withdrawals

Table 4.1: Examples of ratios of wastewater treatment plant discharges to public supply withdrawals and annual average discharges in the White River drainage system, 2007-2017.

Region	Sub-Basins	Quarterly Values Q1 (–)	Q2 (–)	Q3 (–)	Q4 (–)	Annual Averages WWTP (MGD)	PS (MGD)	CSO
White R. to Noblesville WWTP	1,2,3	2.1	2.0	1.2	1.5	46	27	Yes
Cicero Creek to Arcadia	4	4.1	3.8	2.1	3.1	1.4	0.45	Yes
Noblesville through Nora	5	0.94	0.86	0.46	0.62	22	33	No
Indianapolis with Belmont and Southport WWTPs	8,11,13	2.1	2.2	1.5	1.8	174	93	Yes
White Lick Crk. to Mooresville	12	2.1	1.8	1.2	1.7	12	7	Yes

Notes: MGD = million gallons per day. CSO = combined sewer overflow.

WWTP = Wastewater Treatment Plant. PS = Public Supply.

from Sub-basin 5. Sanitary systems in this region do not include CSOs, but there is heavy water use during Quarters 3 and 4, presumable related to watering of private lawns. Here, the relationship between supply and returns is inverted: during Quarters 3 and 4, there is significantly more water withdrawn than returned, and the curves approach each other during Quarters 1 and 2. On an annual basis, much more water is withdrawn than returned directly to the river.

Finally, Figure 4.1 (*bottom*) illustrates the relationship for the region along the White River from Nora through the Southport treatment plant. Withdrawals occur in Sub-basins 8 and 11, with return flows concentrated at the Bellmont and Southport Advanced Wastewater Treatment Plants. The region serviced by the treatment plants is highly urbanized with an extensive system of CSOs. Once again, we see a relationship similar to that illustrated on the top of the figure, with annual return flows exceeding withdrawals more significantly here.

Figure 4.2 illustrates the regional relationships between public supply withdrawals and wastewater treatment plant return flows for the three drainage systems in the study area: White River drainage system (*top*), tributaries of the Wabash River drainage system (*middle*), and the East Fork White River and tributaries (*bottom*).

Relationships have been identified in each of the three drainage systems of the study area, and are used to predict future quarterly average wastewater treatment plant returns based on predictions of changes in public supply withdrawals. The regions and quarterly relationships identified from the 2007-2017 records are summarized in Tables 4.1 and 4.2. The White River drainage system is subdivided into smaller regions, while the tributaries of the Wabash and the East Fork White River and tributaries are not.

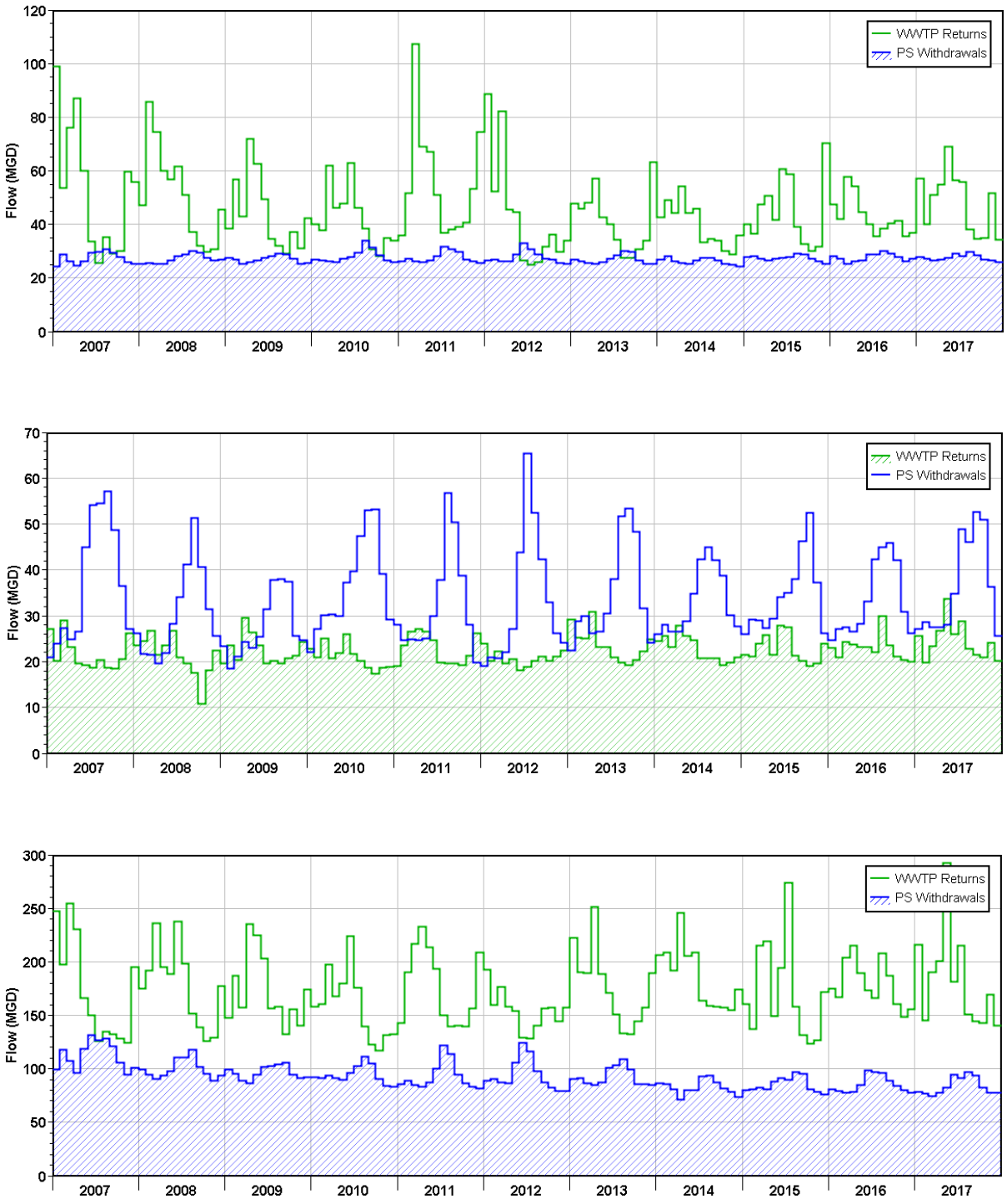

Figure 4.1: Relationship between withdrawals for public supply and returns at WWTPs. *White River through Noblesville (top), Carmel region from Noblesville to Nora (middle), and Indianapolis from Nora through Southport (bottom).*

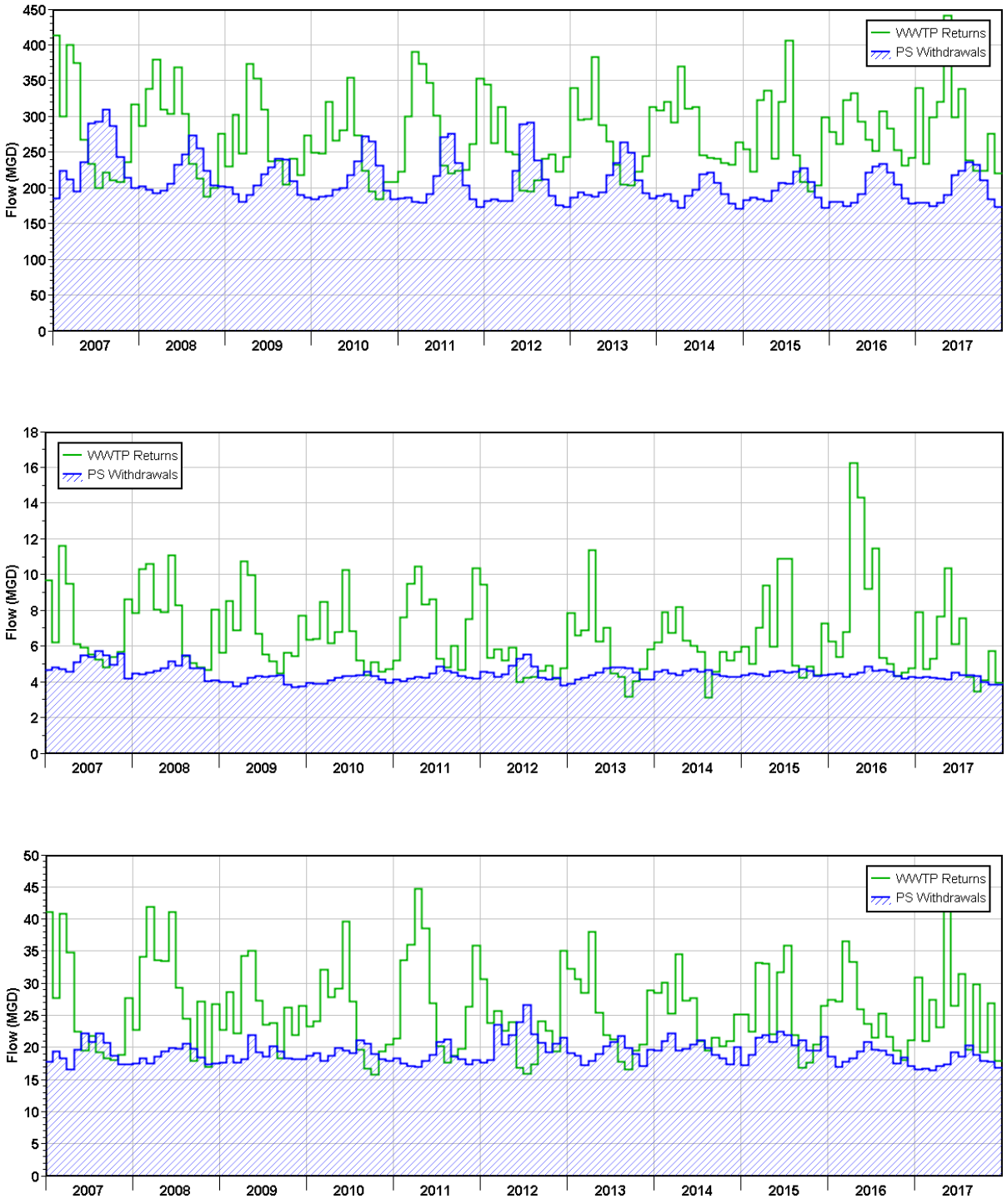

Figure 4.2: Relationship between withdrawals for public supply and returns at WWTPs. *White River drainage system (top), tributaries of the Wabash River (middle), and East Fork White River and tributaries (bottom).*

Table 4.2: Ratios of wastewater treatment plant discharges to public supply withdrawals, and annual average discharges in the Wabash River tributaries and East Fork White River and tributaries drainage systems, 2007-2017.

Region	Sub-Basins	Quarterly Values Q1 (–)	Q2 (–)	Q3 (–)	Q4 (–)	Annual Averages WWTP (MGD)	PS (MGD)	CSO
Wabash Tributaries	1-4	1.7	1.9	1.2	1.3	6.6	4.4	Yes
East Fork and Tributaries	1-8	1.6	1.5	1.1	1.2	26	19	Yes

Notes: MGD = million gallons per day. CSO = combined sewer overflow.

WWTP = Wastewater Treatment Plant. PS = Public Supply.

4.2 DigIndy Deep Rock Tunnel System

The DigIndy Tunnel System is a 28 mile long network of 18 foot diameter tunnels constructed up to 250 feet below ground under the City of Indianapolis. The Tunnel system is designed to reduce combined sewer overflows into rivers and waterways, satisfying a consent decree by the U.S. EPA and IDEM. The Tunnel System will be capable of storing of more than 250 million gallons of combined sewage during and after wet weather, and then slowly pumping the sewage, at a maximum rate of 30 MGD, to the Southport Advanced Wastewater Treatment Plant. After treatment, the clean water is discharged to the White River (Citizens, 2020b).

Expansions and improvements to both the Belmont and Southport Advanced Wastewater Treatment Plants are included in the tunnel project. Improvements to Belmont plant, completed in 2012, included 34 million gallons of wet-weather storage basins, and expanded treatment capacity to 300 MGD. These improvements eliminate the need to bypass sewage from Belmont to the Southport Plant during wet weather. Figure 4.3 illustrates the monthly and annual average discharges from the Belmont (*top*) and Southport (*middle*) treatment plants. Return flows from Belmont increase upon completion of the 2012 upgrades, while the Southport returns decrease slightly with bypass flows from Belmont eliminated. The combined returns from the two plants are illustrated in the bottom figure, showing little change in total discharge through 2017.

The Southport plant completed a significant system expansion in 2018, to allow a peak treatment rate of 250 MGD. The Southport plant has been redesigned to receive flow directly from the Deep Rock Tunnel Connector Pump Station when the tunnel system becomes active. Future water availability will be impacted through increased return flows from both major treatment plants. In addition, the Tunnel will capture stormflows that in the past would have discharged directly to surface waters. The stormflow is stored in the tunnel system and released slowly to the Southport plant, acting like a detention basin. This will, to an unknown extent, reduce stormflows in the White River and tributaries while increasing baseflow. This

slow release from storage is not considered in the estimates of future availability presented in Section 6.

4.3 Energy Sector

Within the last decade, three large energy producers have completed plant conversions from coal to natural gas, reducing water withdrawals significantly. All reside in the White River drainage system, and include the Perry K Steam Plant, the Harding Street Station, and the Eagle Valley Generating Station.

The Perry K Steam Plant, currently owned by Citizens Energy Group, provides steam for heat and hot water and chilled water to commercial and industrial buildings in downtown Indianapolis (Citizens, 2020c). The plant began conversion from coal to natural gas in 1998, and completed the conversion in 2014. The plant withdrawals water from the White River for non-contact cooling water and discharges return flows back to the White River. Both water withdrawals and returns have been significantly reduced since 2011, as illustrated in Figure 4.4 (*top*).

Indianapolis Power and Light (IPL) completed conversion of the Harding Street Station from coal to natural gas in 2016 (IPL, 2020b). The conversion greatly reduced water withdrawals and return flows to the White River, as illustrated in Figure 4.4 (*middle*). IPL has also retired the coal system at Eagle Valley Generating Station in Martinsville, and constructed a combined cycle gas turbine plant. Construction began in 2016 and was completed in 2018 (IPL, 2020a). Figure 4.4 (*bottom*) illustrates the decrease in water withdrawals and returns at the Eagle Valley Plant, as the coal plants were retired and construction began on a new plant.

As discussed in the Phase 1 report, water withdrawals for energy generation are very high, but have decreased significantly in the recent past, due to conversion of power plants from coal to natural gas. Even at the high withdrawal levels of the past, only minimal consumptive use of water was required by the energy sector. Most of the water withdrawals for energy generation were returned to the River, as illustrated in Figure 4.4. Consumptive use (withdrawals minus returns) for each of the plants appears to be within the reporting error for return flows. For future conditions, presented in Section 6, given the investment the energy sector has made, we assume the consumptive use of the energy sector remains negligible, meaning that returns are equal to withdrawals.

4.4 Mining Sector

In the Central Indiana region, mining-sector withdrawals and returns typically balance, as withdrawals reflect dewatering of quarries or gravel pits and returns represent dewatering discharges to surface water. However, there are discrepancies between reported withdrawals and returns for major dewatering operations in the region. We discuss small-scale and large-scale dewatering operations in the region, and data discrepancies below.

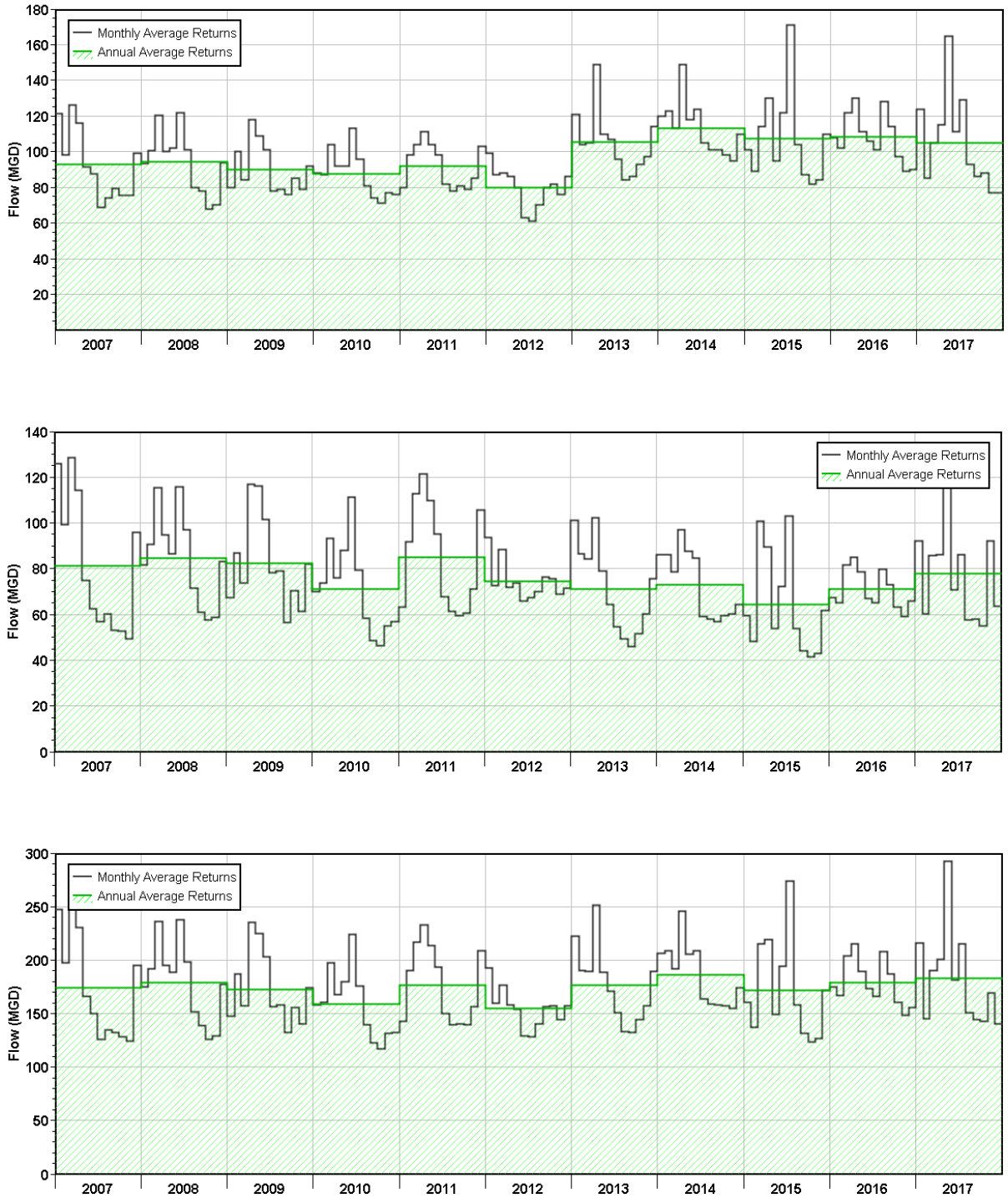

Figure 4.3: Returns flows at Belmont AWTP (*top*), Southport AWTP (*middle*), and the total returns from both plants (*bottom*).

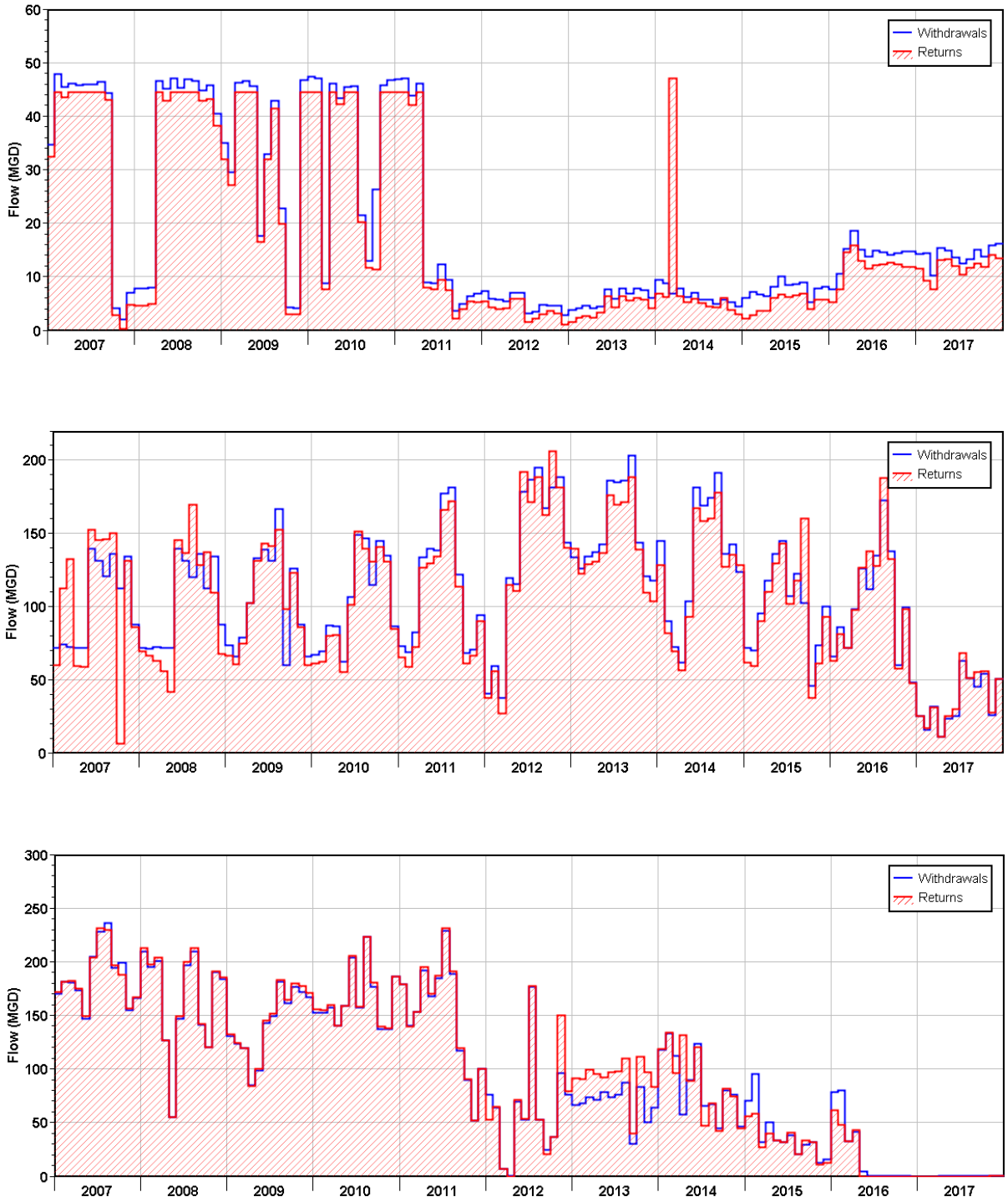

Figure 4.4: Water withdrawals and return flows at major energy producers. *Perry K steam plant in Sub-basin 8 (top), IPL Harding Street station in Sub-basin 13 (middle), and IPL Eagle Valley (bottom) downstream from Sub-Basin 13. All plants are in the White River drainage system.*

4.4.1 Small-Scale Dewatering Operations

There are many small quarry and sand and gravel operations throughout the Central Indiana region, reporting small water withdrawals. Water withdrawals and return flows are typically generated for these systems by the need to dewater or remove water from the operation. Figure 4.5 illustrates water withdrawal and return records for two small-scale dewatering operations. Figure 4.5 (*top*) illustrates conditions at a quarry along Stony Creek in Sub-basin 5 of the White River drainage system, owned by Irving Materials. The figure shows that, in general, withdrawals match returns except for some discrepancies. The discrepancies may indicate errors in reporting either water withdrawals or NPDES return flows. For example, the period from 2014 through 2016 was investigated by the IDNR Division of Water, who found that reporting for that period was made in the wrong units (Personal Communication, Mark Basch, IDNR, July 21, 2020). Figure 4.5 (*botto*m) illustrates conditions at Hanson Aggregates in Sub-basin 13 of the White River drainage system. At this site, the dewatering operation appears to have been expanded in 2014 with increasing return flows starting in 2015. It is unclear if there is a reporting error in return for 2015; in this case, the cumulative withdrawals and returns are similar. In both examples, total withdrawals and return flows are similar, and net consumptive use of water appears to be negligible.

4.4.2 Large-Scale Dewatering Operations

Several large quarries also exist in the White River drainage system, reporting more significant water withdrawals. Water withdrawals for dewatering at these quarries is often returned to an inactive quarry or pond on-site. These return flows do not require an NPDES permit. Typically, the only monitoring requirement for dewatering discharges is suspended solids, and if water is returned on-site to a pond, the suspended solids would likely be removed before discharging to a water of the State. Dewatering withdrawals may also be used for aggregate washing and dust control. The consumptive use at these sites cannot be determined with the available data, yet all water withdrawn is returned to the hydrologic system, either directly through NPDES permitted outfalls, or indirectly through concentrated infiltration from inactive quarries.

Figure 4.6 shows withdrawals and returns at three major quarry operation owned by Martin-Marietta. In each case, reported withdrawals greatly exceed reported returns.

4.4.3 Comments on Quality and Interpretation of Data Sets

Any database of self-reported information will include reporting errors, and some errors may be significant. Some errors in reporting water withdrawals were identified in Section 4.4.1. Other errors appear in the EPA ECHO database. Return flows for three Martin Marietta operations illustrated in Figure 4.6 appear to be negligible from 2007 through 2011, when querying the online ECHO database to report average daily discharges. Closer investigation, and comparison with EPA facility records downloaded directly from facility reports suggest that reporting

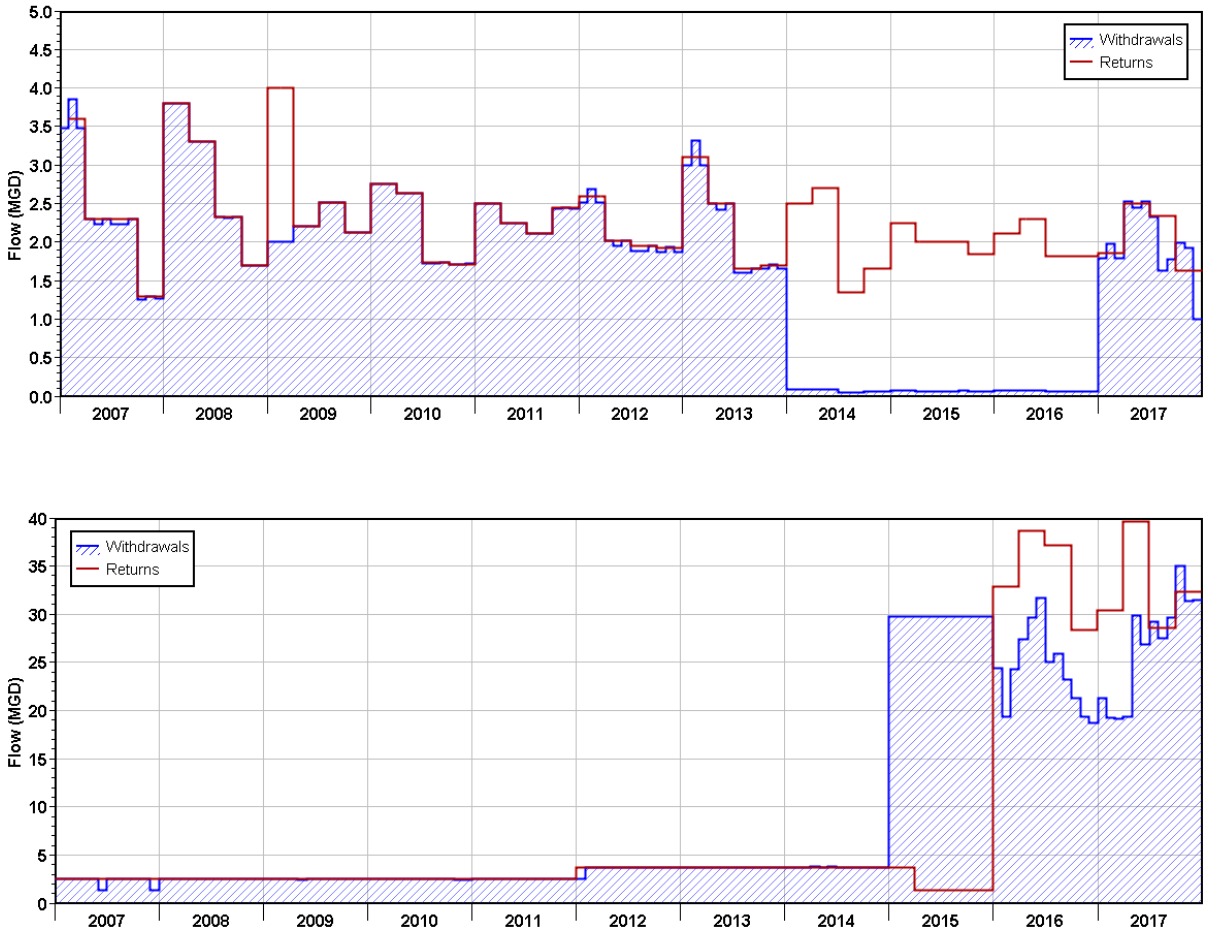

Figure 4.5: Typical mining withdrawals and return flows. *Iriving Mateirals (Stony Creek) in Sub-basin 5 (top), and Hanson Aggregates in Sub-basin 13 of the White River system (bottom).*

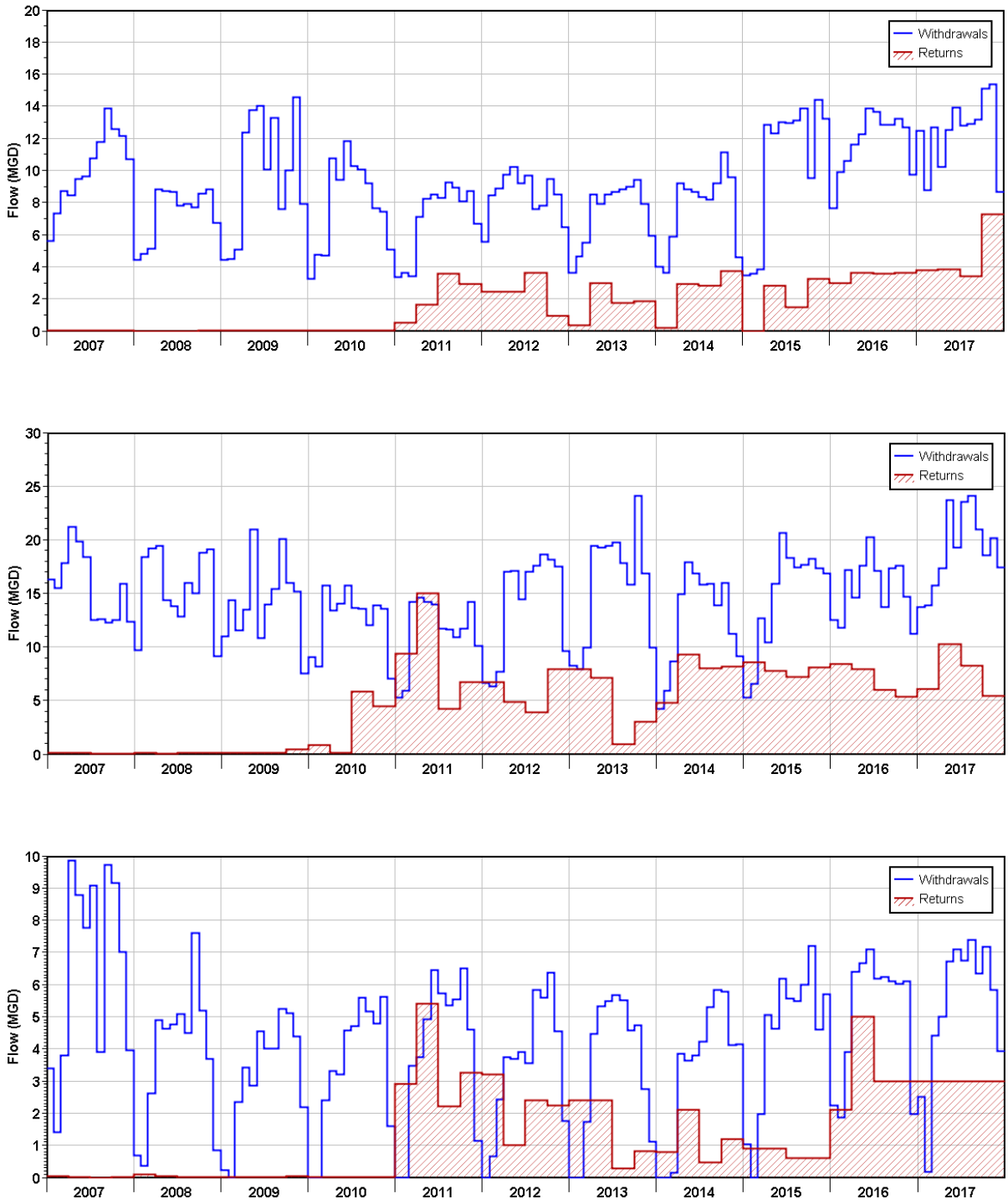

Figure 4.6: Water withdrawals and return flows for larger mining operations in the White River drainage system. *Martin Marietta operations in Noblesville (top) and North Indianapolis (middle) in Sub-basin 5, and south of Harding Street (bottom) in Sub-basin 13.*

requirements for Martin Marietta changed in 2011. Prior to that year, ***maximum*** daily discharge per quarter was reported; starting in 2011 the ***average*** daily discharge per quarter was reported. When reporting average monthly flows, we conjecture that the ECHO database miss-interprets the maximum quarterly discharge as total volume discharged per quarter and calculates an erroneous average daily flow.

These are just two examples that illustrate the potential errors inherent in the databases used for this study. These errors can be expected to occur. The approach used in this study of tracking and comparing both withdrawals and returns for a facility, provides one approach to quality control.

4.5 Citizens Water Infrastructure Projects

Since acquiring the Indianapolis water supply utility in 2011, Citizens has conducted infrastructure improvement projects to expand water accessibility and availability in their service areas and provide a more resilient water supply. Projects include the new 30th Street surface-water intake. In 2018, Citizens opened a surface-water intake north of 30th Street, able to divert water from the White River to the Central Canal. The intake is located in Sub-Basin 8 of the White River drainage system. Currently the intake cannot be operated due to failure of the Emerich Dam at 16th Street in 2018. Before failure, the dam maintained an upstream pool allowing the intake to operate during periods of low streamflow. A new rock ramp structure is planned for construction in Riverside Park to recreate the pool and allow the intake to operate. The intake will be used to meet peak water demand during summer and drought conditions by diverting up to 10 MGD from the White River. In addition, a new intake was constructed near 16th Street that allows water to be transferred from Fall Creek to the Central Canal. Both of these intakes are assumed to be operable in all assessments of future excess water availability.

The new intakes increase the accessibility to water in the White River and Fall Creek, especially during low flows. This increase in accessibility also results in an increase in water availability. Citizens two reservoirs (Morse and Geist) store water to be released to supplement streamflow during drought conditions. In the past, the inability to capture the water released from the reservoirs at low streamflows limited the use of reservoir storage. Here, increased accessibility leads to increased availability as water that previously would have remained in storage will now be released from the reservoirs to be captured downstream. Citizens infrastructure improvements will allow for full use of reservoir storage during drought conditions.

In 2019, Citizens Energy Group began converting a former limestone quarry adjacent to Geist Reservoir into a water-storage reservoir, named Citizens Reservoir. The quarry lies at the northern, upstream end of Geist Reservoir, and was formerly owned and operated by Irving Materials Inc. The quarry site is shown in Figure 4.7. When completed, the reservoir will have a relatively small surface area of approximately 90 acres, with a large depth of 220 feet. When full, the reservoir will hold up to three billion gallons of stored water. The reservoir will be operated solely for purposes of water storage with no public access for development or

recreation. The reservoir is planned to be operational in 2021 (Citizens, 2020a).

Operation of the reservoir will include diverting excess flows from Fall Creek during high flow periods to fill the reservoir. During drought conditions or periods of high water consumption, up to 30 MGD can be pumped from the reservoir into Geist Reservoir. The pumped water will flow from Geist reservoir downstream in Fall Creek, making the released water available for withdrawal by Citizens water-supply wells and surface intakes.

When operational, the Citizens Reservoir will provide a flexible and reliable storage source to supplement drought supplies in the region. Other storage reservoirs including Morse and Geist, have complications related to emergency supply diversions, including public relations related to significant reductions in lake levels that have negative impacts on recreation and lake frontage real estate. Water levels in Citizens Reservoir can change without public notice, allowing greater flexibility as a drought supply. Also, the large surface areas of Morse and Geist Reservoirs result in high evaporative losses at rates of 7 to 9 MGD during summer months, whereas the small footprint of the Citizens Reservoir results in much smaller losses during critical drought periods of less than 0.5 MGD.

Figure 4.8 illustrates the impacts Citizens infrastructure projects have had on regional water availability. The figure presents cumulative water availability for three scenarios, based on Quarter 3, 2012 hydrologic conditions: the dotted blue line represents cumulative water availability based on historic use of Geist and Morse reservoir; the dashed blue line represents cumulative water availability when full use of reservoir storage is possible, due to construction of the new intakes; and, the solid blue line represents future conditions making full use of existing reservoir storage, and operation of the Citizens Reservoir. In total, the increase in cumulative water availability, and cumulative excess availability in Sub-basin 8 is 56 MGD. These improvements provide for future growth of the public water supply system, adds resiliency to the existing system, and reduces reliance on excess water availability from upstream sub-basins.

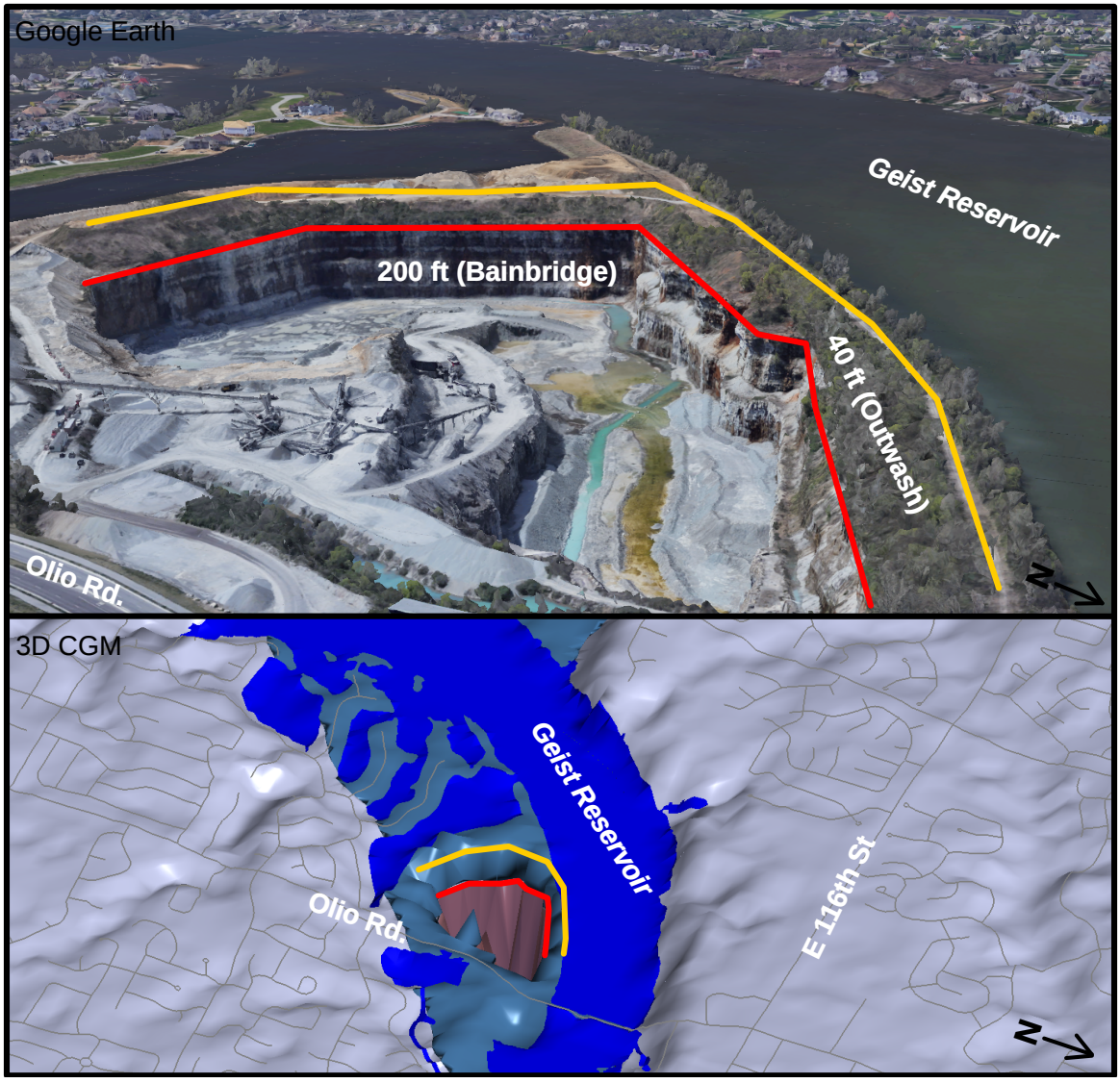

Figure 4.7: Citizens Reservoir, located at the north end of Geist Reservoir in Sub-basin 7 of the White River drainage system. *The reservoir will be capable of providing a 30 MGD supply during low-flow conditions on Fall Creek when completed. The top figure shows aerial photography of the empty reservoir; the bottom figure shows the Geologic model with surfaces between formations.*

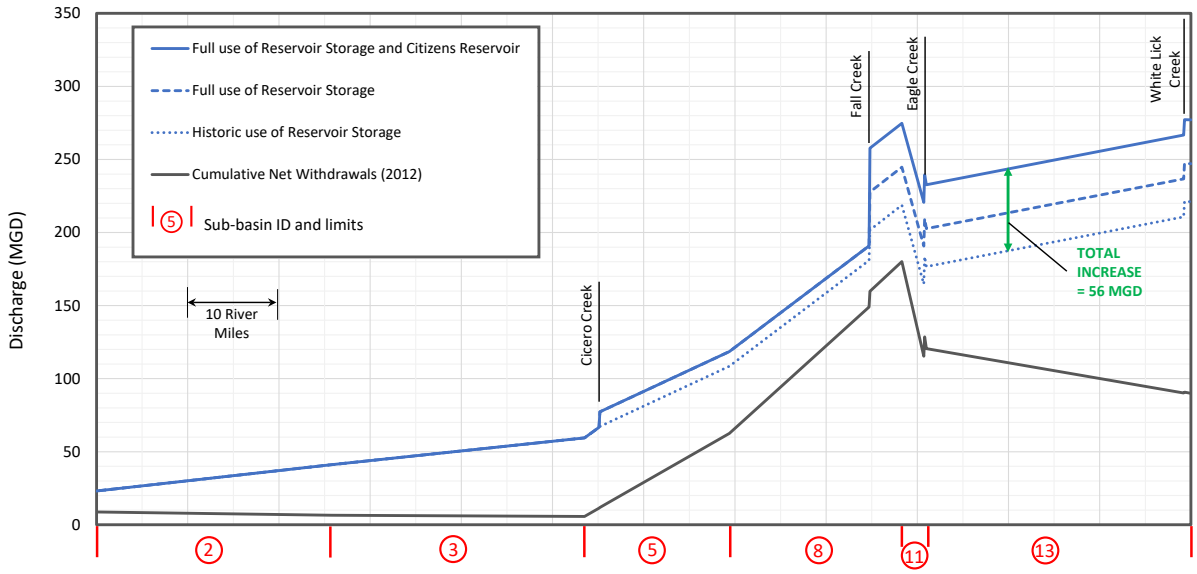

Figure 4.8: Impacts of Citizens infrastructure projects on cumulative water availability (*blue lines*), relative to cumulative net withdrawals.

4.6 Summary

Major features of, and major changes to water use and return flows in the Central Indiana region are described above. While all are hydrologically important, only a subset has an impact on regional water availability and excess availability. These include the relationship between public supply withdrawals and discharges from wastewater treatment plants, and Citizens infrastructure improvements. Changes in the water withdrawals and returns in the energy sector described above have no net impact on water availability; withdrawals generally equal return flows, and intakes and outfalls typically lie within a short distance from each other, in the same sub-basin. Withdrawals and returns in the mining sector suggest negative impacts to net excess water availability; however, this is likely due to a lack of understanding of the plant water budgets in the large quarry operations.

The presence or absence of CSOs in a sub-basin is the dominant feature controlling the annual and quarterly relationship between public supply withdrawals and wastewater treatment plant returns. As illustrated in Figures 4.1 and 4.2, annual average return flows in basin with CSOs are typically larger than annual average withdrawals for public supply. This is due to the combined sewer systems delivering stormwater runoff to the treatment plant during wet periods. However, during dry periods, such as Quarter 3, stormwater runoff is minimal and return flows approach public supply withdrawals. While CSOs have a major impact on surface water quality caused by release of sanitary water to stormwater outfalls, their impacts on excess water availability during the critical Quarter 3 period is less significant. The impacts are related to the transfer of excess availability within and between sub-basins, without significant impact

on net excess availability. The implication for future availability, addressed in Section 6, is that increases in withdrawals for public supply will largely be offset by return flows from wastewater treatment plants. The cumulative excess availability in a region may not change, but the distribution of excess availability within sub-basins and between sub-basins will change.

Transfer of combined sewer overflows into temporary storage in the Deep Tunnel system will produce a net increase in annual discharge from the Belmont and Southport treatment plants. Combined stormwater and sanitary overflows will be directed to temporary storage in the tunnel system rather than discharging directly to surface waters. The stored water will then be treated and released at a rate dependent on the capacity of the treatment plants. This may result in a significant increase in return flows during Quarters 1 and 2, but in Quarter 3 when stormflows are minimal, return flows at treatment plants may not increase. The true effects during Quarter 3 will not be known until the system becomes fully operational. During drought conditions, however, it is unlikely that treatment plant discharges will increase above public supply withdrawals when the system becomes operational.

5 Climate Change Impacts on Water Availability

Precipitation in Indiana, in both the spring and summer, has generally been above the long term average since 1990 (Frankson and Kunkel, 2015). Temperatures in the 2000s have been higher than any other historical period with the exception of the 1930s. These trends are commonly attributed to climate change, and are expected to continue into the future.

Continuing changes in precipitation and temperature will impact water availability in the Central Indiana region in two ways: first, through changes in water demand and use, and second through changes in watershed processes controlling the natural baseflow in streams. Climate change impacts on the demand in the Public Water Supply sector have been assessed in the Phase I study of water demand. Changes in watershed processes are most often assessed through predictive simulation. While the Global Climate Models (GCMs) are adequate to address anticipated global changes in climate, their scale is too coarse to properly address regional or watershed-scale issues. Down-scaling of the GCM results is necessary to consider the impacts of climate change on local hydrologic systems and streamflow. Several down-scaling methods exist, but all increase the uncertainty already inherent in the GCM results. The down-scaled climate predictions are then used as input to hydrologic models to predict the changes to local watershed hydrology. The hydrologic models themselves introduce significant additional uncertainty to the predictions.

Projected changes in temperature and precipitation in Indiana through 2100 have been made using an ensemble of over 30 GCMs (Hamlet et al., 2018). In the models, climate change is driven by assumed carbon dioxide emissions, known as Representative Concentration Pathways (RCPs). The RCPs have been standardized and include medium emission scenarios (RCP 4.5) and high emission scenarios (RCP 8.5). In general, the Global Climate Models agree that both temperatures and precipitation in Indiana will continue to rise under medium or high emission scenarios. While the models agree on climate trends, there is a high level of uncertainty in the ensemble results (Hamlet et al., 2018).

Three studies of the impacts of climate change on watershed hydrology in the Central Indiana region are available. These include a study conducted at Indiana University (IU) of the Wabash River watershed (Dierauer and Zhu, 2020), a national study with resolution at HUC-8 watershed scale by the USGS (Alder and Hostetler, 2013; Hostetler and Alder, 2016), and a study of the Ohio River basin (Drum et al., 2017) conducted by the U.S. Army Corps of Engineers (USACE) and National Oceanic and Atmospheric Administration (NOAA). The studies show significant differences in predictions of the effects of climate change on streamflow in the Central Indiana region, highlighting the uncertainty introduced by hydrologic modeling, in addition to the uncertainty inherent in the GCMs. We compare results from the three studies below.

Table 5.1: Regional studies linking results of Global Climate Models to streamflow in Indiana.

Study	Region of focus	Minimum sub-unit	GCM model ensembles[1]	Emissions scenario [2]	Hydrologic Model [3]
1. IU*	Wabash basin	HUC 12	CMIP5 (10 models)	RCP 4.5, 8.5	SWAT
2. USGS**	National	HUC 8	CMIP5 (33 models)	RCP 4.5,8.5	MWBM
3. USACE***	Ohio River basin	NOAA gages	CMIP3 (9 models)	A1B, A2 (medium)	CHPS

* IU = Indiana University. Reference: Dierauer and Zhu (2020).

**USGS = Unites States Geological Survey. Reference: Hostetler and Alder (2016).

***USACE = Unites States Army Corps of Engineers. Reference: Drum et.al (2017).

1. GCM = Global Cimate Model.
   CMIP = Coupled Model Intercomparison Project; 5 = Phase 5; 3 = Phase 3.
2. RCP = Representative Concentration Pathway; 4.5 = medium emissions, 8.5 = high emissions.
3. SWAT = Soil and Water Assessment Tool. MWBM= Monthly Water Balance Model.
   CHPS = Community Hydrologic Prediction System.

5.1 Three Watershed-Scale Studies

Table 5.1 summarizes three regional hydrologic studies linking output from ensemble Global Climate Models to streamflow. The table is intended to provide a brief overview of the data and tools used, highlighting the similarities and differences between the studies. The primary difference is the hydrologic model used to translate global climate change predictions to changes in regional watershed hydrology. The full details of each methodology are included in the references provided for each study. This analysis only considers the results of each study.

The Upper White River is a major watershed where the three models overlap, and is therefore used as a point of comparison. There is a disparity in how each study reports results; an attempt has been made to normalize the comparisons. Figure 5.1 shows a comparison of the predicted streamflow changes for the 2020s and 2080s. Figure 5.1 (*top*) shows the percent change in monthly streamflow throughout the year relative to the historical conditions (1971-2000). Results for the IU and USGS studies show the mean of ensemble model predictions. The study by the USACE also presents the mean of ensemble results; however, the ensemble means are presented at discrete months on color flood maps with ranges specified for each color. Results of the USACE study are presented here as a vertical bar indicating the range. Figure 5.1 (*bottom*) shows the mean monthly streamflow presented as inches of runoff. Results for RCP loading 4.5 are presented for the IU and USGS studies, to compare with the medium emissions scenario used in the USACE study. Results of simulations using RCP 8.5 in studies 1 and 2, may be found in the referenced sources.

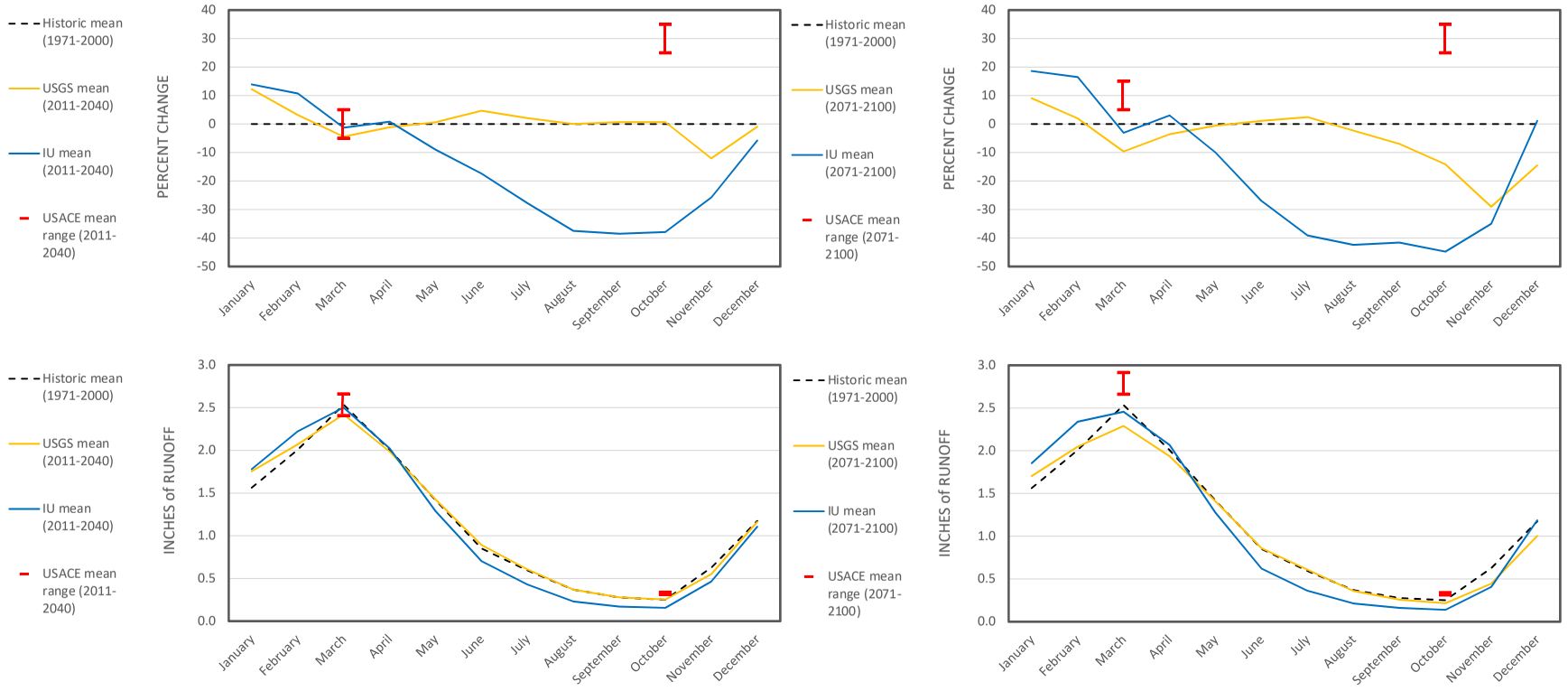

Figure 5.1: Comparison of three estimates of climate change impacts on streamflow in the Upper White River watershed. *Estimates are based on medium emission scenarios: prediction for the 2020s (left) and 2080s (right). Note the significant disagreement between predictions, most apparent in the upper two figures.*

5.2 Audit of the Indiana University Results

The Indiana University study of the Wabash River (Dierauer and Zhu, 2020) predicts significant decreases in summer and fall streamflow and baseflow throughout the watershed, for both RCP 4.5 and 8.5. The study considers three predictive periods: 2020s (2011-2040), 2050s (2041-2070), and 2080s (2071-2100). An auditing of the model for the first 9 years of the 2020 prediction period is possible using actual precipitation and streamflow data, and derived baseflow data for 2011-2019. We chose watersheds in the White River basin with minor anthropogenic effects to make comparisons with the IU predictions for the 2020s. The watersheds include the White River at Muncie (USGS station 003347000), Fall Creek near Fortville (03351500), and White Lick Creek at Mooresville (03353800). Results in the three watersheds were similar; for brevity, only the results for the White River at Muncie are presented here.

Figure 5.2 presents a comparison of mean monthly precipitation. The blue line represents the mean for the period 2011-2040, derived from the ensemble of GCMs used in the study; the shaded region represents the spread of the ensemble predictions. The historic mean precipitation (1971-2000) is shown as the dashed black line, while the actual mean precipitation for the period 2011 through 2019 is shown with the solid black line. The actual mean precipitation for the first third of the prediction period shows significant increases over the historic mean for all months except July. With the exception of July and December, observed precipitation lies near or above the maximum of the ensemble model predictions.

Historic, actual, and predicted mean monthly streamflow and baseflow for RCP 4.5 are presented in Figure 5.3. The IU predictions indicate significant reductions in both streamflow and baseflow in the months May through November, with slight increases in January through April. The actual mean streamflow for 2011-2019 lies far outside the bounds of the ensemble model results in March through December, with increases in streamflow and baseflow above historic means for all months. While actual precipitation mostly lies within the range of model results (Figure 5.2), translating precipitation into streamflow appears to be problematic.

5.3 Assuming the Worst: Impact of IU Predictions on Water Availability

We demonstrate the impact of the IU predictions of reduced baseflow on excess water availability, using Sub-basin 1 of the White River drainage system. Sub-basin 1 coincides with the watershed for USGS station 003347000, White River at Muncie, IN, which is the headwaters of the White River drainage system. We assume that water use remains unchanged from the 2007-2017 period documented in this report. Figure 5.4 presents the components of the excess water availability for Quarter 3 of the 2007-2017 period and predicted excess availability based on the reduced natural baseflow predicted by the IU study for the period 2011-2040 (2020s). The plot on the right, based on reduced natural baseflow, shows that current water demands will not be met by baseflow generated in the sub-basin; the figure shows excess water availability to be negative for median and mean conditions, nearly extending to the third quartile. Similar results will cascade through the downstream sub-basins, where excess availability from

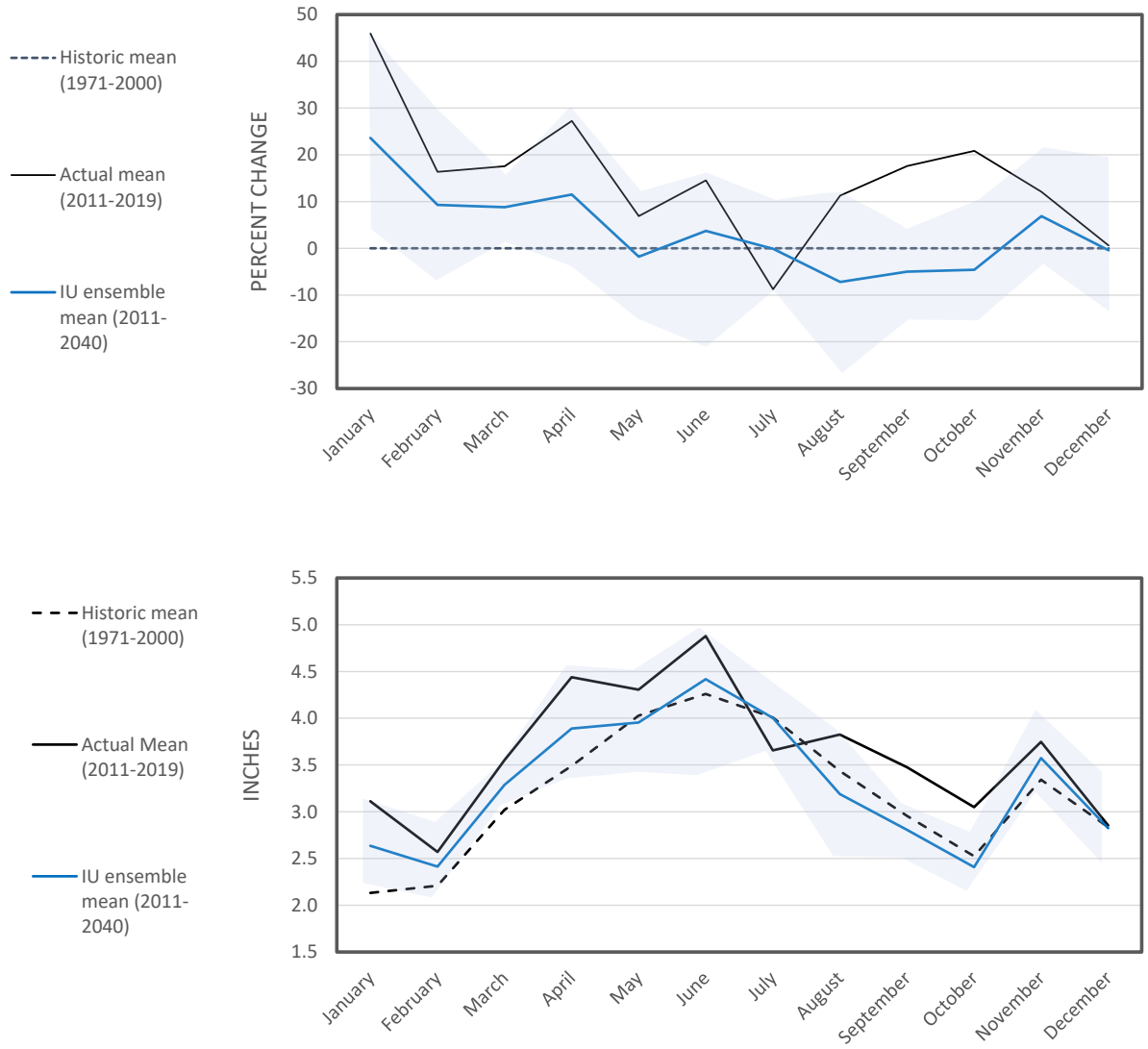

Figure 5.2: Predicted and observed monthly precipitation in the Muncie watershed (USGS station 003347000). *Note that the actual mean monthly precipitation for 2011-2019 (black line) plot near the upper bounds of the ensemble climate change predictions (blue shaded region).*

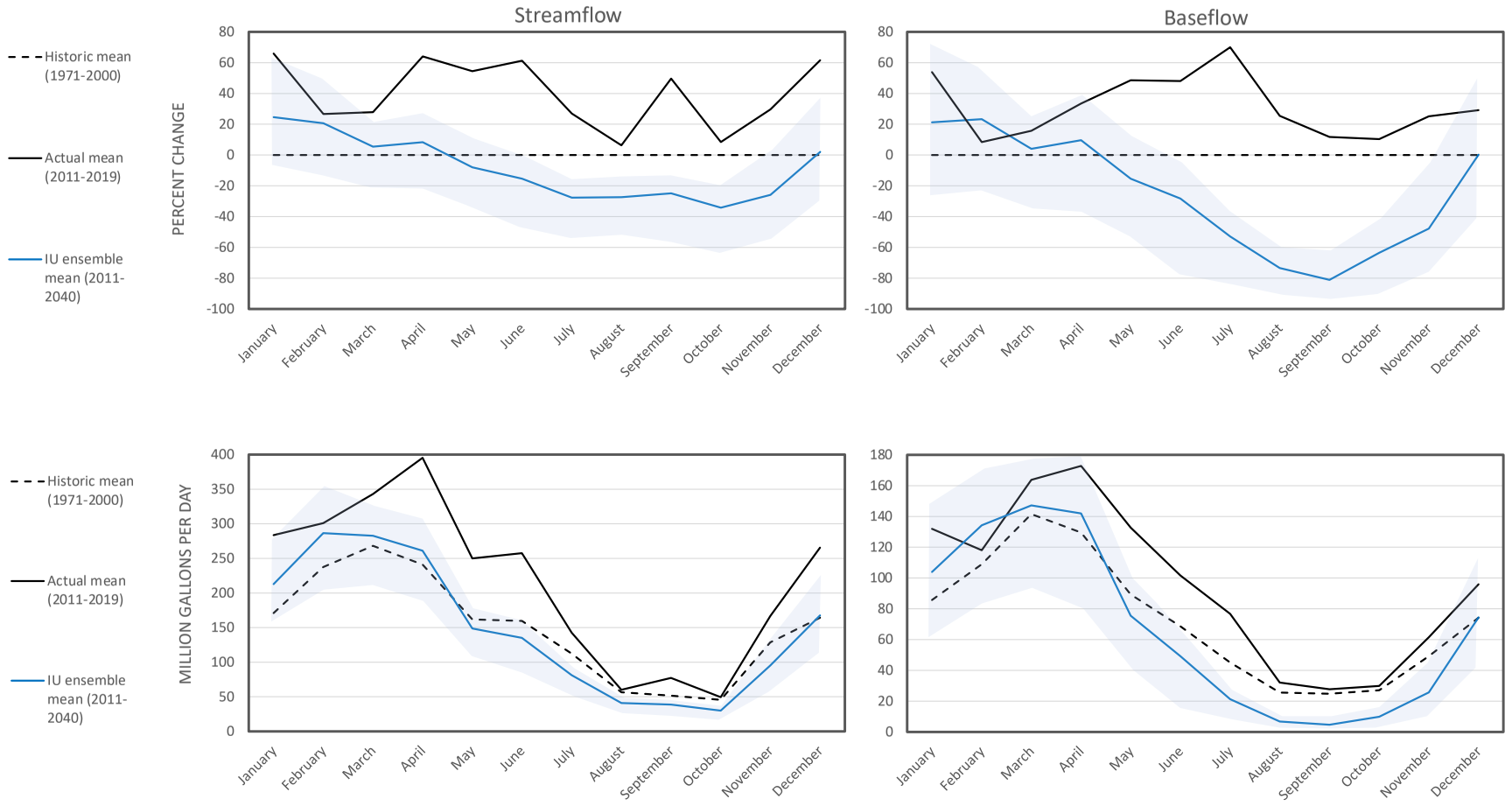

Figure 5.3: Predicted mean flows for the period 2011-2040, and observed flows, 2011-2019. *Changes in streamflow on the left, and changes in baseflow on the right. Changes shown as a percent change from the 1971-2000 period on top, and in million gallons per day on the bottom. Note that the actual mean streamflow and baseflow for 2011-2019 plots above the historic mean, and the ensemble climate change predictions (blue shaded region).*

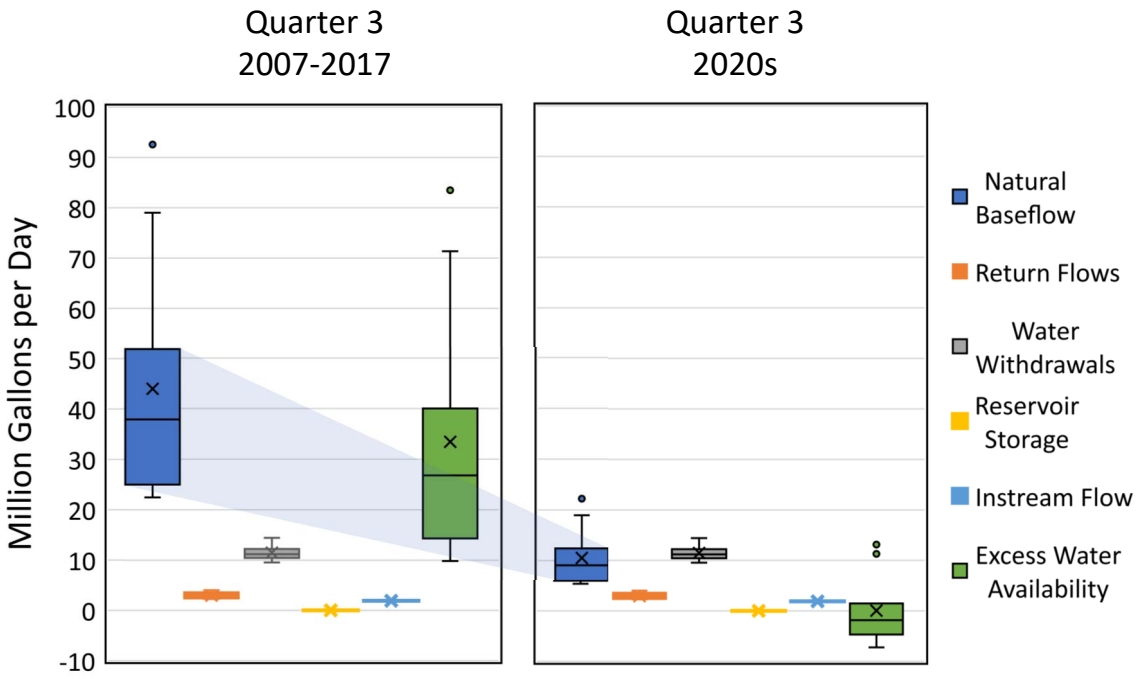

Figure 5.4: Results of assuming the worst. *Actual Quarter 3 excess water availability for the Sub-basin 1 of the White River (left) and availability with current demand and reduced natural baseflow based on the IU climate change predictions (right).*

upstream sub-basins is required to meet current demands.

5.4 Summary

Observations of temperature, precipitation, and streamflow in Indiana over the last 100 years show increasing average annual temperatures, increasing annual precipitation, and increasing annual streamflow, with rates of change increasing over the last 20 years. These observations are consistent with trends in temperature and precipitation predicted by global climate models.

Predicting the impacts of global climate change on streamflow and baseflow conditions in Indiana at a sub-regional scale requires down-scaling results from global climate models and applying projected temperatures and precipitations as input to watershed models. Results from independent researchers conducting watershed-scale studies have been inconsistent: of the three studies considered here, one shows significant reductions in summer and fall streamflows and baseflow moving into the future (IU), one shows small decreases in fall streamflow (USGS), and the third shows increasing late summer and fall streamflows (USACE). A post audit of the streamflow and baseflow predictions of the Indiana University study with observed streamflow and derived baseflow based on the period 2011-2019, shows significant disagreement in the first

nine years of the thirty year prediction cycle. 10 to 70 percent increases in baseflow are observed for the period July to September, while the IU study predicts a 50 to 80 percent reduction in baseflows for the period 2011-2040. Due to this disagreement with the historical data, future water availability assessments should not be based upon the IU study results.

Climate change will have a significant impact on future water availability in the Central Indiana region as it will have a direct impact to baseflow, which is the dependable source of supply. It remains unclear whether the observed trend of increasing baseflow, and therefore increasing water availability, will continue into the future.

6 Water-Availability Assessment, 2070

Results from Phase I of the Central Indiana Water Study (IFA, 2020) are used as a basis for evaluating water availability in the future. In addition to demand projections from that study, return flows are projected in this study. The translation of future demands to sub-basin demands, as well as the projection of future return flows are described below.

6.1 Water Withdrawal Projections

Water withdrawal projections are taken from IFA (2020), which predicts future regional water demand. The study forecasts water withdrawals in 5-year increments from 2020–2070 for each water-use sector. Sectors include Irrigation and Agriculture, Power Generation, Commercial and Industrial, and Domestic and Public Water Supply; Mining Supply is also defined in the report as a sub-sector of the Commercial and Industrial sector. The withdrawal projections are made at the county scale for all of the sectors except for Public Water Supply, which was forecast by service area for each water utility. Water withdrawal forecasts for the year 2070 are used for the assessment of future water availability.

To translate county or utility-wide withdrawal forecasts in each sector reported in IFA (2020) into forecasts for each sub-basin, the aggregated forecast for each sector was distributed among the withdrawal points in the SWWF database. Withdrawals in the Public Water Supply sector are distributed differently between surface-water intakes and groundwater wells than were recorded in the past. The maximum withdrawal rate for an existing surface-water intake is assumed to be the average of Quarter 3 withdrawals during 2014-2018. In assigning this value to existing intakes, we are assuming the intakes are currently operating at their maximum capacity. The sole exception to this occurs at Citizens White River Plant in Sub-basin 8 of the White River drainage system, where an additional 10 MGD future surface-water withdrawal is projected. This is a result of Citizens 30th Street intake allowing for increased withdrawals at the Plant (see Section 4.5).

The remainder of the aggregate withdrawal projections, after each intake was assigned its maximum withdrawal rate, is distributed across each sector's groundwater withdrawal sites according to the historical distribution during the 2014-2018 period. In this way, public supply withdrawals from individual wells are scaled up to represent future conditions (IFA, 2020), and increased future withdrawals are assumed to be made primarily from groundwater wells. For the remaining sectors, surface intakes and groundwater wells were treated equally, and scaled to represent future withdrawals (IFA, 2020) according to their historic distributions. Individual, projected withdrawals for all sectors were then re-aggregated by sub-basin to assess future excess and cumulative excess availability by sub-basin.

Projections for the Domestic Water Supply sector reported in IFA (2020) are not included in the future water availability assessments. Note that domestic supplies are also not included in estimates of current water availability. Net domestic use is difficult to quantify, and at least

in part, is returned to the hydrologic system through domestic septic systems where sanitary service is not available. Where domestic supplies lie within sanitary districts, return flows are reported by wastewater treatment plants, complicating the assessment of impacts of domestic supplies. Here we assume that domestic withdrawals equal domestic returns; both are removed from the analysis of sub-basin excess water availability and cumulative excess availability.

The boundaries of the three major drainage systems investigated in this study extend beyond the Central Indiana region. Outside of the Central Indiana region, there is no 2070 water withdrawal forecast. In those regions the recent five-year average withdrawal for each well and intake was assumed to represent future withdrawals, in all sectors.

6.2 Return Flow Projections

Future return flows are predicted for each of the water use sectors within each basin. As the EPA ECHO database does not identify facilities by the sectors defined in the SWWF, the ECHO data were assigned to sectors on a case-by-case basis by reviewing the name of the permit holder and outfall locations relative to water withdrawals. The future return flows were calculated for each sector as described in the following subsections.

WWTP Returns Wastewater treatment plants (WWTP) receive wastewater from homes and businesses within their service area; the rate of water discharged from a treatment plant is related to the amount withdrawn for the public water supply. The future return for a wastewater treatment plant is assumed to maintain the historical relationship between withdrawals and returns unique to each sub-basin. The future WWTP return flow was scaled up or down from historical discharges based on the increase or decrease in public water supply withdrawals. This calculation was made on an annual and quarterly basis to reflect the ratio of return flows to public supply withdrawals presented in Tables 4.1 and 4.2 in Section 4.1.

Mining In most sub-basins, historic mining withdrawals have been similar or equal to mining returns; most or all of the water withdrawn for mining is discharged back to a stream. Future mining returns were assumed to equal future mining withdrawals, except in cases where returns have historically been significantly different than withdrawals, including the Martin Marietta quarries discussed in Section 4.4. In those cases, mining returns were scaled up proportionally to the projected future mining withdrawals.

Energy Production Similar to mining, the returns for energy production are assumed to be equal to the withdrawals for energy production. This is consistent with the historic relationship between withdrawals and returns for the energy sector, discussed in Section 4.3.

Commercial and Industrial The calculation of future returns for the Commercial and Industrial sector was performed in two ways. In both methods, the historic relationship between

the water withdrawals and returns in the sector remained consistent for each sub-basin. In some, the historic withdrawals were equal to or similar to the historic returns. In these basins, it is assumed that the future returns will continue to be equal to withdrawals. In other sub-basins, the historic returns were higher than the reported historic withdrawals. In these cases, the future return was predicted to be the recent historic average return.

6.3 Reservoir Storage Projections

The assessment of water availability for the 2007-2017 period considered both historic reservoir releases from Morse and Geist Reservoirs (Figures 3.4 and 3.5), as well as full use of the reservoir storage (Figures 3.6 and 3.7). In assessments of future water availability, we assume that the full storage capacity of Morse and Geist Reservoirs is available.

Citizens Reservoir is also included as reservoir storage in the future-condition estimates of excess water availability. We assume that a value of Q_{stor} of 30 MGD throughout the third quarter is available within Sub-basin 7. This level of supply would last approximately 100 days before the reservoir is depleted. We apply 30 MGD over 3 months in the water availability model. The diverted water required to refill the reservoir after the storage is depleted is assumed to come entirely from stormflow: baseflow discharges to Fall Creek are not impacted by the diversion.

6.4 Natural Baseflow Projections

The review of climate-change studies in Indiana, reported in Section 5, illustrates the lack of consensus between hyrdologists as to how climate change will affect streamflow and baseflow in the Central Indiana region. Rather than making our own assumptions about the effects of climate change, we use the natural baseflows evaluated for the period 2007-2017 to represent hydrologic variability in the future. Note that this approach of basing future conditions on 2007-2017 observations is similar to following the results of the Army Corps of Engineers study (Drum et al., 2017), which predicts an increase in streamflow over 1971-2000 conditions, as has been observed in the period 2007-2017.

6.5 Instream Flow Projections

Instream flow values reported in Section 2.9 are used to represent future instream flow requirements. Both the annual Q_{90} and $Q_{7,10}$ used as minimum flow requirements are based on a statistical analysis of USGS daily streamflow records through 2011, and reported by Fowler and Wilson (2015).

6.6 Results, Baseline 2070 Demand

Results of the water availability model with average, projected 2070 withdrawals (baseline conditions per IFA (2020)) and returns are summarized in Tables 6.1 through 6.6, and Figures

6.1 through 6.4. Tables 6.1 through 6.3 present the projected, minimum Quarter 3 excess water availability by sub-basin. The first column of the tables summarizes the change in minimum excess availability from current conditions (2007-2017 with historic use of reservoirs). Note that for many sub-basins the values lie in the range -5 to +5, which indicate little change. In the sub-basins of the White River drainage system, larger decreases in availability occur in Sub-basins 3 and 5, primarily due to increased withdrawals for public supply. In Sub-basin 3 the increased demand is exacerbated by low returns at wastewater treatment plants, resulting in a significant increase in the deficit. Significant positive changes occur in Sub-basins 7 and 11. The increase in Sub-Basin 7 is due to the operation of the Citizens Reservoir, while the increase in Sub-basin 11 is due to increasing return flows at the Belmont Advanced Wastewater Treatment Plant. Changes in the sub-basins of other major drainage systems are small, except for Sub-basin 8 of the East Fork drainage system, which is a result of increased withdrawals in the Irrigation and Agriculture Sector in Quarter 3.

Projected cumulative excess availability is presented in Tables 6.4 through 6.6 and Figures 6.3 and 6.4. Note that in the White River and tributaries of the Wabash River drainage systems, the minimum cumulative excess availability remains positive in all sub-basins. Small negative cumulative values occur in the East Fork drainage system in Sub-basins 6 and 7.

Table 6.1: 2070 excess water availability in each sub-basin of the White River drainage system during Quarter 3.

Sub-Basin ID	USGS station at outlet of Sub-Basin	Change in Minimum*** (MGD)	Minimum (MGD)	Lower Quartile (MGD)	Median (MGD)
1	03347000 White River at Muncie, IN	+4	14	16	29
2	03348130 White River at Raible Ave. at Anderson, IN	+3	24	38	61
3	03349000 White River at Noblesville, IN	-9	6	12	48
4	03349510 Cicero Creek at Arcadia, IN	+0	3	4	8
5	03351000 White River near Nora, IN*	-14	-51	-8	14
5	03351000 White River near Nora, IN**	-23	-33	10	32
6	03351500 Fall Creek near Fortville, IN	-1	13	19	41
7	03352500 Fall Creek at Millersville, IN	+45	36	38	42
8	03353000 White River at Indianapolis, IN	-5	-59	-50	-8
9	03353200 Eagle Creek at Zionsville, IN	+2	4	9	11
10	03353500 Eagle Creek at Indianapolis, IN	+2	-1	2	5
11	03353611 White River at Stout Gen. Stn., Indianapolis, IN	+61	73	73	78
12	03353800 White Lick Creek at Mooresville, IN	+4	14	18	47
13	03354000 White River near Centerton, IN	-4	-8	37	58

Notes: MGD = million gallons per day.

* Availability includes withdrawals and returns as reported by Martin Marietta.

** Availability assumes returns and withdrawals by Martin Marietta are equal (see Section 4.4).

*** Change relative to availability based on historic reservoir releases.

Table 6.2: 2070 excess water availability in each sub-basin of the Wabash River drainage system during Quarter 3.

Sub-Basin ID	USGS station at outlet of Sub-Basin	Change in Minimum (MGD)	Minimum (MGD)	Lower Quartile (MGD)	Median (MGD)
1	03339280 Prairie Creek near Lebanon, IN	+1	2	2	3
2	03339500 Sugar Creek at Crawfordsville, IN	+3	10	28	53
3	03340800 Big Raccoon Creek near Fincastle, IN	+1	1	6	13
4	03357330 Big Walnut Creek near Roachdale, IN	+0	1	8	13

Notes: MGD = million gallons per day.

Table 6.3: 2070 excess water availability in each sub-basin of the East Fork White River drainage system during Quarter 3.

Sub-Basin ID	USGS station at outlet of Sub-Basin	Change in Minimum (MGD)	Minimum (MGD)	Lower Quartile (MGD)	Median (MGD)
1	03361500 Big Blue River at Shelbyville, IN	+2	16	39	79
2	03361650 Sugar Creek at New Palestine, IN	+0	2	3	8
3	03361850 Buck Creek at Acton, IN	+0	1	7	12
4	03362000 Youngs Creek near Edinburgh, IN	+2	5	11	22
5	03362500 Sugar Creek near Edinburgh, IN	-6	-21	-2	20
6	03363500 Flatrock River at St. Paul, IN	-5	-2	9	39
7	03363900 Flatrock River at Columbus, IN	+3	0	10	37
8	03364000 East Fork White River at Columbus, IN	-8	-36	18	89

Notes: MGD = million gallons per day.

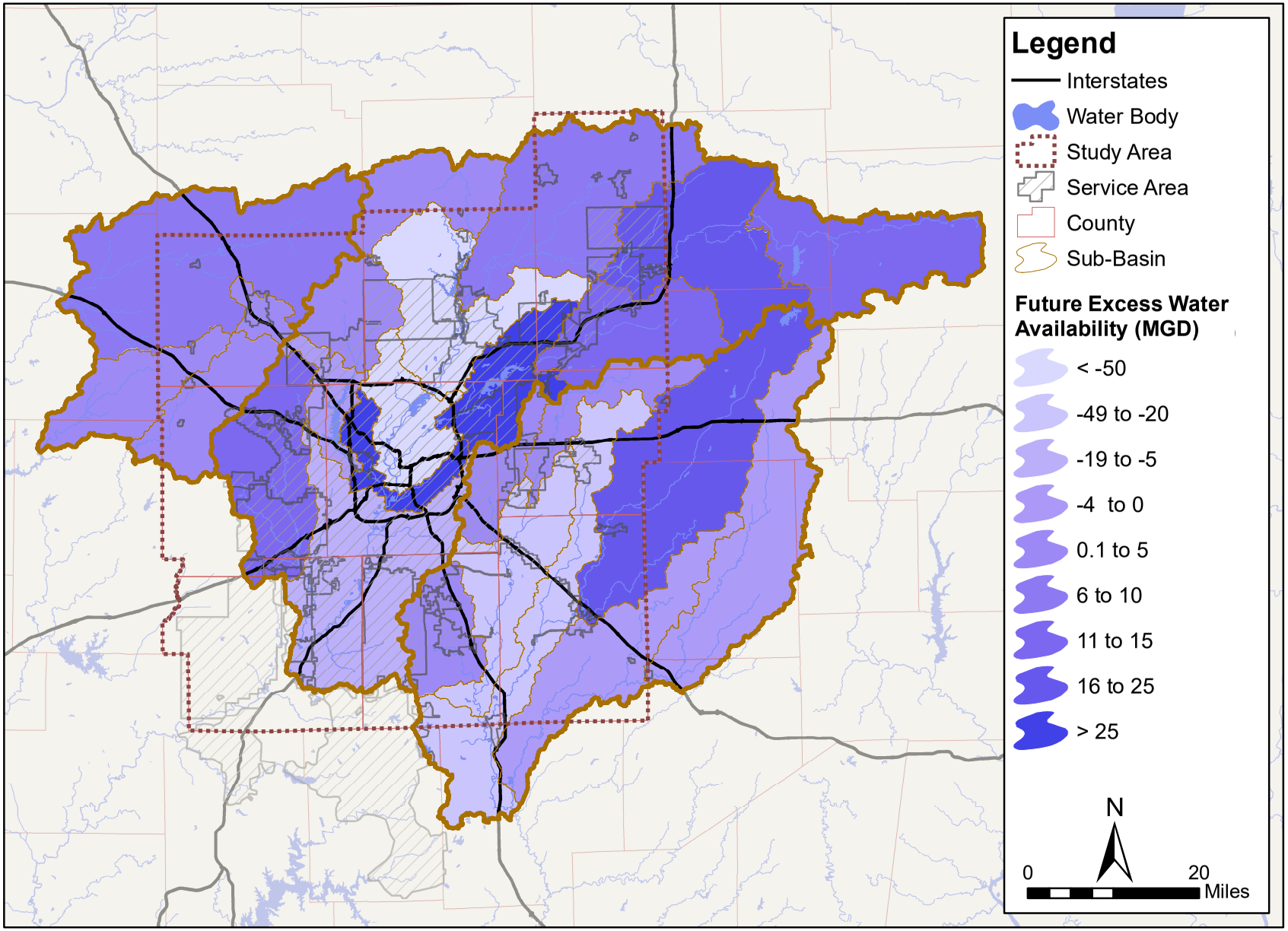

Figure 6.1: Minimum projected Quarter 3 excess water availability by sub-basin, 2070. *Note that negative values indicate insufficient water availability generated within the sub-basin to support current water withdrawals. Although colors are applied to an entire sub-basin, excess availability is computed at the downstream end of each sub-basin.*

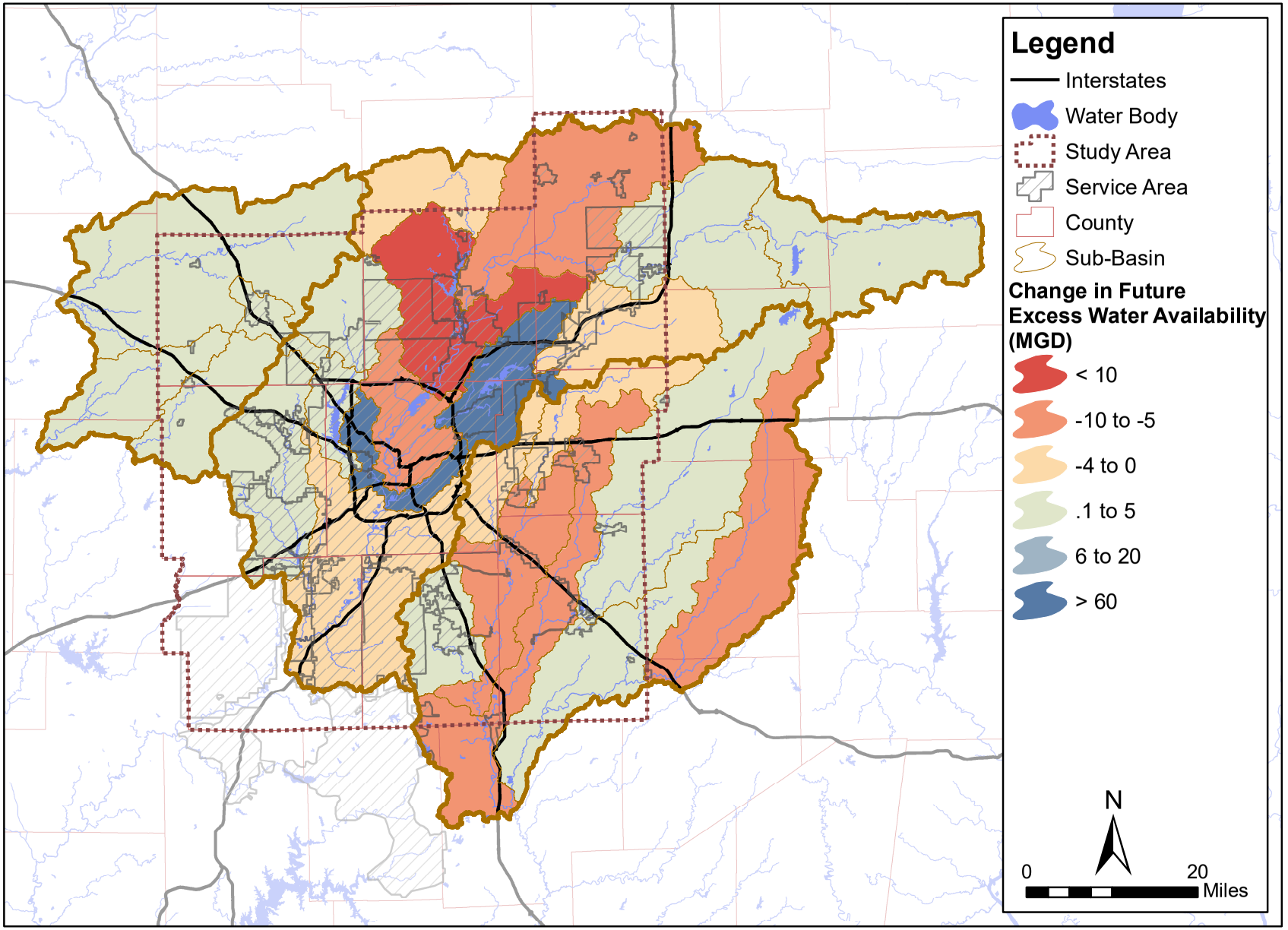

Figure 6.2: The projected change in minimum, Quarter 3, excess water availability by sub-basin, 2070. *The projected change is relative to the 2007-2017 period, with historic reservoir releases. Note that negative values (tan, orange, and red) indicate a decrease in water availability within a sub-basin in the future. Although colors are applied to an entire sub-basin, the change in excess availability is computed at the downstream end of each sub-basin.*

Table 6.4: 2070 cumulative excess water availability in each sub-basin of the White River drainage system during Quarter 3.

Sub-Basin ID	USGS station at outlet of Sub-Basin	Change in Minimum** (MGD)	Minimum (MGD)	Lower Quartile (MGD)	Median (MGD)
1	03347000 White River at Muncie, IN	+4	14	16	29
2	03348130 White River at Raible Ave. at Anderson, IN	+7	39	52	91
3	03349000 White River at Noblesville, IN	+1	55	87	112
4	03349510 Cicero Creek at Arcadia, IN	+0	3	4	8
5	03351000 White River near Nora, IN*	-5	41	55	132
6	03351500 Fall Creek near Fortville, IN	-1	13	19	41
7	03352500 Fall Creek at Millersville, IN	+44	51	61	83
8	03353000 White River at Indianapolis, IN	+39	72	167	231
9	03353200 Eagle Creek at Zionsville, IN	+2	4	9	11
10	03353500 Eagle Creek at Indianapolis, IN	+3	9	13	18
11	03353611 White River at Stout Gen. Stn., Indianapolis, IN	+99	155	272	329
12	03353800 White Lick Creek at Mooresville, IN	+4	14	18	47
13	03354000 White River near Centerton, IN	+97	228	362	399

Notes: MGD = million gallons per day.

* Availability includes withdrawals and returns as reported by Martin Marietta.

** Change relative to availability based on historic reservoir releases.

Table 6.5: 2070 cumulative excess water availability in each sub-basin of the Wabash River drainage system during Quarter 3.

Sub-Basin ID	USGS station at outlet of Sub-Basin	Change in Minimum (MGD)	Minimum (MGD)	Lower Quartile (MGD)	Median (MGD)
1	03339280 Prairie Creek near Lebanon, IN	+1	2	2	3
2	03339500 Sugar Creek at Crawfordsville, IN	+3	9	23	49
3	03340800 Big Raccoon Creek near Fincastle, IN	+1	1	6	13
4	03357330 Big Walnut Creek near Roachdale, IN	+0	1	8	13

Notes: MGD = million gallons per day.

Table 6.6: 2070 cumulative excess water availability in each sub-basin of the East Fork White River drainage system during Quarter 3.

Sub-Basin ID	USGS station at outlet of Sub-Basin	Change in Minimum (MGD)	Minimum (MGD)	Lower Quartile (MGD)	Median (MGD)
1	03361500 Big Blue River at Shelbyville, IN	+2	16	39	79
2	03361650 Sugar Creek at New Palestine, IN	+0	2	3	8
3	03361850 Buck Creek at Acton, IN	+0	1	7	12
4	03362000 Youngs Creek near Edinburgh, IN	+2	5	11	22
5	03362500 Sugar Creek near Edinburgh, IN	-6	5	39	94
6	03363500 Flatrock River at St. Paul, IN	-5	-2	9	39
7	03363900 Flatrock River at Columbus, IN	-2	-2	19	77
8	03364000 East Fork White River at Columbus, IN	-2	47	98	374

Notes: MGD = million gallons per day.

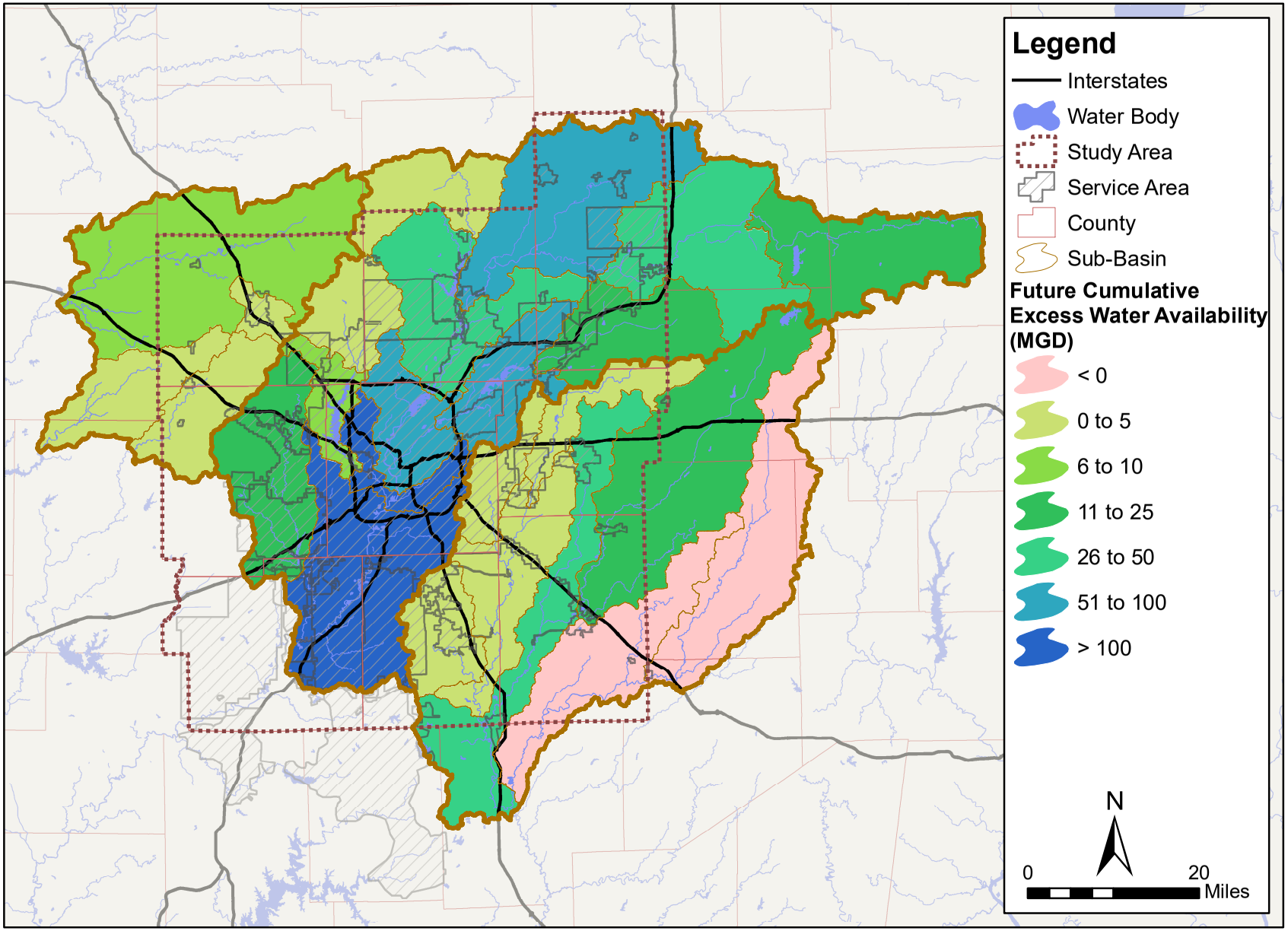

Figure 6.3: Minimum projected Quarter 3 cumulative excess water availability by sub-basin, 2070. *Excess water from upstream sub-basins is used in downstream sub-basins with negative excess availability. Note the small negative values to the southeast. Although colors are applied to an entire sub-basin, cumulative excess availability is computed at the downstream end of each sub-basin.*

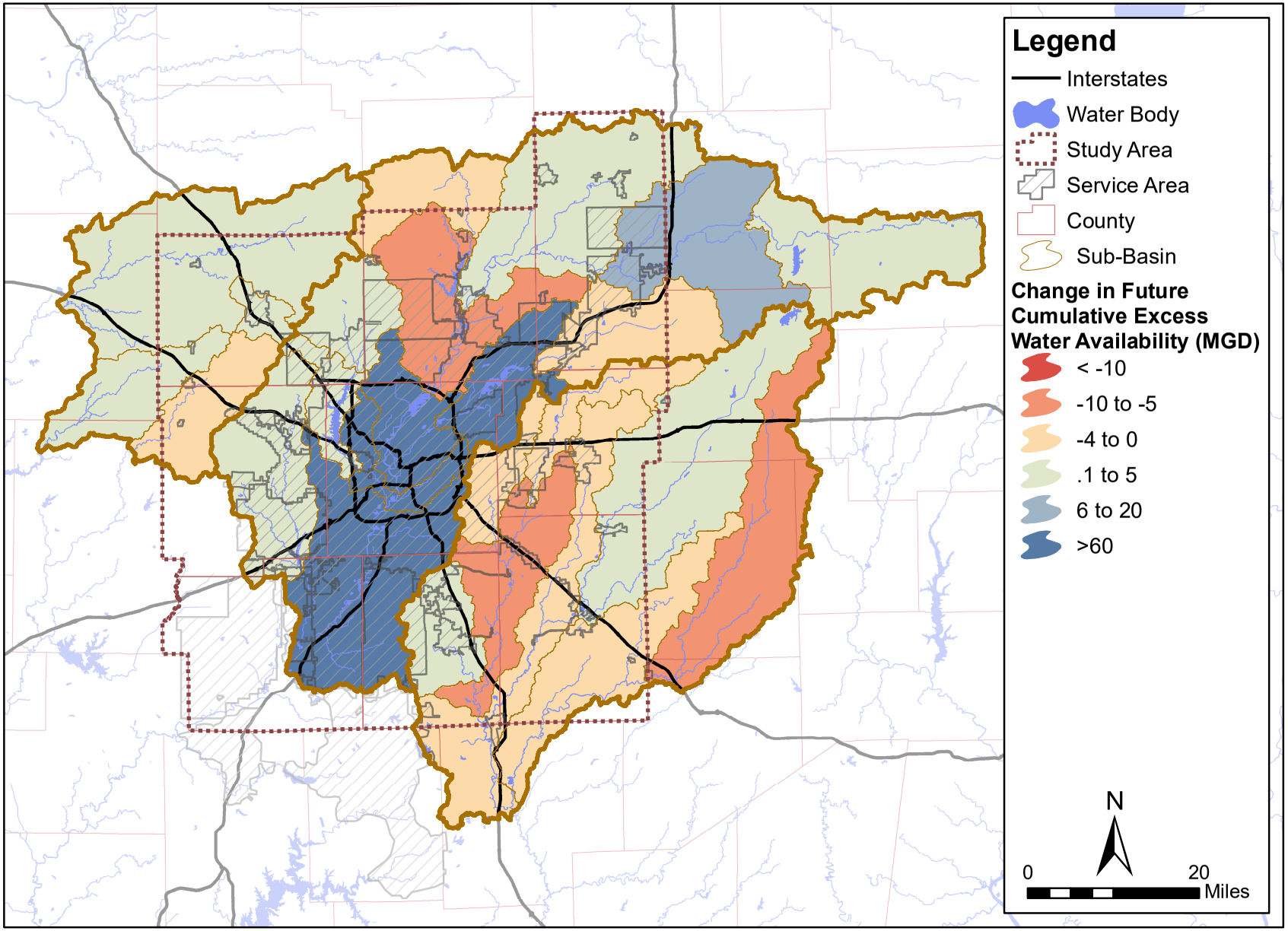

Figure 6.4: The projected change in minimum, Quarter 3, cumulative excess water availability by sub-basin, 2070. *The projected change is relative to the 2007-2017 period, with historic reservoir releases. Note that negative values (tan, orange, and red) indicate a decrease in cumulative water availability within a sub-basin in the future. Although colors are applied to an entire sub-basin, the change in excess availability is computed at the downstream end of each sub-basin.*

6.7 Results, 2070 Demand Under Climate Change

As discussed above, the impacts of climate change on the future natural baseflow is incorporated by specifying the future variability in baseflow to be the same as the variability evaluated for the 2007-2017 period. Details of how climate change scenarios were incorporated into demand projections are provided in the Phase I Demand Study (IFA, 2020). Here we use three Public Supply demand scenarios developed in that report along with the related projected returns at wastewater treatment plants to project changes in minimum, Quarter 3, excess water availability by sub-basin. The climate scenarios as described in IFA (2020) include, in order of increasing Public Supply demands, Warm/Wet, Hot/Dry, and 30% Drought.

Results are presented in Tables 6.7 through 6.9 for each scenario as the change in minimum Quarter 3 excess availability relative to the baseline 2070 conditions. In the White River drainage system, the changes are small, except in Sub-basins 5, 7, and 11. In the tributaries of the Wabash and East Fork White River drainage systems, the results between scenarios are mostly identical. As shown in the tables, the total cumulative change in excess water availability for each drainage system is minimal, ranging from zero to minus 2 MGD. Once again, this reinforces the importance of increasing return flows from wastewater treatment plants along with increasing withdrawals for public supply, even when considering climate change scenarios.

6.8 Cumulative Availability along the White River, 2070

Figure 6.5 presents the components of cumulative water availability by river mile along the White River for projected, Quarter 3, 2070 conditions. Note that the cumulative natural baseflow and cumulative instream flow curves are identical to those in Figure 3.8, representing 2012 conditions. The cumulative 2070 reservoir storage has increased from the 2012 values from the junction with Fall Creek through the outlet of Sub-basin 1; this increase is due to operation of Citizens Reservoir. As a result, the cumulative water availability downstream from Fall Creek also increases by 30 MGD in the future water availability model. The 2012 cumulative reservoir storage curve is also illustrated on the figure for comparison.

Figure 6.6 presents cumulative water availability and cumulative net withdrawals by river mile along the White River from Sub-basin 2 through 13. The cumulative net withdrawals are equal to the sum of all upstream water withdrawals minus the sum of all upstream return flows. Two lines are shown for cummulative net withdrawals: the dotted black line represents 2070 baseline demand conditions; the solid black line represents the 2070 climate change scenario with a 30% drought condition (IFA, 2020). The climate change scenario results in the cumulative excess water availability just upstream of Fall Creek to drop within 10 MGD of the cumulative water availability curve. Downstream of Fall Creek, the cumulative excess water availability increases to 50 MGD.

Table 6.7: Change in excess water availability in each sub-basin of the White River drainage system due to climate change. *The reported change is relative to the 2070 baseline conditions, and all cases represent minimum, Quarter 3 excess availability.*

		Baseline	Warm/Wet	Hot/Dry	30% Drought
Sub-Basin ID	USGS station at outlet of Sub-Basin	Minimum (MGD)	Change in Minimum (MGD)	Change in Minimum (MGD)	Change in Minimum (MGD)
1	03347000 White River at Muncie, IN	14	0	0	0
2	03348130 White River at Raible Ave. at Anderson, IN	24	0	0	0
3	03349000 White River at Noblesville, IN	6	0	0	-1
4	03349510 Cicero Creek at Arcadia, IN	3	0	0	0
5	03351000 White River near Nora, IN	-51	-6	-3	-6
6	03351500 Fall Creek near Fortville, IN	13	0	0	0
7	03352500 Fall Creek at Millersville, IN	36	0	-2	-2
8	03353000 White River at Indianapolis, IN	-59	-4	-7	-14
9	03353200 Eagle Creek at Zionsville, IN	4	0	0	0
10	03353500 Eagle Creek at Indianapolis, IN	-1	0	-1	-1
11	03353611 White River at Stout Gen. Stn., Indianapolis, IN	73	+5	+10	+17
12	03353800 White Lick Creek at Mooresville, IN	14	0	0	0
13	03354000 White River near Centerton, IN	-8	+6	+2	+5
		Cumulative Change	+1	-1	-2

Notes: MGD = million gallons per day.

Table 6.8: Change in excess water availability in each sub-basin of the Wabash River drainage system due to climate change. *The reported change is relative to the 2070 baseline conditions, and all cases represent minimum, Quarter 3 excess availability.*

		Baseline	Warm/Wet	Hot/Dry	30% Drought
Sub-Basin ID	USGS station at outlet of Sub-Basin	Minimum (MGD)	Change in Minimum (MGD)	Change in Minimum (MGD)	Change in Minimum (MGD)
1	03339280 Prairie Creek near Lebanon, IN	2	0	0	0
2	03339500 Sugar Creek at Crawfordsville, IN	10	0	0	0
3	03340800 Big Raccoon Creek near Fincastle, IN	1	0	0	0
4	03357330 Big Walnut Creek near Roachdale, IN	0	0	0	0
		Cumulative Change	0	0	0

Notes: MGD = million gallons per day.

Table 6.9: Change in excess water availability in each sub-basin of the East Fork White River drainage system due to climate change. *The reported change is relative to the 2070 baseline conditions, and all cases represent minimum, Quarter 3 excess availability.*

		Baseline	Warm/Wet	Hot/Dry	30% Drought
Sub-Basin ID	USGS station at outlet of Sub-Basin	Minimum (MGD)	Change in Minimum (MGD)	Change in Minimum (MGD)	Change in Minimum (MGD)
1	03361500 Big Blue River at Shelbyville, IN	16	0	0	0
2	03361650 Sugar Creek at New Palestine, IN	2	0	0	0
3	03361850 Buck Creek at Acton, IN	1	0	0	0
4	03362000 Youngs Creek near Edinburgh, IN	5	0	0	0
5	03362500 Sugar Creek near Edinburgh, IN	-21	-1	-1	-1
6	03363500 Flatrock River at St. Paul, IN	-2	0	0	0
7	03363900 Flatrock River at Columbus, IN	0	0	0	0
8	03364000 East Fork White River at Columbus, IN	-36	0	0	0
		Cumulative Change	-1	-1	-1

Notes: MGD = million gallons per day.

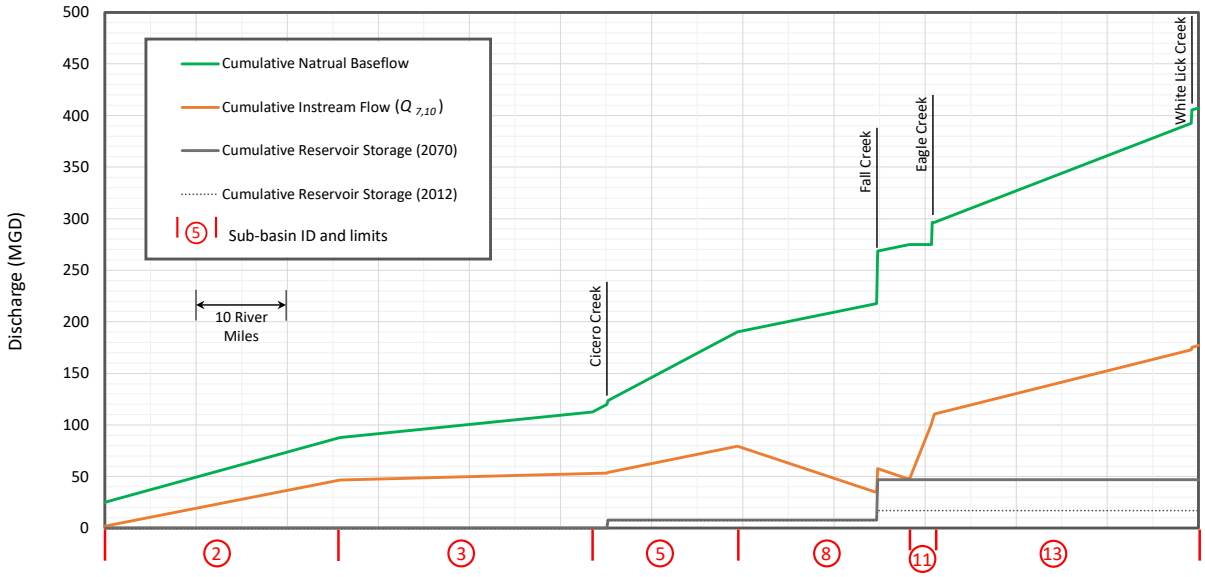

Figure 6.5: Components of cumulative water availability by river mile along the White River, Quarter 3, 2070. *Each component is assumed to vary linearly between sub-basin boundaries, except at junctures with major tributaries, where each component increases abruptly. Assessment based on full use of storage in Morse, Geist, and Citizens Reservoirs.*

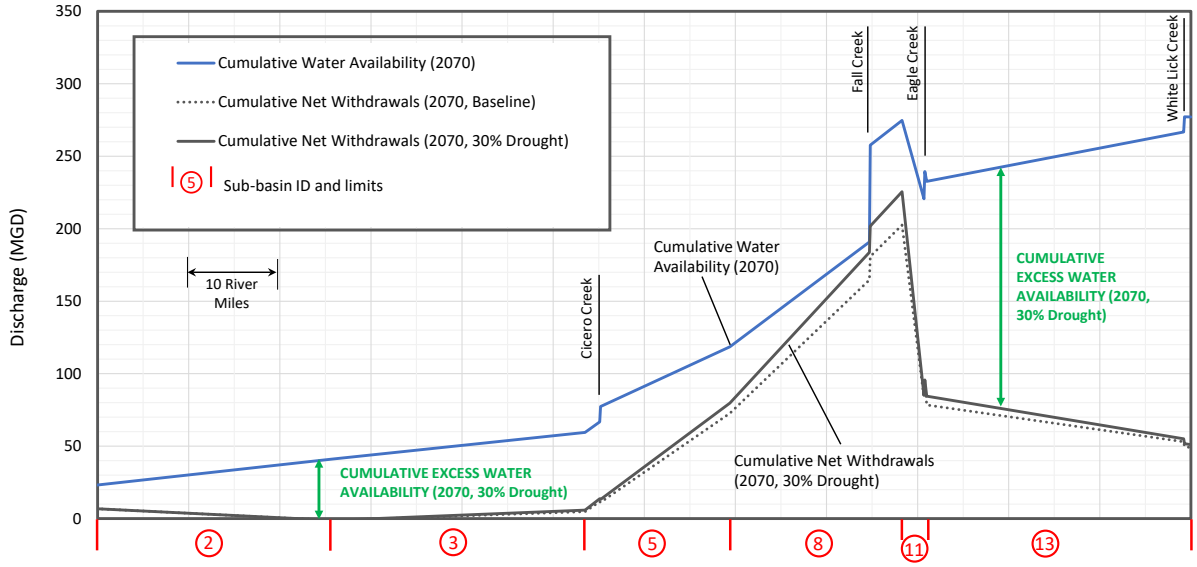

Figure 6.6: Cumulative water availability, net withdrawals, and excess water availability by river mile along the White River, Quarter 3, 2070: baseline and 30% drought demand. *Net withdrawals includes all upstream water withdrawals minus all return flows. Each component is assumed to vary linearly between sub-basin boundaries, except at junctures with major tributaries, where each component increases abruptly. Assessment based on full use of storage in Morse, Geist, and Citizens Reservoirs.*

6.9 Summary

The evaluation of 2007-2017 excess water availability and cumulative excess availability presented in Section B is a well-defined problem with few assumptions; in contrast projecting excess water availability into the future requires many assumptions, each with potentially large impacts on results. The assumptions and limitations on projected availability discussed above must be fully understood to properly interpret the results presented in this report.

The Phase I Demand Study (IFA, 2020) predicts an increase in total water withdrawals in the Central Indiana region of 111 MGD over current levels by 2070. This does not result in an equal decrease in excess or cumulative excess water availability, as in most sub-basins, increased withdrawals are offset by increased returns. A major exception occurs in Sub-basin 5 of the White River drainage system in Hamilton County, where the relationship between public supply withdrawals and return flow at wastewater treatment plants is unique in the Central Indiana region. The average Quarter 3 ratio of return flows at wastewater treatment plants (23 MGD) to public supply withdrawals (50 MGD) is 0.46, which is significantly smaller than other regions. There is an average of 27 MGD in the third quarter that is withdrawn for public supply, but not returned at wastewater treatment plants, suggesting that it is used for lawn watering. Hamilton County is the fastest growing region in terms of water demand, so current excess availability deficits seen in the area are exacerbated by future demands. Large projected increases in withdrawals for public supply in Sub-basin 8 (Marion County) are offset by large increases in return flows at Belmont and Southport Advanced Wastewater Treatment Plants in Sub-basins 11 and 13. Minimal population growth and therefore small increases in withdrawals for public supply are expected in the other major drainage regions (tributaries of the Wabash River and East Fork White River and tributaries).

The proposed operation of Citizens Reservoir has a significant positive impact on water availability in the future, as seen as a net increase in availability in Sub-basin 7 of the White River drainage system during Quarter 3. This also increases the cumulative excess availability in Sub-basin 11.

Instream flows and natural baseflow are assumed to remain the same as the 2007-2017 period. Changes to either will directly impact the estimates of future water availability presented here. Climate change has the potential to have a much larger impact on water availability in the Central Indiana region than increasing demand. Increasing annual precipitation and increasing summer temperatures have been observed in climatological records, with trends expected to continue into the future. Translation into changes in watershed processes, however, is a problem that is unresolved. It is unclear whether utilities should plan for decreasing water availability or increasing availability due to climate change impacts on the Central Indiana region. Recent decades have seen increasing streamflow and baseflow in the region. The use of natural baseflows calculated for the 2007-2017 period in estimates of future water availability assumes that the observed increases in that period relative to long-term averages, continue into the future.

Part II
Regional Water Quality

An assessment of water quality data in the Central Indiana region was conducted using surface water, ground water, and potential contaminant source data obtained from various state databases. The objective is to compare surface and groundwater quality data with the estimated water supply availability estimates. Available surface and groundwater supplies that exceed EPA primary and secondary maximum contaminant concentrations would either require water treatment or could be eliminated from the overall water availability.

7 Previous Water Quality Investigations

The United States Geological Survey (USGS) evaluated water quality in the White River Basin from 1992-1996 (Fenelon, 1998) as part of the National Water-Quality Assessment (NAWQA) program. Surface water and groundwater samples were collected in the White River basin, and several chemical parameters (i.e. pesticides, volatile organic compounds, and inorganic water quality parameters) were analyzed. Key findings of the USGS study are summarized below:

- Twenty-five different pesticide or pesticide degradation products (i.e. degradates) were detected in 5 percent of the samples collected from the mouth of the White River. Atrazine and metolachlor were commonly detected, while cyanazine and alachlor were frequently detected. Although a few samples contained concentrations of atrazine, alachlor, or cyanazine above federal drinking water standards or advisories, annual average concentrations of each of the above detected compounds in the White River were below their respective standard or guideline.

- At surface water monitoring sites, the median concentration of nitrate ranged from 2 to 6 milligrams/liter (mg/l), with overall measured surface water concentrations rarely exceeding the federal maximum contaminant level (MCL) of 10 mg/l. Nitrate concentrations in groundwater samples in surficial sand and gravel aquifers underlying agricultural crop land exceeded the MCL in 17% of the shallow monitoring wells. In deeper wells (25 to 50 feet below the water table) in unconfined aquifers had little or no detectable nitrate concentrations.

- Groundwater samples were collected and analyzed for pesticide or pesticide degradation compounds from a network of 94 monitoring wells. Fourteen different pesticides were detected with repeat concentrations detected in 6 monitoring wells. However, all detected pesticide concentrations were well below federal drinking water standard or advisory. In agricultural areas with surficial sand and gravel aquifer used for water supply, trace con-

centrations of atrazine compounds were detected in approximately 66% of the monitoring wells.

- Volatile organic compounds (VOCs) were detected in more than half the urban area shallow monitoring wells, whereas 6% of the shallow wells in crop land area had detects. In urban areas, chloroform was the most common detected VOC. No VOC concentrations above federal MCLs were detected in the study area.

The Indiana Department of Natural Resources (IDNR) Division of Water conducted a regional study (IDNR, 2002) of the groundwater resources of the White and West Fork White River basin. Inorganic water samples were collected in 1989 and 1990 from 372 water wells (157 completed in unconsolidated deposits and 215 completed in the bedrock) and were analyzed to provide insight into the ambient ground water quality throughout the study area.

The White River basin study (IDNR, 2002) used graphical methods to display the areal distribution of dissolved parameters throughout the basin and to further characterize the general chemical characteristics of the ground water of each aquifer system. Major inorganic chemical parameters included calcium, magnesium, sodium, chloride, sulfate, and bicarbonate, whereas minor parameters included potassium, iron, manganese, strontium, zinc, fluoride, and nitrate, alkalinity, hardness, total dissolved solids (TDS), and radon.

Nitrate concentrations in ground water samples in the White River basin ranged from less than 1.0 mg/l (which is below the concentration limit consider for human influence) with six samples having a concentration exceeding the MCL of 10 mg/l (IDNR, 2002). The areal nitrate concentration data illustrated that in the West Fork White River basin the concentrations were below 1 mg/l, and concentrations exceeding the MCL were found in isolated wells or localized areas.

Twenty-eight wells (fifteen completed in bedrock and 13 completed in unconsolidated formation) in the West Fork White River basin were sampled and analyzed for 53 pesticides and 4 metabolites/degradation products (IDNR, 2002). A majority of the analyzed pesticides were not detected at concentrations above analytical laboratory limits. In wells that did contain pesticides or metabolites, concentrations were well below USEPA national drinking water standards. In addition, the greatest percentage of wells (42%) where at least one pesticide was detected coincided with agricultural land overlying fluvial unconsolidated deposits; the lowest percentage of wells (11%) where at least one pesticide was detected correlated with urban land overlying fluvial unconsolidated material.

Fifty-eight volatile organic compounds (VOCs) were also analyzed at part of the White River basin study (IDNR, 2002). No detected VOC had a concentration that exceeded the USEPA national drinking water standard, and most detected VOCs were found in shallow wells coinciding with urban land use. Chloroform was the most common detected VOC with the highest reported concentration of 39 mg/l. The source of the detected chloroform concentrations was believed to related to chlorinated public water supplies (IDNR, 2002).

The USGS conducted an extensive study of Indiana surface water quality from 2000 to 2010 (Risch et al., 2014). The study used a parametric time series model (QWTREND) to develop constituent values adjusted for seasonal variance and serial correlation in order to identify trends independent of stream flow variability. A total of 7,435 water samples were collected from 57 sites (and analyzed for 12 parameters) over a time period of approximately 11 years. The study determined that in the West Fork of the White River near Indianapolis, a trend of increasing concentrations of nitrate and phosphorous was detected. In addition, increases in chloride concentration were detected at three sites located upstream from Indianapolis in the West Fork White River basin.

In 2008, the Ground Water Section of the Drinking Water Branch of the Indiana Department of Environmental Management (IDEM) Office of Water Quality began a field sampling program of the Statewide Groundwater Monitoring Network (IDEM, 2016). The sampling program is conducted across the state to statistically verify background groundwater levels in distinct hydrogeological settings. The program continues today. Once ambient groundwater conditions were established, comparisons between groundwater and surface water could be evaluated and theories concerning ground water/surface water interactions could be formulated and verified. Water samples were collected from public water supply wells and private domestic wells within designated hydrogeological areas to determine the groundwater quality in the various aquifers of Indiana. All of the wells in the monitoring network were sampled for National Drinking Water Contaminants, which include volatile organic compounds (VOCs), synthetic organic compounds, unregulated pesticide/herbicide breakdown products (i.e. degradates), and inorganic compounds.

In the Central Indiana region, study results (IDEM, 2016) indicated that nitrate concentrations ranged from below laboratory detection limits to approximately 10 mg/L. Arsenic concentrations ranged from below laboratory detection limits to over 10 micrograms/liter (ug/L). Additional discussion of arsenic in Indiana groundwater is provided by Spindler and Denney (2018). Herbicide degradates were also detected in the Central Indiana region. The degradate products are more soluble and mobile than the parent herbicide, and therefore there is greater potential for these compounds to be present in surface and groundwater. Although Alachlor ESA, Metolachlor ESA, and Metolachlor OA were detected in portions of the Central Indiana region, the concentrations were low (less than 1 ug/L).

8 Groundwater Quality Assessment

To provide a current assessment of groundwater quality in the Central Indiana Region, unpublished groundwater quality data from 2013 to 2018 from the IDEM Statewide Groundwater Monitoring Network was provided by the IDEM Groundwater Section (Hudson, 2020). For the Central Indiana region, water quality analysis results were obtained from wells located within the nine-county study area. In addition, locations for each sampled well were obtained from

IDEM to provide a more accurate assessment of ground water quality in the Central Indiana region.

The IDEM water quality data does not contain enough consistent, yearly water quality results from individual wells to evaluate long-term water quality trends. Therefore, maps were created illustrating areal distribution of selected water quality parameters for the Central Indiana region from 2013 to 2016, which was the last year that water quality sampling was conducted for the entire study area. In addition, box and whisker plots of water quality concentrations verses well depth were constructed to further evaluate possible water quality trends. Note that monitoring well depth was included in the 2013 to 2108 IDEM data but did not include a specific well construction report to determine what specific geologic formation the well was screened across. However, the 3-D geologic model results and corresponding depth to bedrock data (see Appendix D) was used to provide an approximate determination of unconsolidated formation and bedrock wells.

As previously mentioned, the IDEM Statewide Groundwater Monitoring Network wells are sampled and analyzed for all water quality parameters included in the National Drinking Water Contaminants inventory (IDEM, 2016). For the Central Indiana region, a majority of the sampled wells had no VOC detects, with only a small percentage of wells having VOC concentrations slightly above laboratory detection limits and well below the MCL. Well sample results for pesticide, herbicide and associated degradates also had either no detects or very low concentrations below MCLs. Note that pesticide and herbicide degradates currently do not have an established MCL or health guidelines (IDEM, 2016). For the Central Indiana region water quality assessment, arsenic, nitrates, iron, sodium, and chloride were analyzed. Previous studies (Fenelon, 1998; IDNR, 2002; IDEM, 2016) noted that higher concentrations of these parameters were detected in the Central Indiana region. In addition, concentrations of these parameters above primary and secondary MCLs would require expensive treatment processes to meet potable water quality standards.

Figures 8.1, 8.3, 8.5, 8.7, and 8.9 illustrate the areal concentration of arsenic, nitrate, chloride, sodium and iron, respectively. Note these figures also illustrate the extent of unconsolidated deposits (river, lake and outwash) and the inferred aquifer designation (unconsolidated or bedrock) for each sampled well. Figures 8.2, 8.4, 8.6, 8.8, and 8.10 are box and whisker plots of concentration as compared to well depth for arsenic, nitrate, chloride, sodium, and iron, respectively. These figures also illustrate the MCL and four concentration range quartile percentages (10, 25, 75 and 90). A brief summary of the key findings of Figures 8.1 through 8.10 are as follows:

- Arsenic concentrations range from non-detect to greater than 10 ug/L (which is the MCL for arsenic). A majority of the sampled wells that had an arsenic concentration above the MCL appear to be completed in unconsolidated deposits. Figure 8.2 illustrates that the largest range of arsenic concentrations coincide with wells that have a total depth between approximately 201 to 250 feet.

- A majority of the nitrate concentrations range from non-detect to less than 10 mg/L. One unconsolidated well in Morgan County had a nitrate concentration that exceeded the MCL of 10 mg/L. Figure 8.4 illustrates that the highest range of nitrate concentrations appear to coincide with wells that are relatively shallow (less than 50 feet total depth), which is consistent with a previous study (Fenelon, 1998).

- A majority of the chloride concentrations in the central Indiana region were below the secondary MCL of 250 mg/L, whereas 4 wells had concentrations above the secondary MCL. Figure 8.6 indicates that the highest range of chloride concentrations coincides with wells that are relatively shallow (less than 50 feet of total depth).

- Sodium does not have an MCL, although the USEPA suggests a maximum concentration of 20 mg/L in drinking water due to the potential for an increase in high blood pressure with higher sodium concentrations (USEPA, 2003). In Central Indiana region, sodium concentrations above 250 mg/L were detected. Figure 8.8 illustrates that the highest sodium concentrations coincide with wells that are relatively shallow (less than 50 feet), and with wells also constructed to a total depth of approximately 201 to 250 feet.

- A majority of the iron concentrations were above the secondary MCL of 0.3 mg/L. A majority of the wells with iron concentrations above the secondary MCL appear to be constructed in unconsolidated deposits. Figure 8.10 illustrates that the range in iron concentration with depth is highly variable. This observed trend suggests that iron concentrations are highly dependent on local hydrogeologic and geochemical conditions in the aquifer.

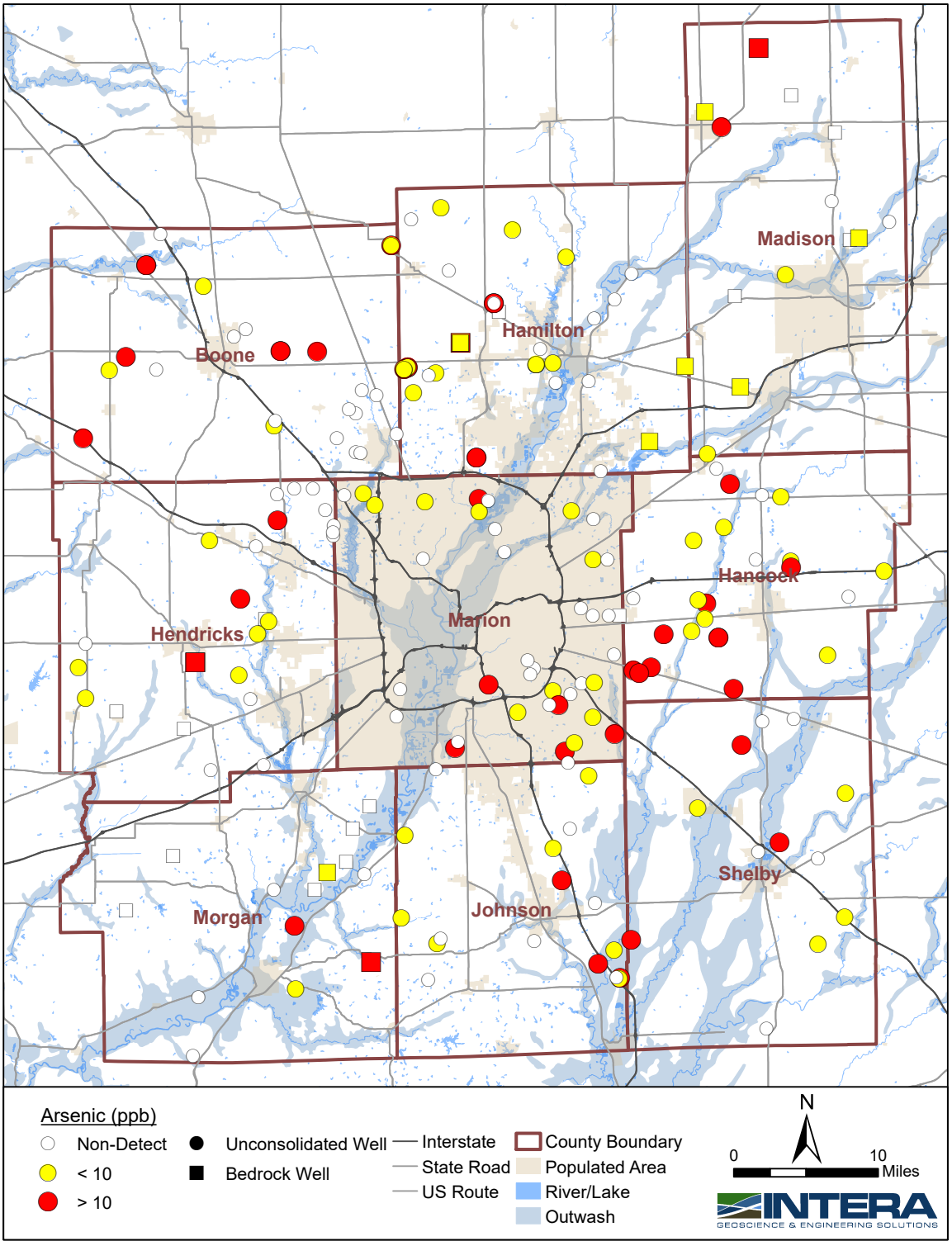

Figure 8.1: Areal distribution of Arsenic concentration in the Central Indiana region. *Data provided by IDEM Groundwater Section.*

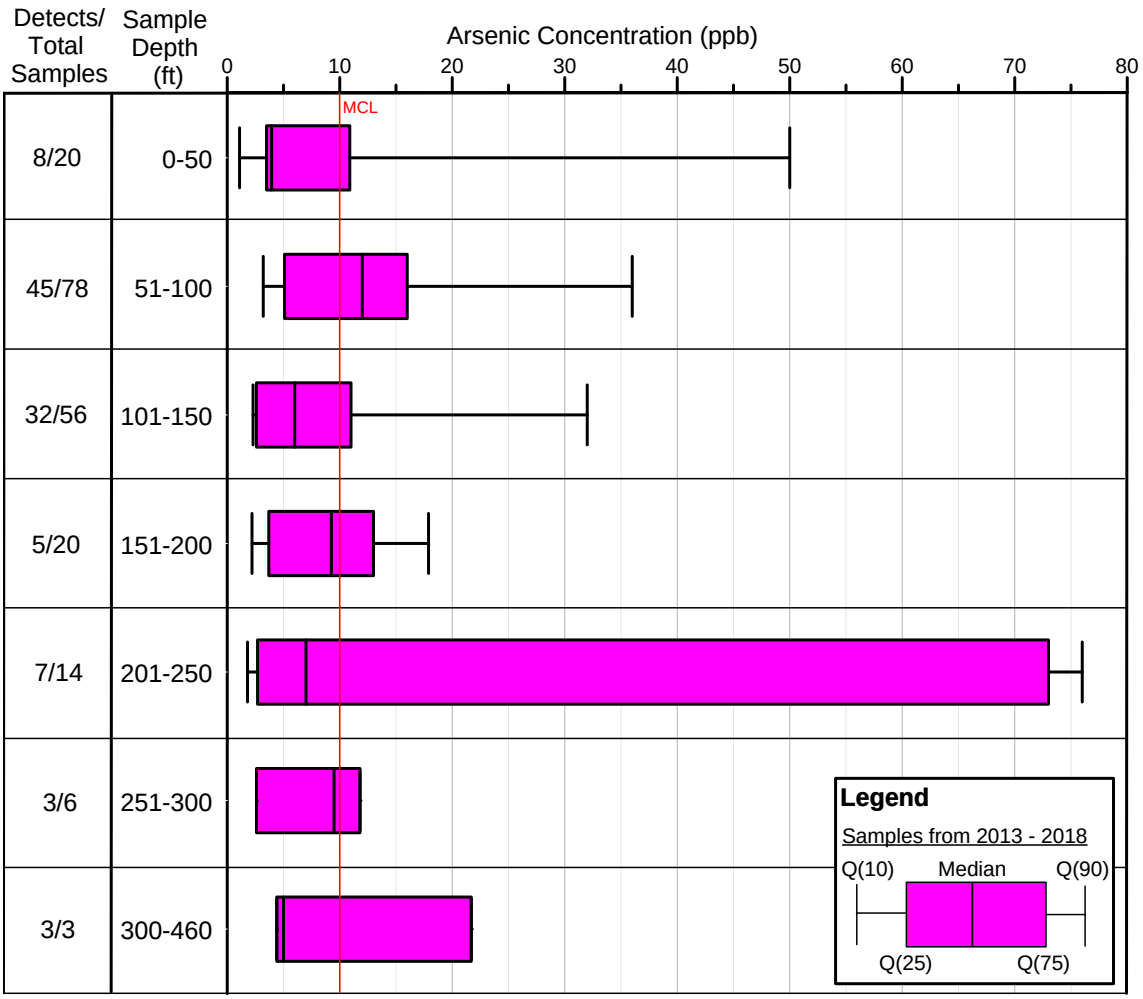

Figure 8.2: Arsenic concentrations as compared to well depth. *Data provided by IDEM Groundwater Section.*

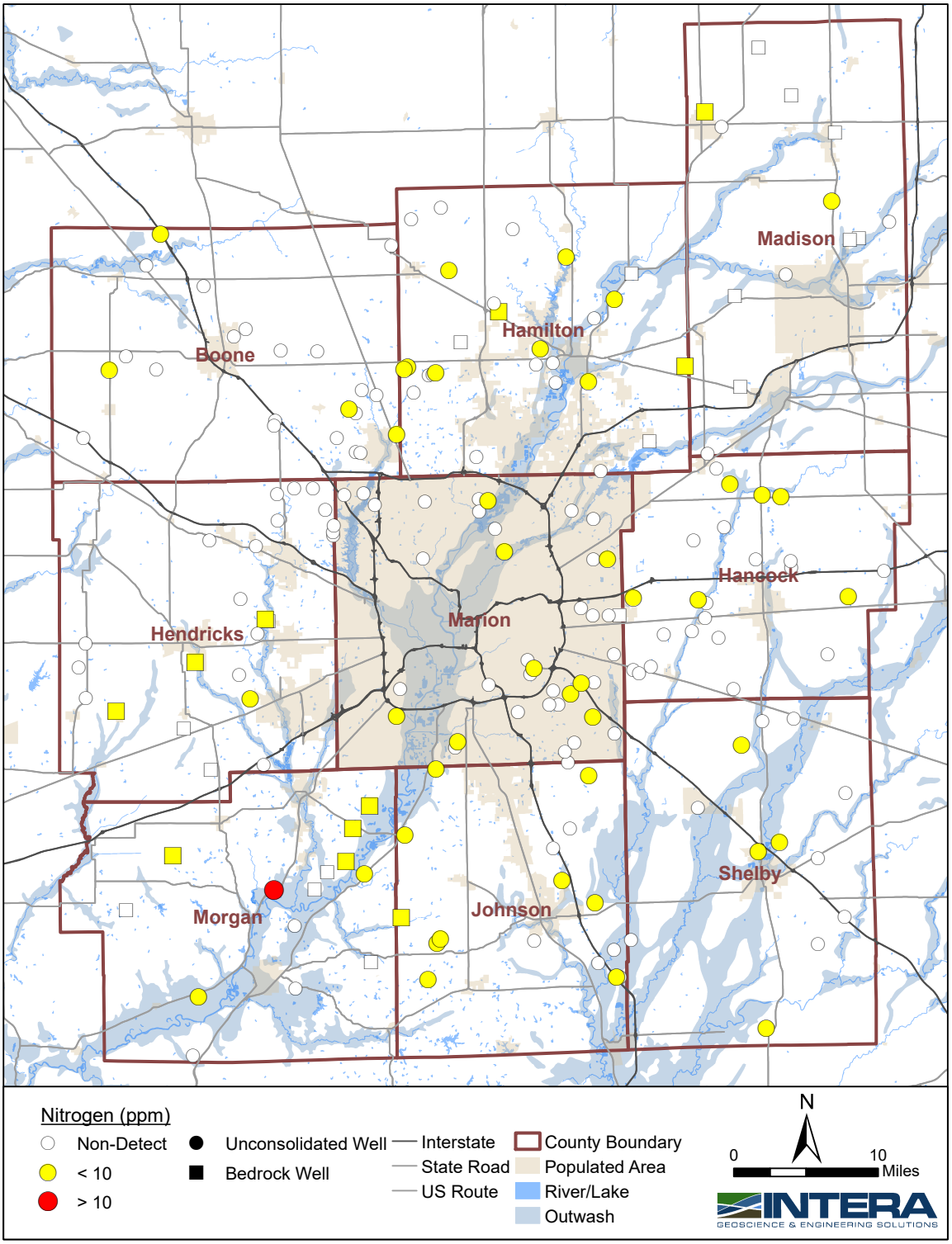

Figure 8.3: Areal distribution of Nitrate concentration in the Central Indiana region. *Data provided by IDEM Groundwater Section.*

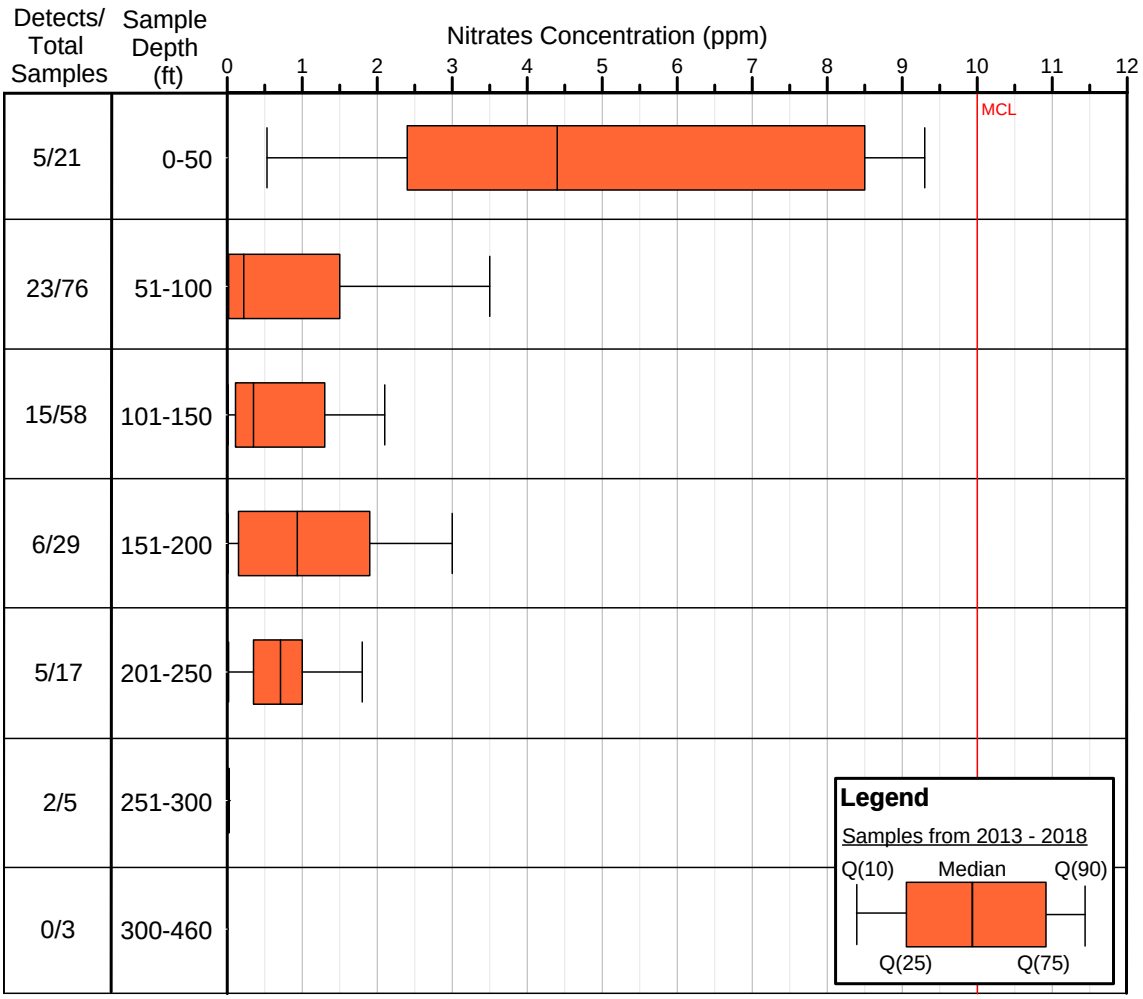

Figure 8.4: Nitrate concentrations as compared to well depth. *Data provided by IDEM Groundwater Section.*

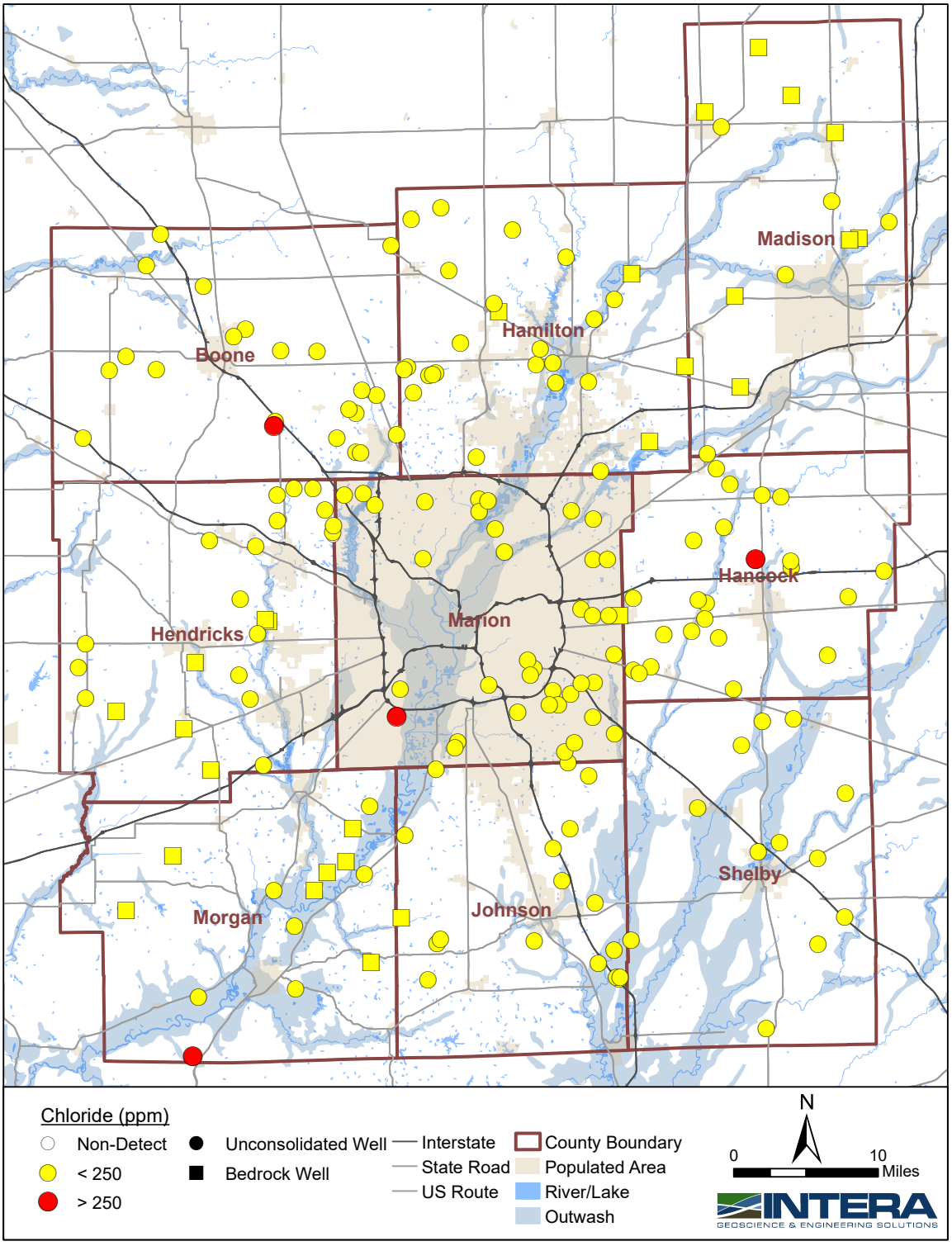

Figure 8.5: Areal distribution of Chloride concentration in the Central Indiana region. *Data provided by IDEM Groundwater Section.*

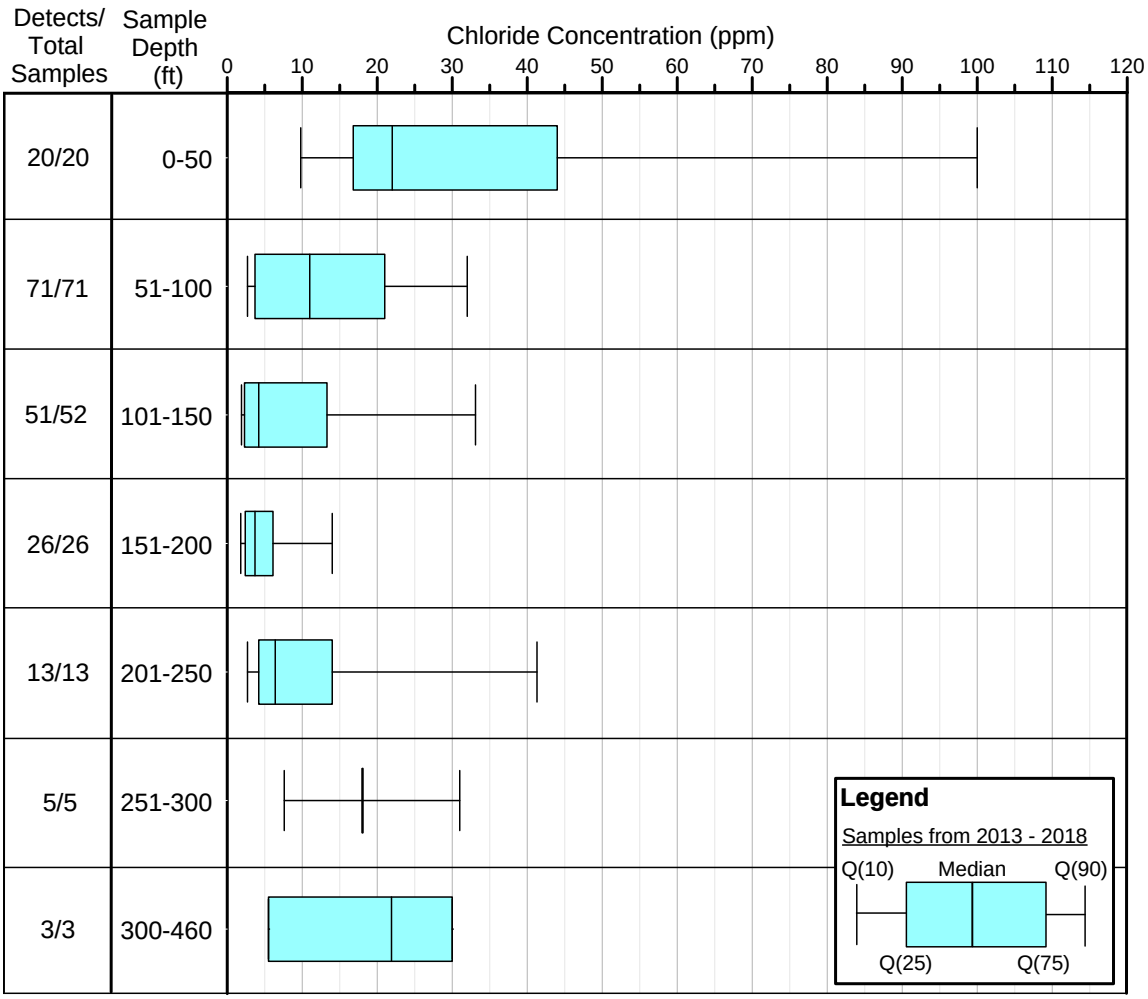

Figure 8.6: Chloride concentrations as compared to well depth. *Data provided by IDEM Groundwater Section.*

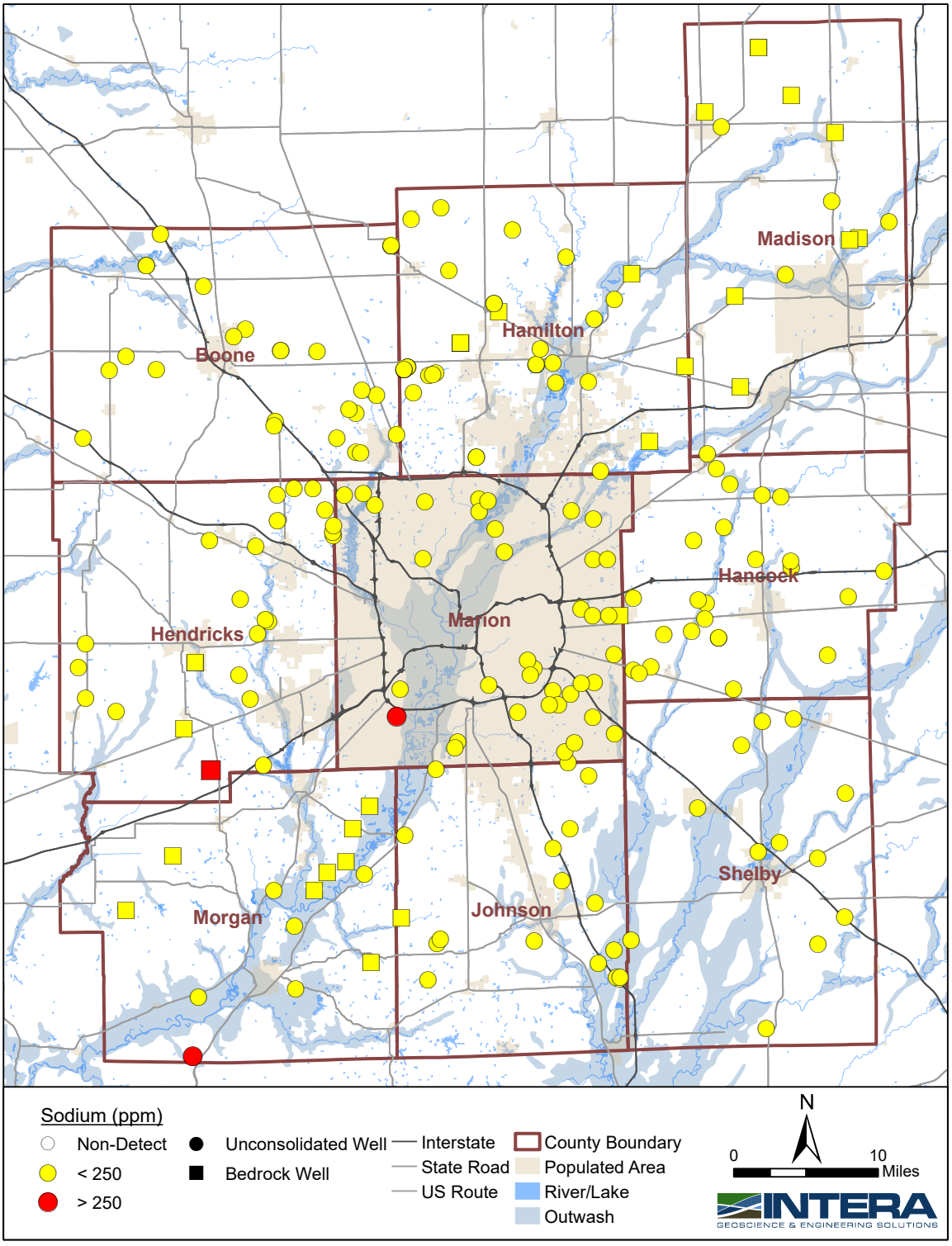

Figure 8.7: Areal distribution of Sodium concentration in the Central Indiana region. *Data provided by IDEM Groundwater Section.*

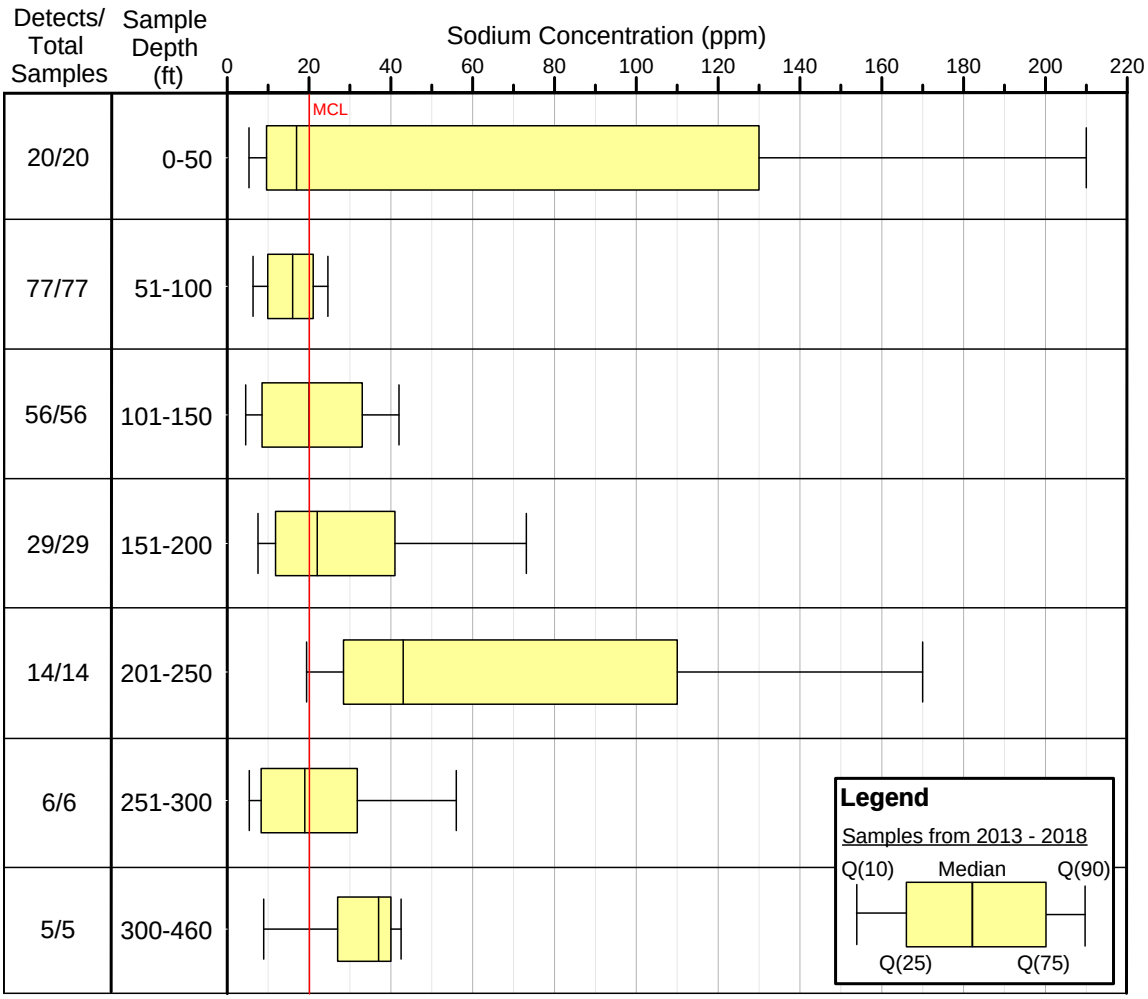

Figure 8.8: Sodium concentrations as compared to well depth. *Data provided by IDEM Groundwater Section.*

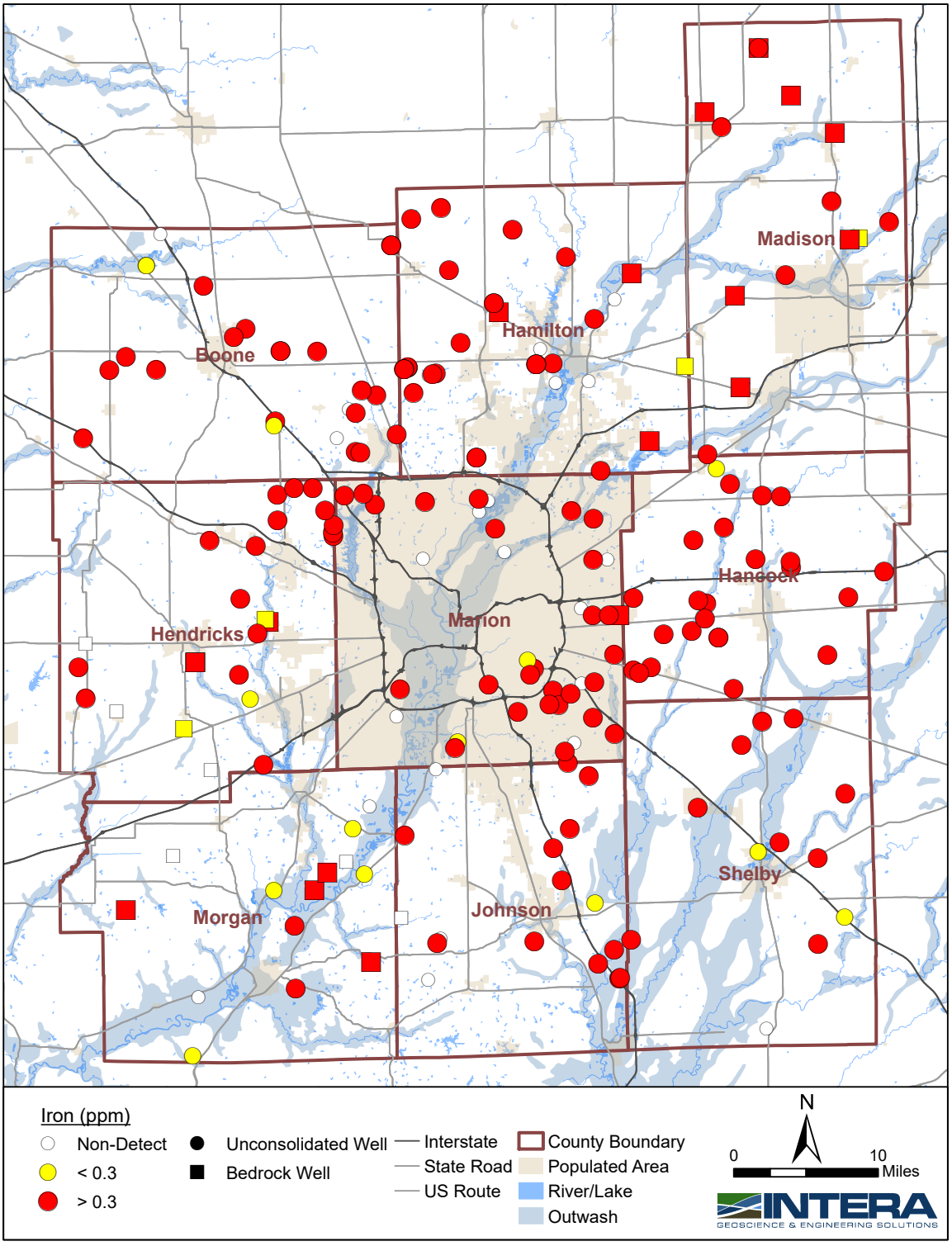

Figure 8.9: Areal distribution of Iron concentration in the Central Indiana region. *Data provided by IDEM Groundwater Section.*

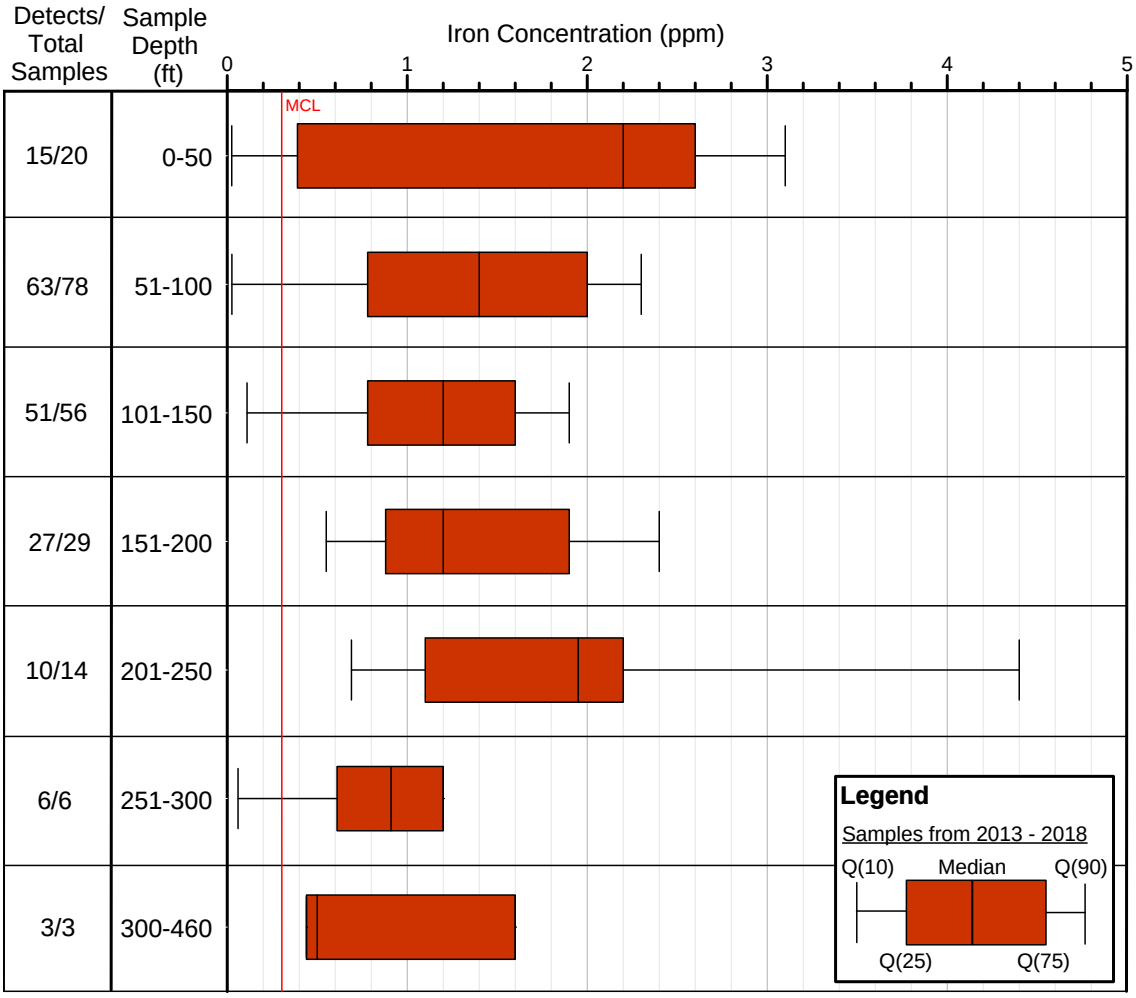

Figure 8.10: Iron concentrations as compared to well depth. *Data provided by IDEM Groundwater Section.*

9 Potential Contaminant Source Inventory

To further evaluate groundwater quality in the Central Indiana region, a potential contaminant source (PCS) inventory was conducted by accessing known environmental sites from the IndianaMap GIS database (IGWS, 2020b). The PCS inventory represents sites that have either resulted in contaminant migration into surface or groundwater flow systems or have a potential for impacting groundwater quality in their vicinity. A buffer distance around the various sites was also calculated to provide an exclusion zone for developing water supplies. A 200-foot buffer was used for interstates, active rail lines, waste tire sites, voluntary remediation program sites, brownfield and manufactured gas plants, whereas a 1000-foot buffer was used for Superfund sites. The site boundary was used for coal waste impoundments, and waste disposal facilities. The PCS inventory represents an initial attempt to identify potential areas of groundwater quality concern. Additional investigative efforts would be needed to determine if groundwater quality impacts are present, and their magnitude and extent.

Figure 9.11 (*left panel*) summarizes the PCS inventory for the Central Indiana region. Figure 9.11 illustrates that a majority of the PCS sites are located in Marion County and coincide with approximately 11.3% of delineated outwash deposits. For the remaining counties, the delineated PCS sites have a lower density as compared to Marion County, and the percent of outwash deposits coinciding with delineated PCS areas ranges from approximately 1.1 to 3.1 percent. This suggests that these counties have a lower potential for water quality impacts associated with known PCS sites as compared to Marion County. The right panel of Figure 9.11 shows the PCS inventory for central Marion County, along with water withdrawal location for public water supply. These maps show potential sources only; there is no mapping of known contaminant plumes included. Contaminant plumes are monitored and tracked through individual state and federal enforcement actions, but there is currently no way to readily access and map all plume data to determine regional impacts to water availability.

10 Surface-Water Quality Assessment

Providing a current quantitative assessment of surface water quality in the Central Indiana region would require a comprehensive study involving the collection of numerous water samples throughout the year and the analysis of multiple chemical parameters similar in scope to the previous USGS study (Risch et al., 2014). The required scope of work to conduct this type of study is beyond the scope and time frame of the Central Indiana region study.

A preliminary surface water quality assessment of the Central Indiana region was conducted using the Indiana 303(d) Impaired Water List (IDEM, 2020). Figure 10.12 summarizes the 303(d) Impaired Waters List for the Central Indiana region. Figure 10.12 illustrates that numerous surface water bodies are impacted by a large range in chemical, bacterial, and biological parameters.

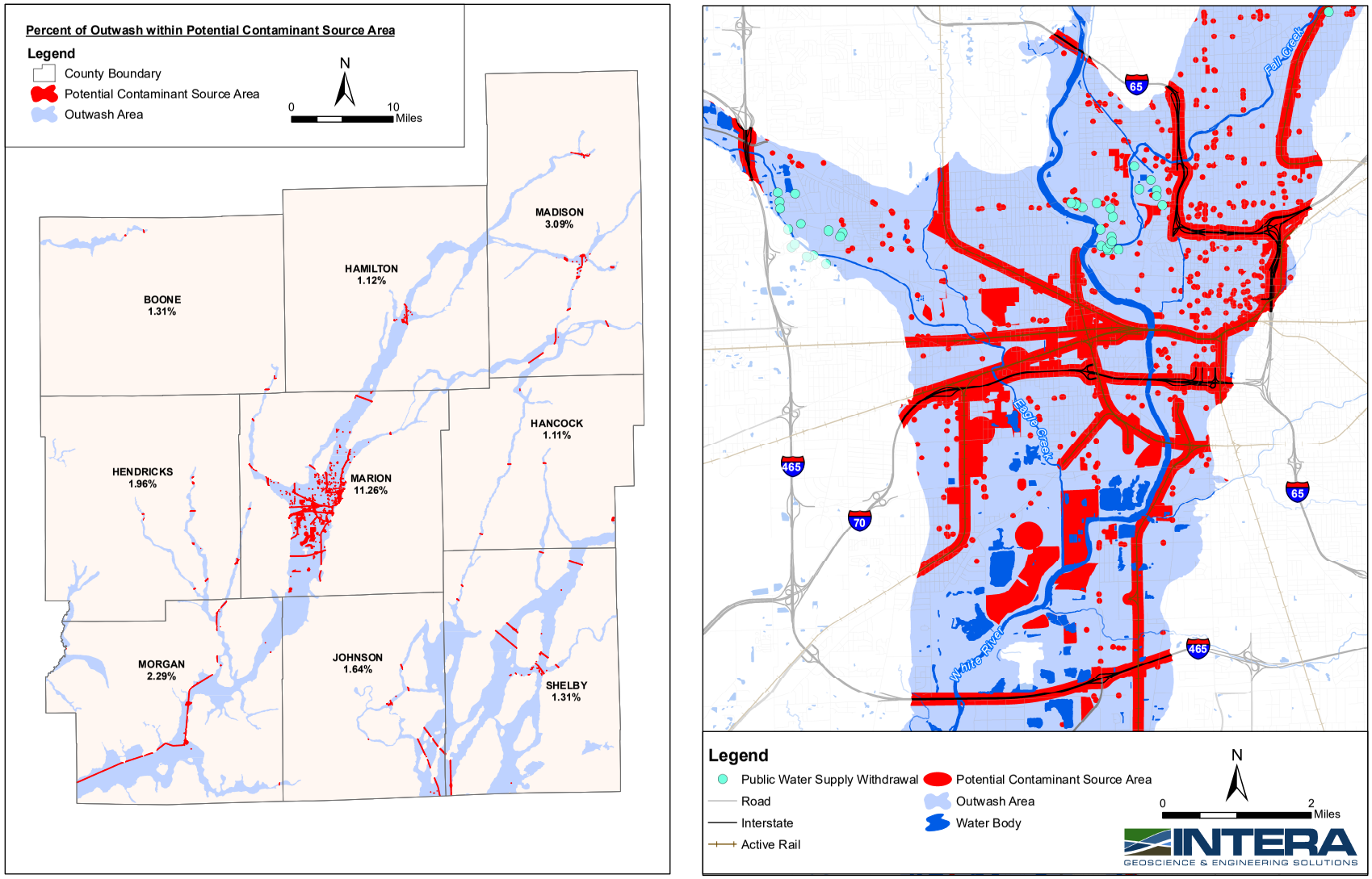

Figure 9.11: Potential Contaminant Source Inventory map.

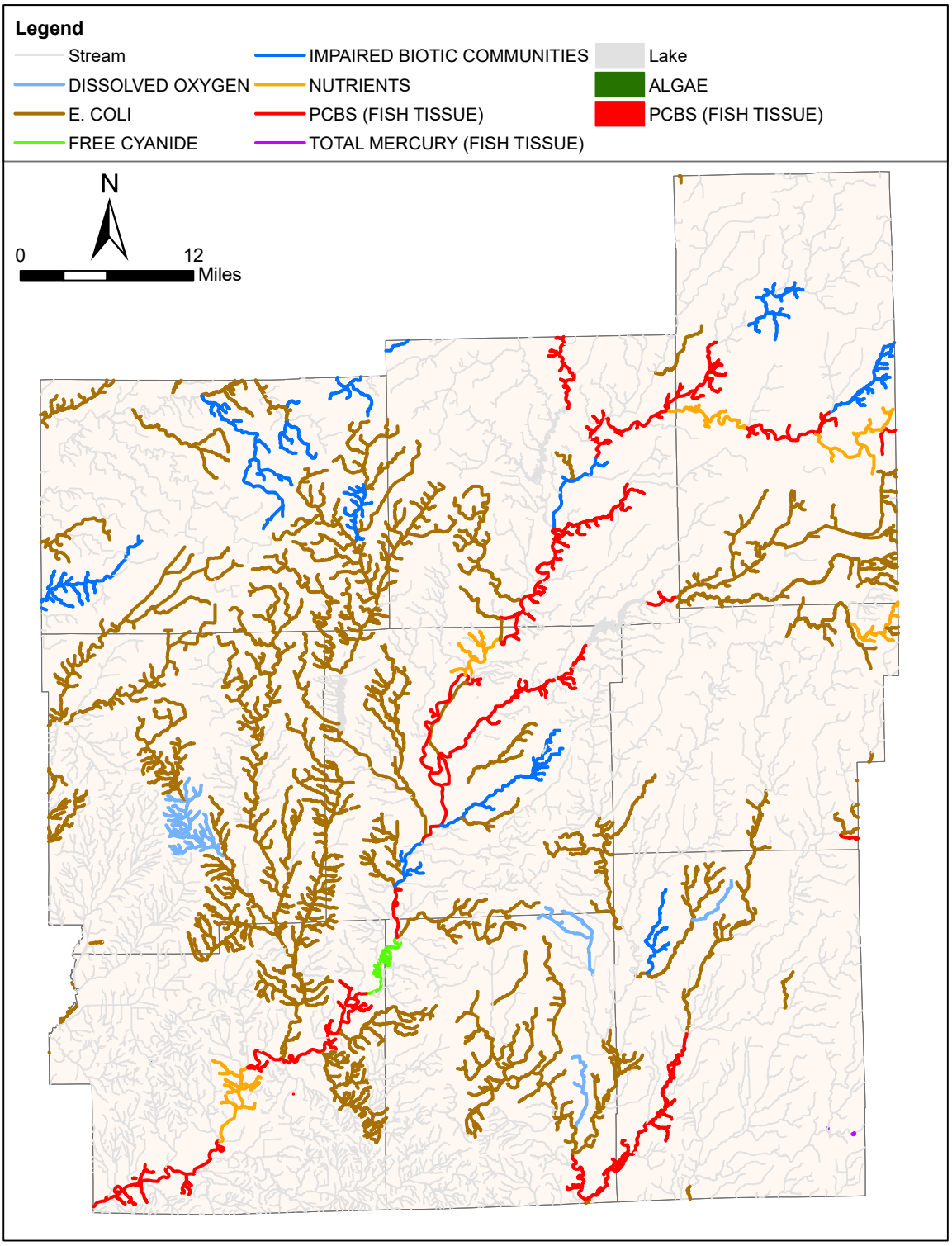

Figure 10.12: Summary of 303(d) impaired waters.

11 Summary

The surface water and groundwater quality issues faced in the Central Indiana region are typical of most suburban to urbanized settings. This is stated not to minimize the impacts of water quality or the importance of continued monitoring, but rather to recognize that the water quality issues faced by Central Indiana are not unique. Conclusions of the water quality review and assessment presented here include the following:

- Ambient groundwater quality in the Central Indiana region is well-characterized by the ongoing statewide monitoring activities conducted by the Groundwater Section of IDEM. The assessment of regional groundwater quality, based on current IDEM data, does not limit the potential sources for groundwater supply for a large water utility. While several constituents occur at levels greater than the MCL, most can be removed by standard treatment to provide a potable water supply. The mapping of ambient groundwater quality prepared by IDEM (2016), and the mapping presented here, provide guidance for identifying or eliminating potential sources for smaller utilities and domestic supplies, where standard treatment costs may be prohibitive. These results provide a guide for groundwater quality only. Any natural, or ambient water quality issues must be dealt with on a case-by-case basis, with detailed site investigations, to determine the actual impacts on groundwater availability.

- Groundwater contamination from historic contaminant releases poses a larger threat to groundwater supply, accessibility and availability in the Central Indiana region than ambient conditions. A potential contaminant source inventory was conducted here to address this concern. The inventory suggests that impacts to groundwater availability are primarily of concern in Marion County, where many potential and actual contamination sources exist. Contaminant plumes are monitored and tracked through individual state and federal enforcement actions, but there is currently no way to readily access and map all plume data to determine regional impacts to water availability. The potential contaminant source mapping alone accounts for over 11% of the surface area of the outwash deposits in Marion County, which are the primary source of groundwater supply in the county. Substantially more area is covered by known contaminant plumes, but those areas remain un-mapped on a regional scale. No changes in the water availability model were made to account for historic contaminant releases. Again, these results provide a guide for groundwater quality only. Any historic contaminant releases must be dealt with on a case-by-case basis, with detailed site investigations, to determine the actual impacts on groundwater availability.

- An overview of surface water quality in the region is provided by the current federal 303(d) listing of impaired waterways, which shows most major rivers and streams in the region to be impaired by a large range in chemical, bacterial, and biological parameters. Surface-water quality in the past has been impacted by combined sewer overflows; conditions in

Marion County will improve significantly with the operation of the deep tunnel interceptor. In addition, major reductions in withdrawal and return of non-contact cooling water by the energy sector will result in improved water quality. As discussed in Section 3.4, wastewater treatment plant effluent is indirectly used for water supplies throughout the region. Compliance with water quality requirements for wastewater plant effluent is necessary for maintaining and improving surface water quality and providing downstream potable water supplies.

Part III
Groundwater Accessibility Model

We address the issue of groundwater accessibility with regional and local models of groundwater flow. The purpose of the models is not to evaluate groundwater availability; groundwater availability was addressed in Part I of this report, through evaluation of the the natural baseflow in rivers and streams throughout the Central Indiana region. Rather, the purpose is to test groundwater impacts due to increased withdrawals at existing water supply wells, and assess the need for additional groundwater infrastructure to support expansion of the water supply system. In addition, we take a detailed look at groundwater conditions in the region between Noblesville and Nora, which has been identified as a sub-basin of rapid growth with significant current and future water deficits.

We adopt the step-wise modeling approach discussed at length by Haitjema (1995), for example, and take the following steps:

1. Develop a steady-state, regional model of each major drainage system in the region, using GFLOW software (Haitjema, 1995). The purpose of the regional models is to simulate critical Quarter 3 natural baseflows to approximate regional conditions during a drought. Conjunctive groundwater-surface water modeling of the natural baseflow generated in each sub-basin is performed to calibrate the model. The regional models are developed without consideration of groundwater withdrawals at wells, and therefore represent natural conditions. The details of this regional modeling work and summary of results are presented in Section 14.

2. Refine the regional GFLOW models in critical regions to include detailed surface water features, current and projected groundwater withdrawals, local heterogeneity, and other significant hydrologic features. The refined models are calibrated to available head data from the iLITH database and Quarter 3, low-flow stream discharges. The refined models remain single layer, steady state models, and are used to evaluate groundwater accessibility in regions of major public supply withdrawals. The details of this sub-regional modeling work and summary of results are presented in Section 15.

3. Extract a MODFLOW inset model from the refined regional model using GFLOW tools. Local detail is added to the inset model, including quarry dewatering, vertical layering, and variations in base, aquifer transmissivity, and streambed conductance. The purpose of this work is to demonstrate the transition from a regional GFLOW model to a local MODFLOW model, and to construct a detailed three-dimensional model to investige a critical region with a deficit in current and future excess water availability. The details of the inset modeling work and summary of results are presented in Section 16.

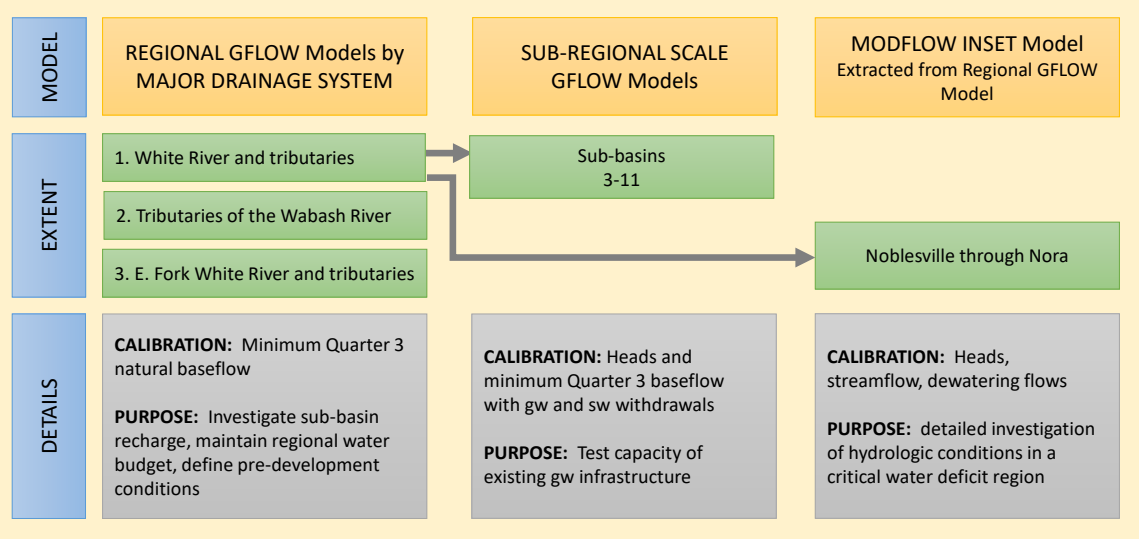

Figure 11.13: Overview of the step-wise approach to groundwater flow modeling applied to the Central Indiana region.

An overview of the step-wise process used to model groundwater flow in the Central Indiana region is presented in Figure 11.13. In the modeling approach described above, the 3D geologic solid model (Appendix D) was used extensively for defining conceptual models of aquifer flow, as a repository for aquifer geometry, for defining outwash geometry, as a repository for groundwater and surface water withdrawals, and as a repository for calibration data sets of head. Results from field testing (Appendix E) were used to aid in defining streambed properties in the local-scale inset model.

12 Geologic Complexity

A 3D geologic solid model, described in Appendix D, was constructed to interpret regional and local geologic and hydrologic conditions. A typical section through the unconsolidated materials including an outwash channel, developed with the model is presented in Figure 12.1. The complexity of the unconsolidated system hinders the automated generation of flow boundaries and aquifer properties directly from the solid model. With interpretation, surfaces bounding a groundwater model can be defined, however, there is not enough information to reliably initialize a three-dimensional description of the hydraulic conductivity field. The regional geometry of the bedrock surfaces is better understood, and more regular, but properties of the bedrock are only known at a few isolated locations.

The common modeling workflow of defining surfaces, automatic assignment of hydraulic properties based on material descriptions from well logs, and calibration to refine hydraulic properties, becomes futile in light of the scale and complexity of the unconsolidated formation.

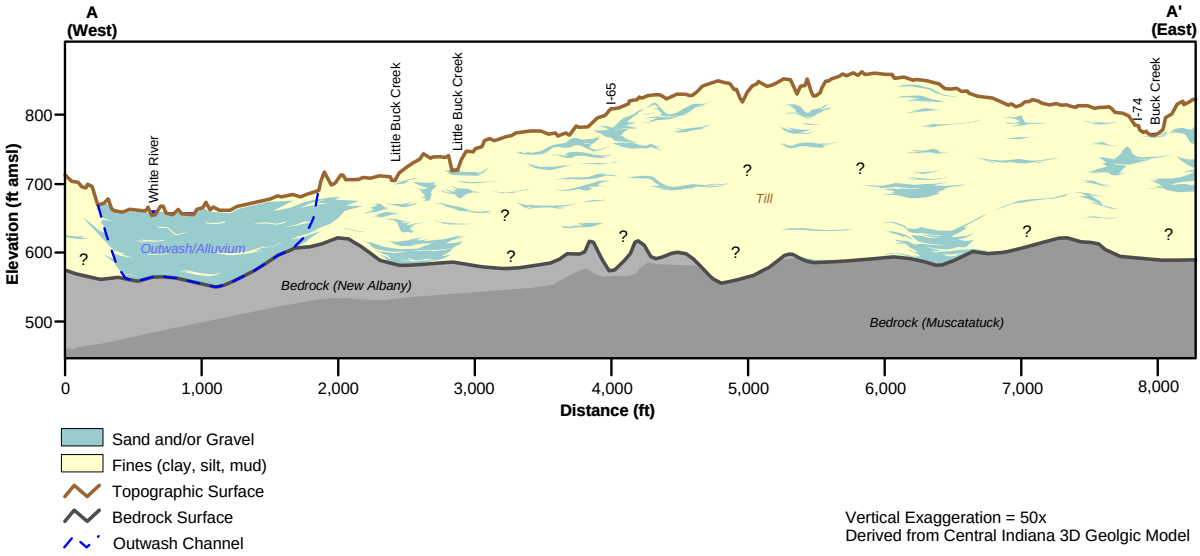

Figure 12.1: Geologic section through the unconsolidated material. *The details illustrate the futility of defining surfaces and a hydraulic conductivity field for a regional flow model. Section developed with the 3D geologic model.*

Extensive interpretation is required to define connectivity between sand and gravel lenses in the till, as well as in the outwash channels. Instead, following the step-wise approach presented above, we begin modeling the complex system with a simplified description that can accurately simulate total discharges throughout the entire system. Local geologic complexity is added as the modeling process proceeds and as local field studies are conducted.

13 The Comprehensive Discharge

Practical difficulties associated with regional modeling of the high transmissivity lenses of buried sand and gravel overlying multiple layers of lower transmissivity bedrock are addressed by modeling vertically-integrated flow using the approach presented by Strack (2017). Strack et al. (2017; 1989; 2015; 2005) define a comprehensive discharge vector and a comprehensive potential to evaluate the vertically-integrated flow in an aquifer system. The advantage of the use of the comprehensive discharge is that the extremely complex flow system of the Central Indiana region can be treated in a straightforward manner. As discussed by Strack (2017), the approach is particularly useful for assessing groundwater sustainability, as a relatively simple regional model can be constructed prior to developing a local, fully three-dimensional numerical model. The Dupuit approximation is used to generate an approximate, comprehensive head field in the aquifer system.

Application of this modeling approach to the Central Indiana region is discussed below. In the approach, all aquifers are represented by a single-layer in the groundwater flow model, with vertically-integrated properties. For a confined aquifer system, a comprehensive transmissivity,

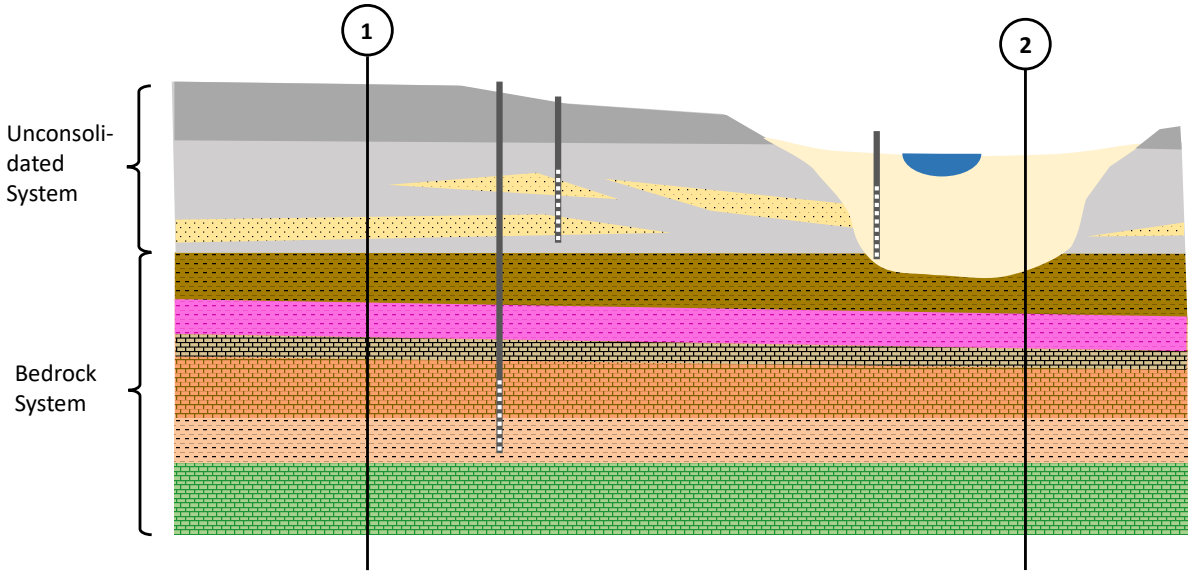

Figure 13.1: Typical section through a river valley, illustrating the bedrock and unconsolidated aquifer system. *Not to scale.*

T_c, may be defined

$$T_c = \int_{z_b}^{z_t} k(z)dz = \sum_{n=1}^{N} k_n H_n = \sum_{n=1}^{N} T_n \tag{14}$$

where N is the number of layers in the aquifer system; k_n, H_n and T_n are the hydraulic conductivity, thickness, and transmissivity of the n th layer, respectively; z is the vertical coordinate and z_b and z_t represent the elevations of the bottom and top, respectively, of the aquifer system. While comprehensive discharges are exact, hydraulic heads computed with the model must be interpreted through the Dupuit approximation (Strack, 2017)

$$h_c = (\sum_{n=1}^{N} T_n h_n)/T_c \tag{15}$$

where h_c is the comprehensive head in the aquifer system and h_n is the head in each aquifer layer. Note that the method does not allow for evaluation of h_n, only h_c. For an unconfined system, the expressions become more complex, and the reader is referred to Strack (2017). The interpretation, however, is similar: the comprehensive head at a location is equal to the average, transmissivity-weighted head over a vertical section at that location.

As an example, we consider the aquifer system illustrated in Figure 13.1, which includes 6 bedrock layers and discontinuous lenses of permeable unconsolidated material. The comprehensive transmissivity (T_c) at a section is the sum of the transmissivities of each layer in the aquifer system from the bottom to the top. For example, at Section 1, the comprehensive

Table 13.1: Ranges of transmissivities of the aquifer system (**?**).

	Reported Transmissivity (ft^2/day)	Example Value (ft^2/day)
Unconsolidated System		
Outwash system	2,000 – 20,000	10,000
Outwash sub-system	260 – 7,300	4,000
Tipton Till system	400 – 4,000	4,000
Clays and silts	–	0
Bedrock System		
Sanders Group	10 – 140	50
Borden Group	16 – 220	100
New Albany Shale	15 – 150	50
Muscatatuck and Bainbridge Group	25 – 500	100
Maquoketa Group	–	0
Trenton Limestone	–	0

Notes: ft^2/day = square feet per day.

transmissivity is calculated as:

$$T_c = \sum_{n=1}^{6} T_n + \sum_{m=1}^{3} T_m \tag{16}$$

where the first term represents the total transmissivity of the bedrock system including six layers, and the second term, the transmissivity of the unconsolidated system, including three distinct layers in the figure. The unconsolidated system is assumed to be confined on top by impermeable till. Using typical values for aquifers in the Central Indiana region, summarized in Table 13.1 in units of square feet per day, and summing from the bottom up, we obtain

$$T_c = 0 + 0 + 100 + 50 + 100 + 50 + 0 + 4000 + 0 = 4,300\, ft^2/day \tag{17}$$

At section 2 the comprehensive transmissivity becomes

$$T_c = 300 + 10,000 = 10,300\, ft^2/day \tag{18}$$

For this system, the value of the comprehensive transmissivity is largely controlled by the properties of the unconsolidated till or outwash formations.

We build a single-layer groundwater flow model using the comprehensive potential, and interpret calibrated values of T to include bedrock. The simulated comprehensive head is interpreted as the average of transmissivity-weighted heads over the section. For this system, the significant transmissive features are the buried sand and gravel lenses in the unconsolidated material and the outwash deposits. At both sections, the addition to the comprehensive trans-

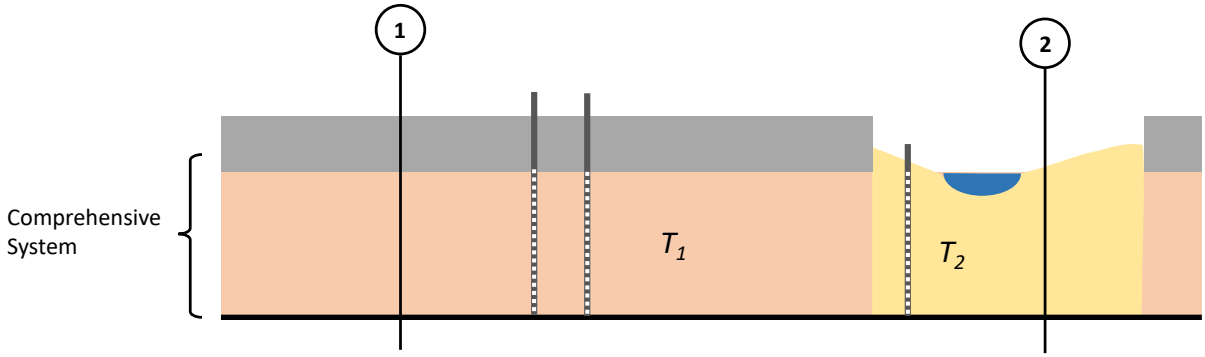

Figure 13.2: Translation of the aquifer system to a single-layer model of the comprehensive potential and discharge.

missivity of the bedrock system is small in comparison to the contribution of the unconsolidated material. As a result, the comprehensive head (equation 15) can be approximately interpreted as the hydraulic head in the unconsolidated material.

Translation from the real aquifer system to the comprehensive system is illustrated in Figure 13.2. In the Figure, the value of the comprehensive transmissivity jumps at vertical lines representing the boundary between the till and outwash. Recharge may be included explicitly without altering the interpretation of model heads or discharges (Strack, 2017). Wells are defined to be fully-penetrating in the comprehensive system, regardless of the layer of the system it is screened over; the comprehensive discharge remains exact. Leakage from surface waters separated from the aquifer by a low permeability stream bed, as illustrated in Figures 13.1 and 13.2, is dependent on the head in the aquifer below them. Thus incorporating this type of boundary results in a further approximation: stream leakage is computed using the computed comprehensive head in the system rather than the head in the aquifer directly below the stream. However, as discussed above, in this setting the comprehensive head is a good approximation of the head in the outwash.

14 Regional Flow Models

Regional models of groundwater flow were developed for each of the three major drainage systems in the Central Indiana region using GFLOW software. The regional models include only primary surface water features, recharge, inhomogeneity boundaries, and impermeable boundaries. The purpose of the regional models is to provide a consistent framework for more detailed local modeling. The primary goal of the regional models is to reproduce the minimum, Quarter 3, natural baseflow as observed in each sub-basin. Natural baseflows in streams are calibrated by varying the recharge applied to each sub-basin. In this way, critical drought conditions observed during 2007 or 2012 are represented by the regional models. Features of the three models overlap: for example, elements from both the Wabash tributaries and East

Fork White River and tributaries drainage systems are included as far-field elements in the model of the White River and tributarites drainge system.

14.1 Data

Surface-water mapping was obtained from the National Hydrography Dataset (NHD) (USGS, 2020c), with surface-water elevations obtained with the National Map Viewer online tool (USGS, 2020a). NHD area features representing major river segments, lakes, reservoirs and quarries are used to define the major surface-water features in each of the regional models of groundwater flow. NHD line features including perennial streams and creeks are not included in the regional models. Inhomogeneities in aquifer hydraulic conductivity and base elevations are included to represent major outwash regions, particularly in the downstream reaches of the White River drainage system and in the downstream reaches of the East Fork White River and tributaries drainage system.

The models are discretized spatially by inhomogeneities in the recharge rate, which are associated with sub-basin boundaries. The network of inhomogeneities provide a framework for refining local recharge, hydraulic conductivity and base elevation. Finally, in each model an impermeable barrier at the south end represents the extent of Wisconsonian glaciation in the region (Fenelon and Bobay, 1994).

Figures 14.1, 14.2, and 14.3 present the analytic elements used in the regional model of the White River and tributaries, the East Fork White River and tributaries, and the tributaries of the Wabash River drainage systems, respectively. The distribution of elements in each regional GFLOW model, including nearfield resistance linesinks and farfield head-specified linesinks representing surface waters, inhomogeneity boundaries where changes in recharge, base elevation and hydruaulic conductivity can occur, and impermeable barriers are presented in the figures.

14.2 Calibration

Calibration of the models to match natural baseflow was performed by varying firstly, recharge and secondly, streambed resistance until the target baseflows in each sub-basin and cumulative baseflows at USGS stations were matched closely. The framework of the regional model, which includes inflows of distributed areal recharge and outflows as discharge at streams, results in baseflow rates that are highly insensitive to aquifer hydraulic conductivity. Regional estimates of the hydraulic conductivity of the aquifer system (Table 13.1) were specified in the model and not varied during calibration.

Natural Baseflow Conjunctive groundwater and surface water simulations were performed in GFLOW for each sub-basin. Examples of GFLOW results showing contours of the comprehensive hydraulic head are presented for each major drainage system (Figures 14.4, 14.6, and 14.8). Results of the conjunctive modeling of groundwater and surface water are displayed on the figures – the width of each nearfield linesink indicates the cumulative baseflow contribution

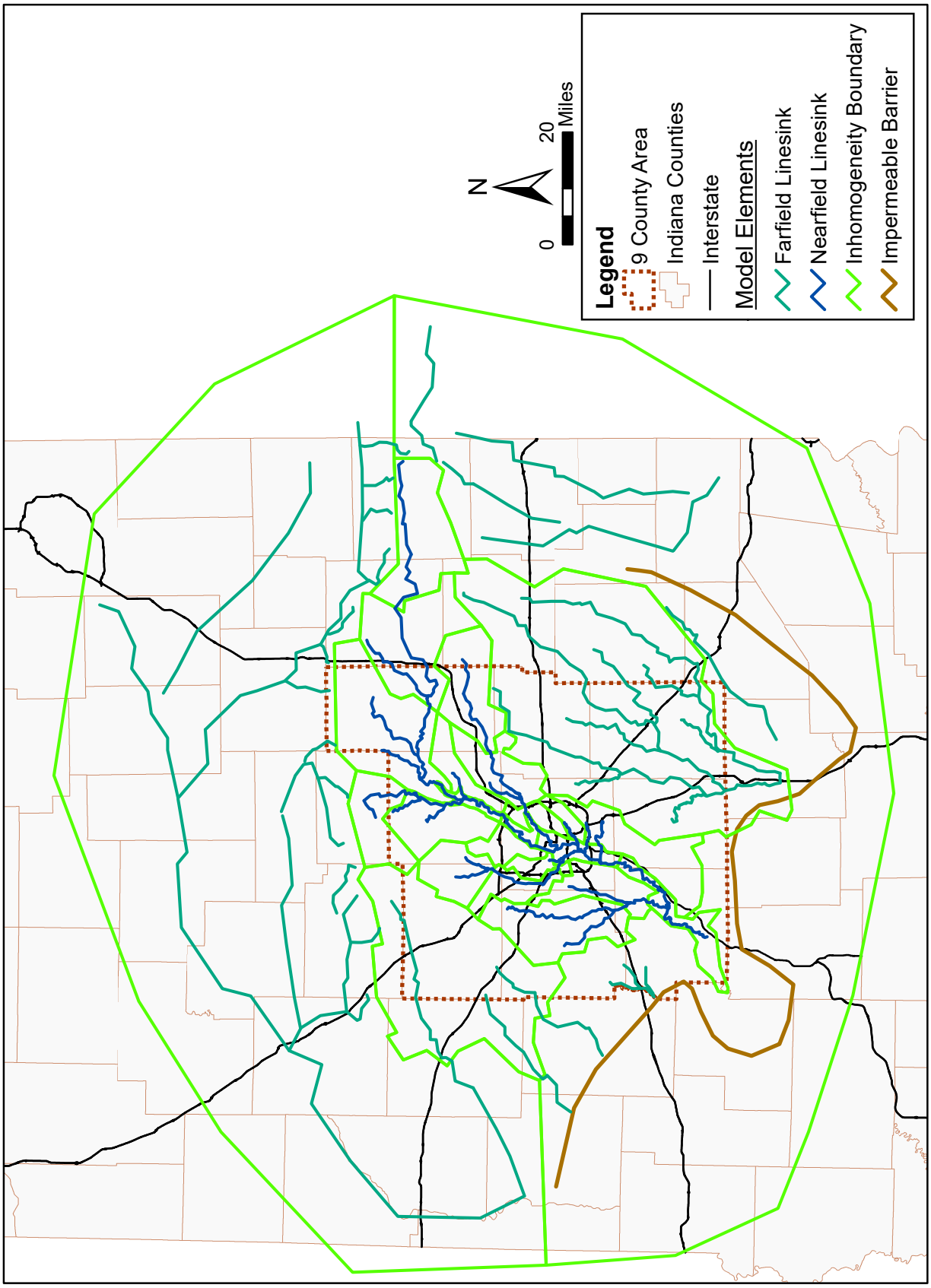

Figure 14.1: Distribution of elements in the regional model of the White River drainage system.

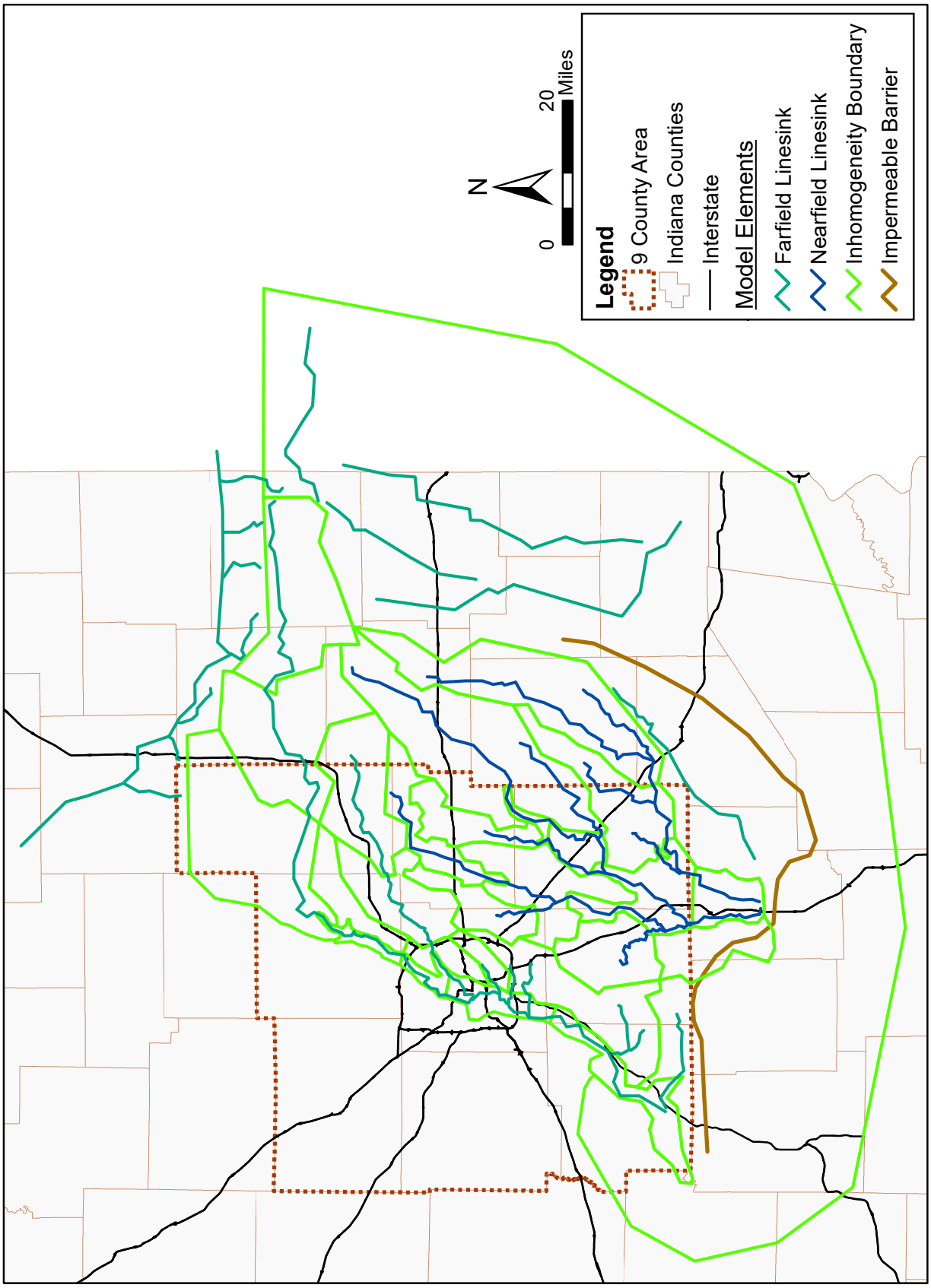

Figure 14.2: Distribution of elements in the regional model of the East Fork White River drainage system.

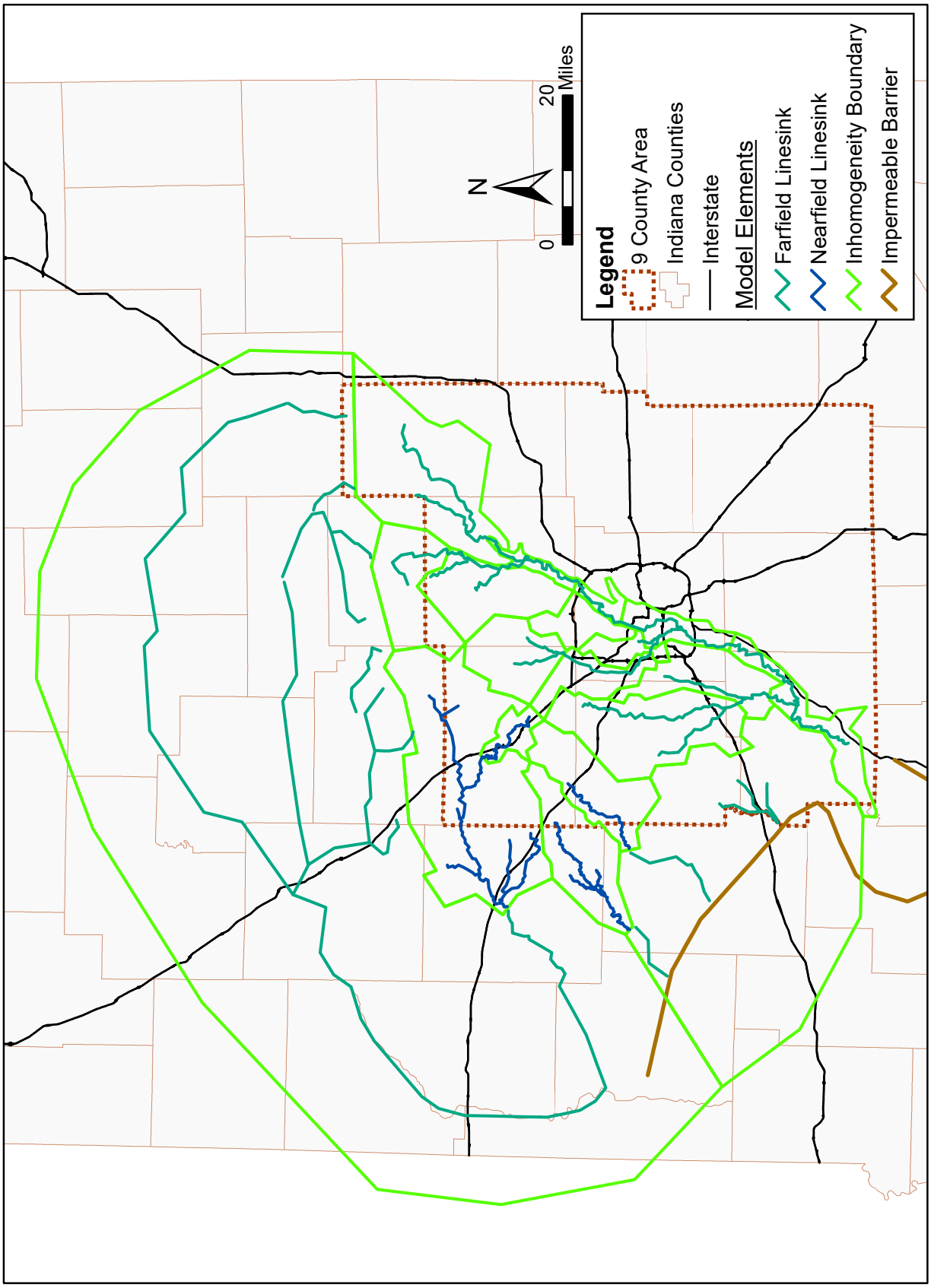

Figure 14.3: Distribution of elements in the regional model of the tributaries of the Wabash River drainage system.

to the stream in each sub-basin. Calibration plots (Figures 14.5, 14.7, and 14.9) and tabulated residuals (Tables 14.3, 14.6, and 14.9) are presented along with a summary of aquifer properties (Tables 14.1, 14.4, and 14.7) and calibrated recharge rates by sub-basin (Tables 14.2, 14.5, and 14.8) for each drainage system.

The three regional GFLOW models reproduce well the critical natural baseflow in all sub-basins, and are framed in a flexible manner for incorporation of local details and refinement required in developing sub-regional scale models of groundwater flow.

Groundwater Levels A regional data set of static head levels was developed from iLITH data for each of the three GFLOW models. Wells in the unconsolidated formations were screened for static water level and construction date. Only records made in calendar year Quarters 3 and 4 were included in the data set to reflect dry season conditions. The target head data are separated by major drainage system and by sub-basin.

The data set is not of high quality as it is based on driller's logs from 1900 through 1999 with varying quality control. No screening of the data was performed to remove outliers. The data set does, however, provide a regional assessment of head variations within the unconsolidated system. The spatial distribution of target points from the data set are presented for each major drainage system in Figures 14.10, 14.12, and 14.14. Plots of simulated heads versus target heads are provided in Figures 14.11, 14.13, and 14.15. The target heads were not used to calibrate the properties of the regional models; rather, the data was simply used to check the reasonableness of model heads after calibration to baseflow targets.

Table 14.10 presents standard calibration statistics used to assess the fit of simulated heads to target heads. Combined results for the three regional models include a Mean Absolute Error (MAE) and a Root Mean Squared Error (RMSE) of 4.9% and 6.9% of the range of target heads, respectively. Despite the low quality of the target head data set, and despite the models not being calibrated to target heads, in all cases average errors fall within 8% of the range of target heads.

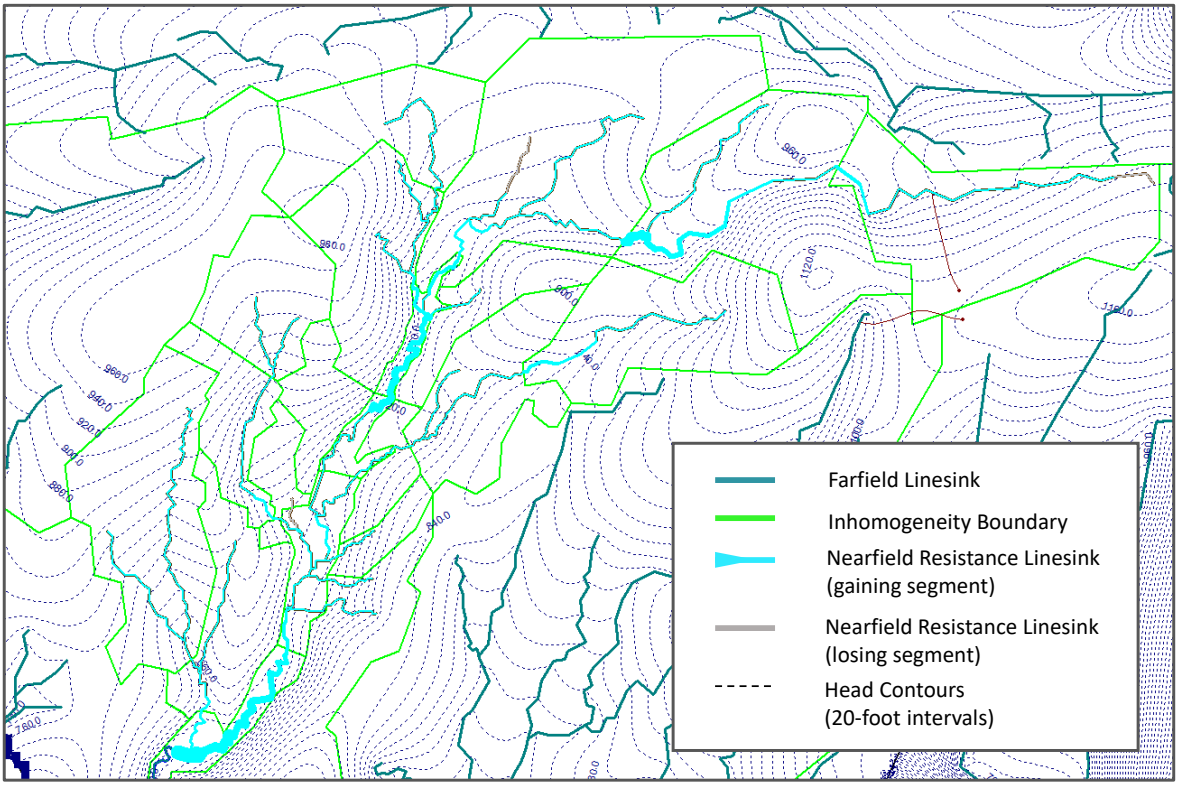

Figure 14.4: Example of GFLOW results for the regional model of the White River and tributaries drainage system.

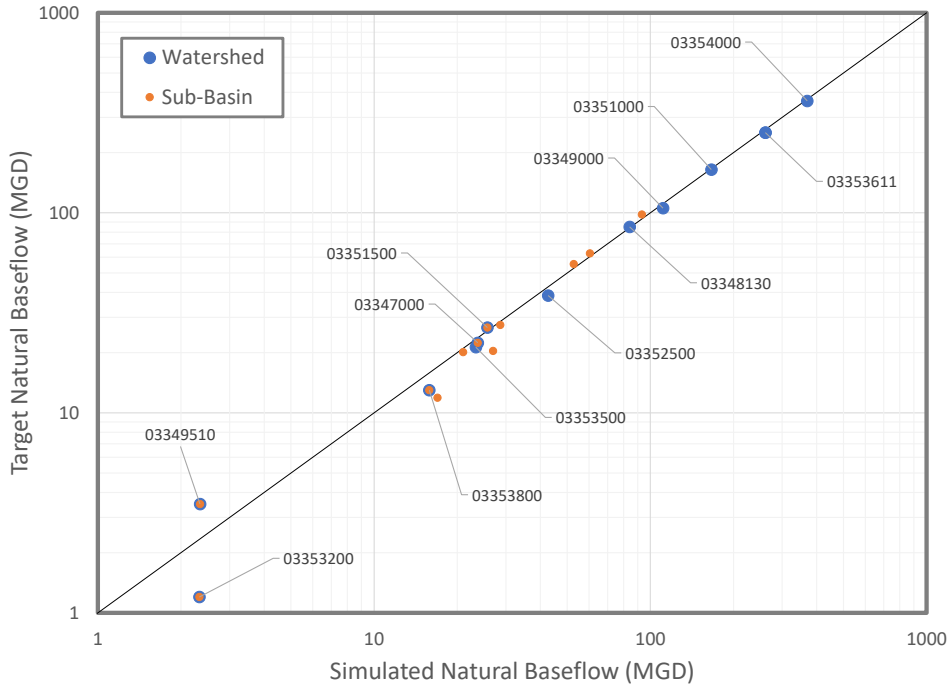

Figure 14.5: Simulated and target discharges in each sub-basin of the White River drainage system, and cumulative discharge by watershed, identified by USGS station number.

Table 14.1: Hydrologic properties of the regional model of the White River drainage system.

Property	Symbol	Value	Units
Regional Base Elevation		600	ft
Regional Transmissivity	T	4,000	ft^2/day
Regional Recharge	N	0.0 – 0.72	inch/month
Outwash Base Elevation		550 – 675	ft
Outwash Hydraulic Conductivity	k	100	ft/day
Outwash Recharge	N	0.0	inch/month
White River Bed Resistance	c	0.1 – 10	days
Tributary Bed Resistance	c	10 – 100	days
Reservoir Bed Resistance	c	100	days

Notes: ft = feet. ft^2/day = square feet per day. ft/day = feet per day.

Table 14.2: Aquifer recharge by sub-basin: Quarter 3, critical conditions (2007 or 2012), White River system.

Sub-Basin ID	USGS Station at outlet of Sub-Basin	Sub-Basin Area (mi^2)	Recharge Rate (inch/month)
1	03347000 White River at Muncie, IN	242.1	0.090
2	03348130 White River at Raible Ave. at Anderson, IN	273.7	0.540
3	03349000 White River at Noblesville, IN	337.6	0.025
4	03349510 Cicero Creek at Arcadia, IN	131.0	0.000
5	03351000 White River near Nora, IN	231.1	0.612
6	03351500 Fall Creek near Fortville, IN	172.7	0.288
7	03352500 Fall Creek at Millersville, IN	129.7	0.252
8	03353000 White River at Indianapolis, IN	118.1	0.252
9	03353200 Eagle Creek at Zionsville, IN	105.7	0.000
10	03353500 Eagle Creek at Indianapolis, IN	68.3	0.360
11	03353611 White River at Stout Gen. Stn., at Indianapolis, IN	64.5	0.252
12	03353800 White Lick Creek at Mooresville, IN	212.0	0.054
13	03354000 White River near Centerton, IN	355.1	0.720

Notes: mi^2= square miles.

Table 14.3: Calibration residuals: Natural baseflow in the White River drainage system.

Sub-Basin ID	Water-shed ID	Simulated baseflow (MGD)	Target baseflow (MGD)	Residual (MGD)
1	03347000	23.7	22.4	+1.3
2		60.4	62.7	-2.3
	03348130	84.1	85.1	-1.0
3		26.9	20.4	+6.5
	03349000	111.1	105.5	+5.6
4	03349510	2.3	3.5	-1.2
5		52.8	55.5	-2.7
	03351000	166.2	164.5	+1.7
6	03351500	25.7	26.7	-1.0
7		17.0	11.9	+5.1
	03352500	42.7	38.6	+4.1
9	03353200	2.3	1.2	+1.1
10		21.0	20.1	+0.9
	03353500	23.3	21.3	+2.0
8 & 11		28.6	27.5	+1.1
	03353611	260.9	251.9	+9.0
12	03353800	15.8	13.0	+2.8
13		93.2	98.1	-4.9
	03354000	369.8	363.0	+6.8

Notes: MGD = million gallons per day.

Residual = simulated minus target baseflow.

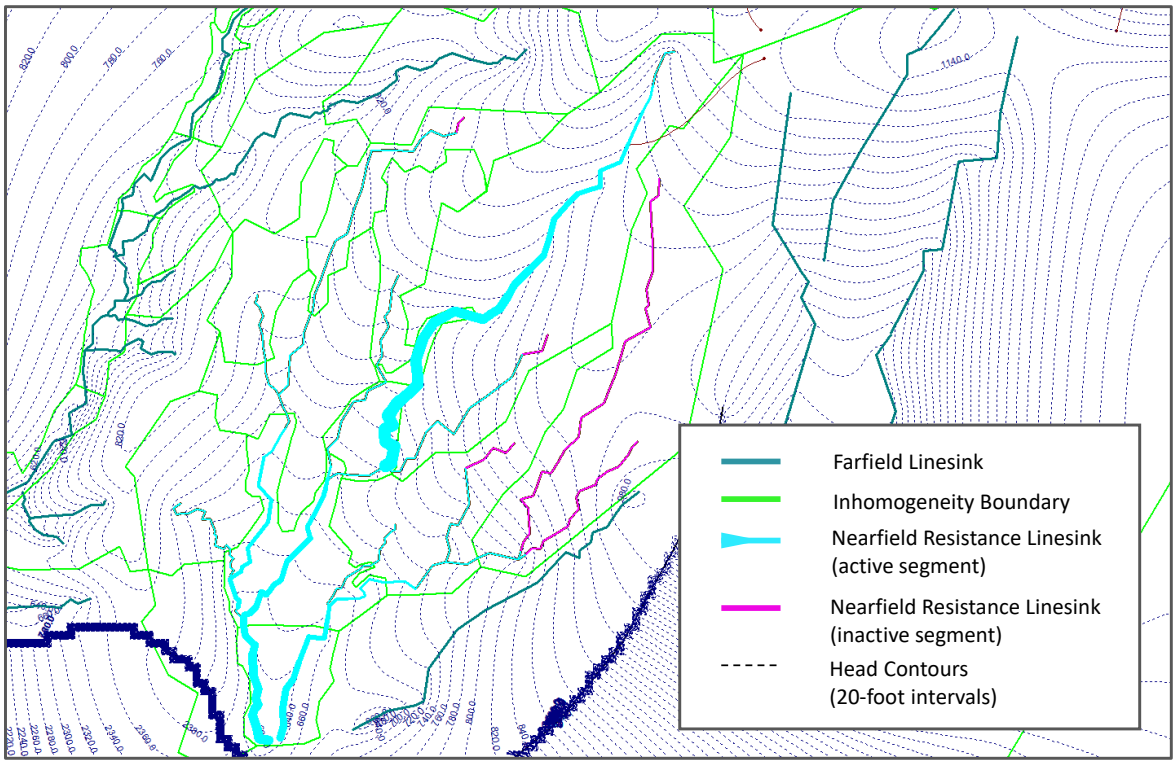

Figure 14.6: Example of GFLOW results for the regional model of the East Fork White River and tributaries drainage system.

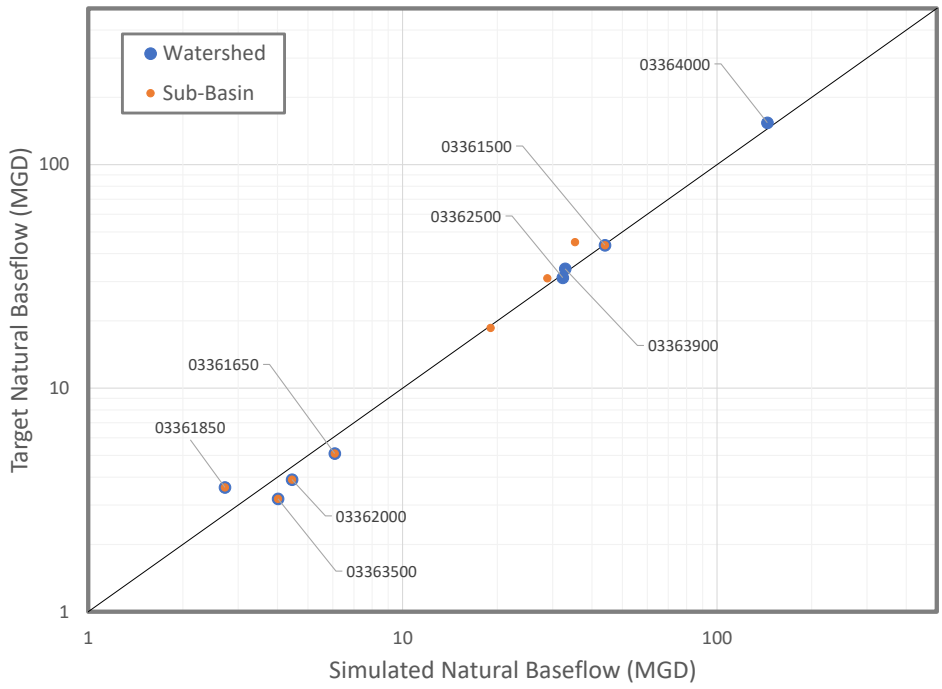

Figure 14.7: Simulated and target discharges in each sub-basin of the East Fork White River drainage system, and cumulative discharge by watershed, identified by USGS station number.

Table 14.4: Hydrologic properties of the regional model of the tributaries to the East Fork White River drainage system.

Property	Symbol	Value	Units
Regional Base Elevation		550	ft
Regional Transmissivity	T	4,000	ft^2/day
Regional Recharge	N	0.0 – 0.277	inch/month
Outwash Base Elevation		550 – 700	ft
Outwash Hydraulic Conductivity	k	100	ft/day
Outwash Recharge	N	0.0005 – 0.001	inch/month
River Bed Resistance	c	0.1 – 10	days
Tributary Bed Resistance	c	10 – 100	days
Reservoir Bed Resistance	c	100	days

Notes: ft = feet. ft^2/day = square feet per day. ft/day = feet per day.

Table 14.5: Aquifer recharge by sub-basin: Quarter 3, critical conditions (2007 or 2012) in the East Fork White River drainage system.

Sub-Basin ID	USGS Station at outlet of Sub-Basin	Sub-Basin Area (mi^2)	Recharge Rate (inch/month)
1	03361500 Big Blue River at Shelbyville, IN	420.4	0.144
2	03361650 Sugar Creek at New Palestine, IN	91.4	0.000
3	03361850 Buck Creek at Acton, IN	78.7	0.000
4	03362000 Youngs Creek near Edinburgh, IN	107.2	0.000
5	03362500 Sugar Creek near Edinburgh, IN	194.2	0.180
6	03363500 Flatrock River at St. Paul, IN	300.7	0.000
7	03363900 Flatrock River at Columbus, IN	234.0	0.277
8	03364000 East Fork White River at Columbus, IN	278.7	0.241

Notes: mi^2= square miles.

Table 14.6: Calibration residuals: Natural baseflow in the East Fork White River drainage system.

Sub-Basin ID	Water-shed ID	Simulated baseflow (MGD)	Target baseflow (MGD)	Residual (MGD)
1	03361500	44.0	43.6	+0.4
2	03361650	6.1	5.1	+1.0
3	03361850	2.7	3.6	-0.9
4	03362000	4.4	3.9	+0.5
5		19.1	18.6	+0.5
	03362500	32.3	31.2	+1.1
6	03363500	4.0	3.2	+0.8
7		28.9	31.0	-2.1
	03363900	32.9	34.2	-1.3
8		35.4	45.0	-9.6
	03364000	144.5	154.0	-9.5

Notes: MGD = million gallons per day.

Residual = simulated minus target baseflow.

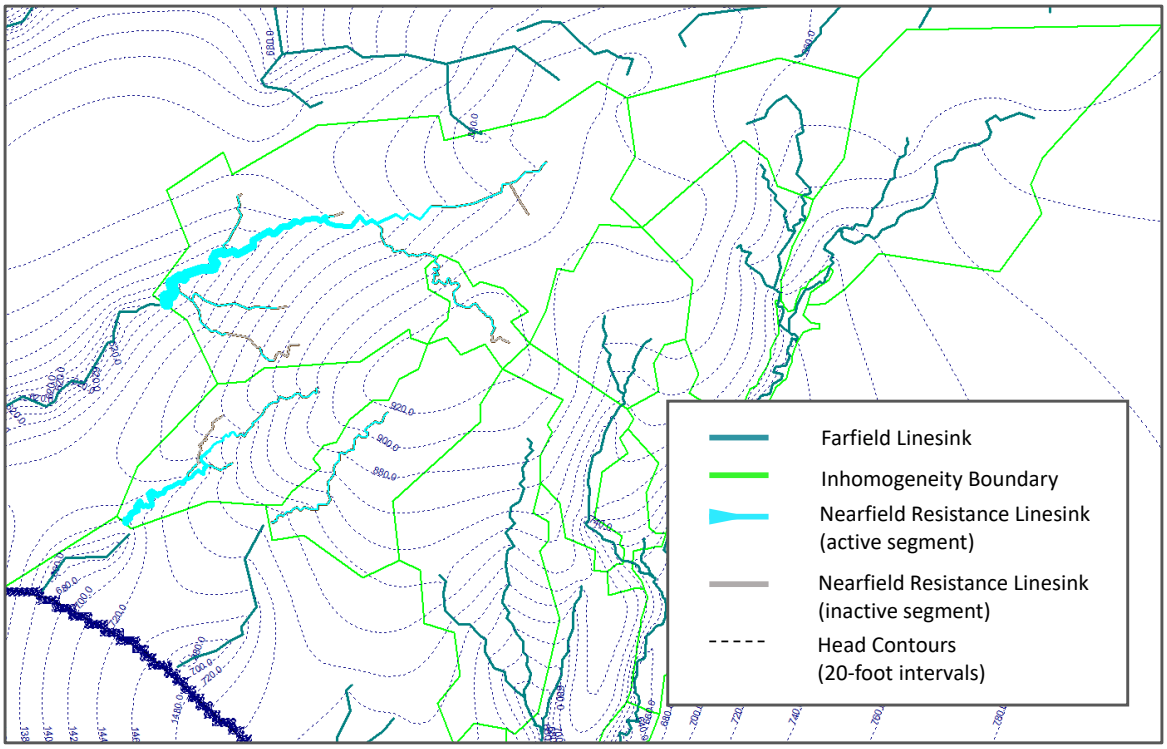

Figure 14.8: Example of GFLOW results for the regional model of the tributaries of the Wabash River drainage system.

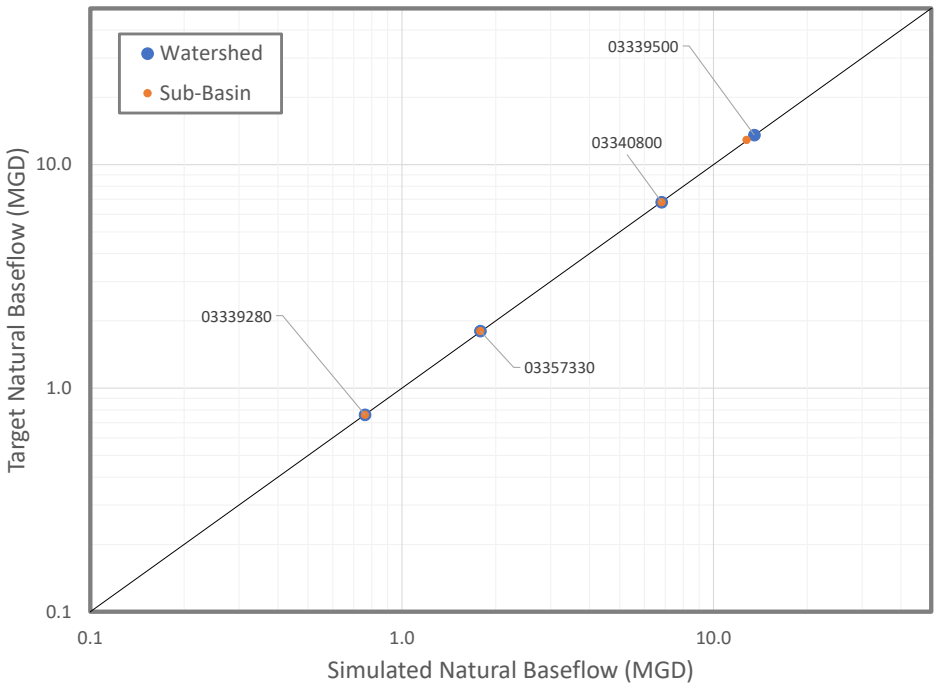

Figure 14.9: Simulated and target discharges in each sub-basin of the tributaries of the Wabash River drainage system, and cumulative discharge by watershed, identified by USGS station number.

Table 14.7: Hydrologic properties of the regional model of the tributaries of the Wabash River drainage system.

Property	Symbol	Value	Units
Regional Base Elevation		600 – 650	ft
Regional Transmissivity	T	2,000 – 4,000	ft^2/day
Regional Recharge	N	0.04 – 0.14	inch/month
River Bed Resistance	c	10	days
Tributary Bed Resistance	c	10	days
Reservoir Bed Resistance	c	–	days

Notes: ft = feet. ft^2/day = square feet per day. ft/day = feet per day.

Table 14.8: Aquifer recharge by sub-basin: Quarter 3, critical conditions (2007 or 2012) in the Wabash River drainage system.

Sub-Basin ID	USGS Station at outlet of Sub-Basin	Sub-Basin Area (mi^2)	Recharge Rate (inch/month)
1	03339280 Prairie Creek near Lebanon, IN	33.3	0.137
2	03339500 Sugar Creek at Crawfordsville, IN	476.6	0.036
3	03340800 Big Raccoon Creek near Fincastle, IN	138.6	0.133
4	03357330 Big Walnut Creek near Roachdale, IN	131.2	0.047

Notes: mi^2= square miles.

Table 14.9: Calibration residuals: Natural baseflow in the Wabash River drainage system.

Sub-Basin ID	Water-shed ID	Simulated baseflow (MGD)	Target baseflow (MGD)	Residual (MGD)
1	03339280	0.8	0.8	+0.0
2		12.8	12.9	-0.1
	03339500	13.5	13.6	-0.1
3	03340800	6.8	6.8	+0.0
4	03357330	1.8	1.8	+0.0

Notes: MGD = million gallons per day.

Residual = simulated minus target baseflow.

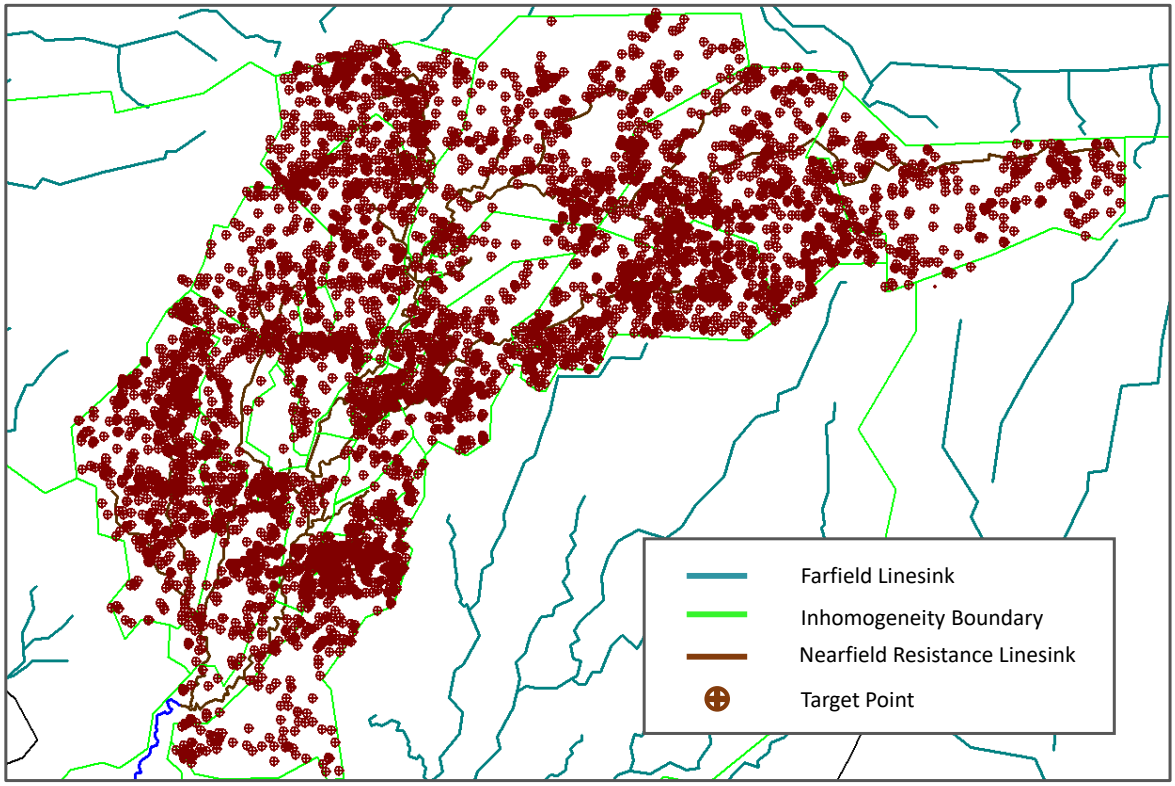

Figure 14.10: Distribution of head target points in the regional model of the White River drainage system.

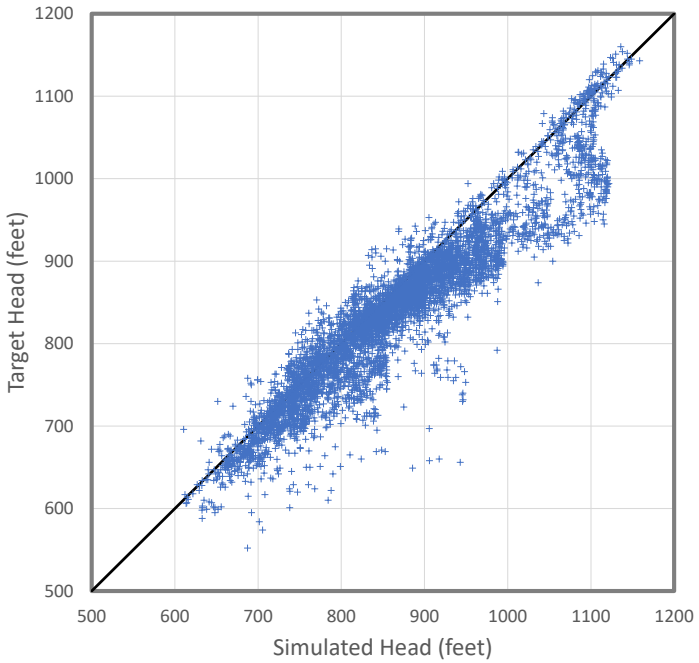

Figure 14.11: Simulated and target heads in the regional model of the White River drainage system.

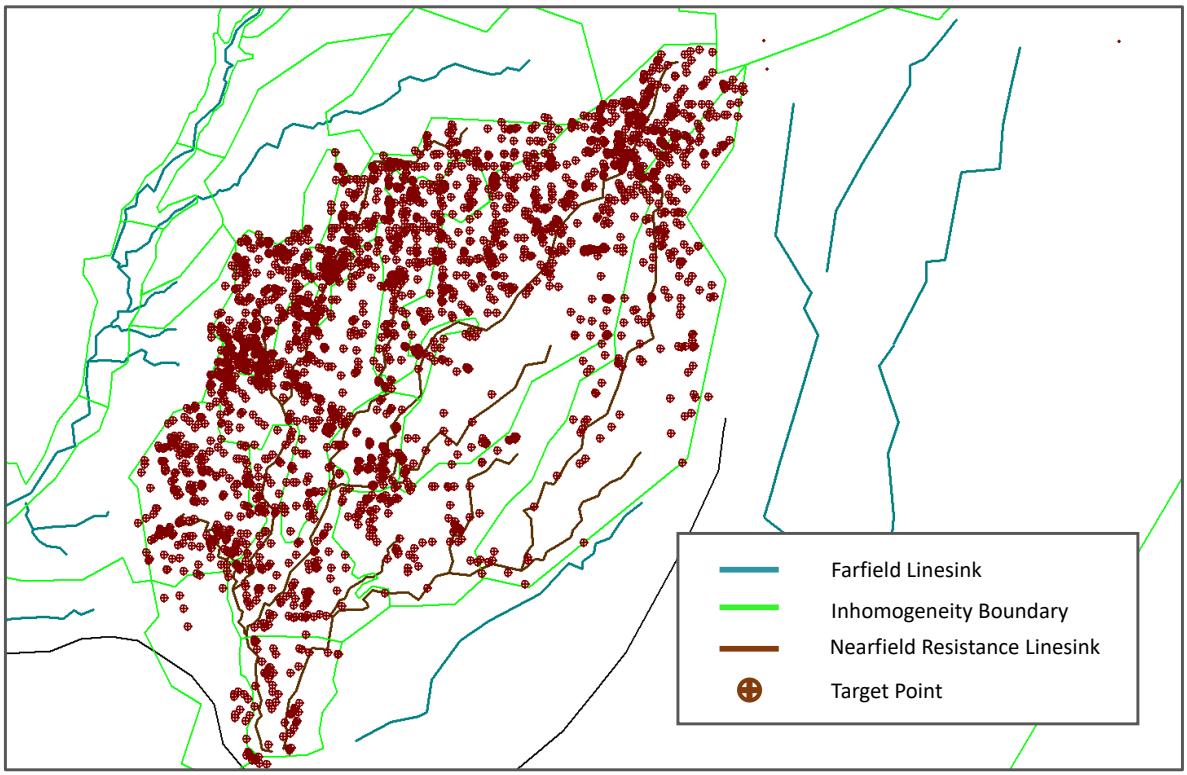

Figure 14.12: Distribution of head target points in the regional model of the East Fork White River drainage system.

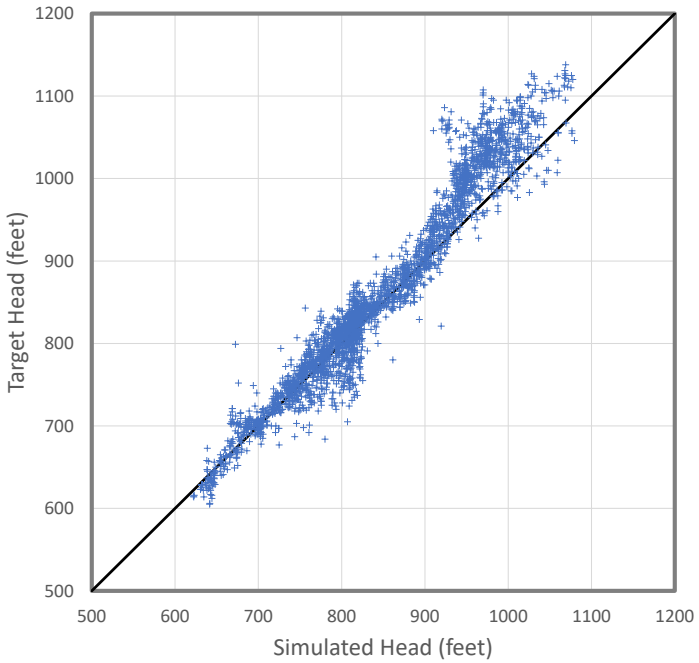

Figure 14.13: Simulated and target heads in the regional model of the East Fork White River an tributaries drainage system.

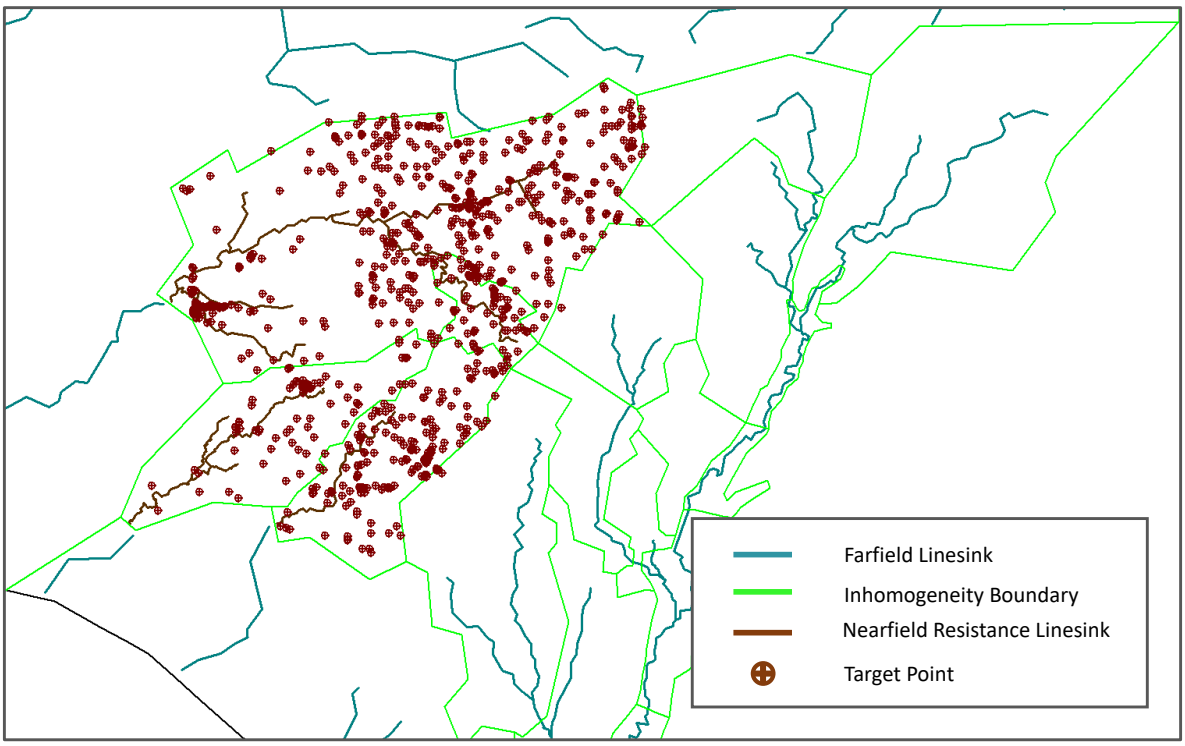

Figure 14.14: Distribution of head target points in the regional model of the tributaries of the Wabash River drainage system.

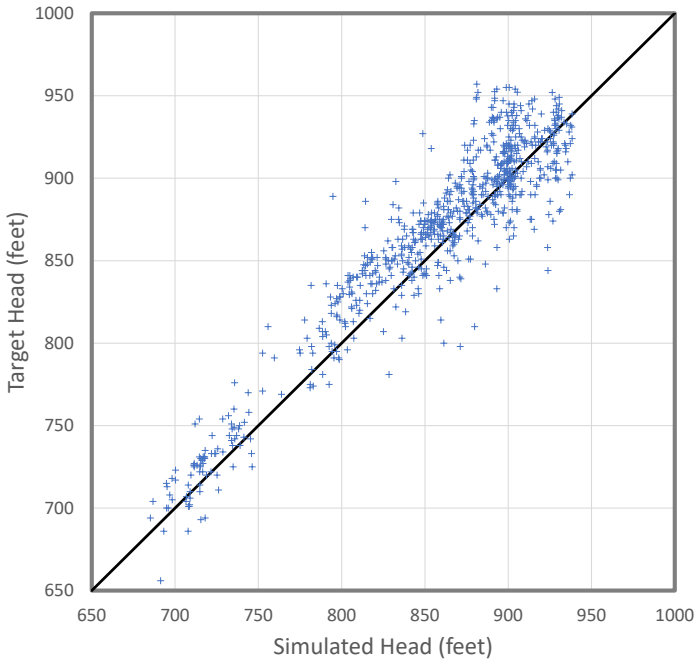

Figure 14.15: Simulated and target heads in the regional model of the tributaries of the Wabash River drainage system.

Table 14.10: Summary of calibration statistics for targeted heads.

	Units	White River and tributaries	East Fork White River and tributaries	Wabash River tributaries	Combined
No. of target points	–	5,690	2,833	808	9,331
Maximum residual	feet	+287	+102	+80	+287
Minimum residual	feet	-86	-163	-152	-163
Average residual	feet	+27	-16	-10	+11
Median residual	feet	+20	-11	-11	+8
MAD	feet	34	26	18	30
RMSE	feet	46	36	24	42
Range of target values	feet	608	533	345	608
MAD (% of range)	%	5.6	4.9	5.2	4.9
RMSE (% of range)	%	7.6	6.8	7.0	6.9

Notes: MAD = mean absolute difference. RMSE = root mean squared error.

Residual = simulated minus target head.

14.3 Summary

The hydrologic system in the Central Indiana region is dominated by surface-water features. As a result, groundwater levels are largely controlled by surface-water levels, and model values for aquifer properties such as transmissivity and streambed resistance are poorly constrained by calibration to target heads. In contrast the sub-basin recharge rates are readily calibrated to estimates of natural baseflow, evaluated in Part I of this report. Calibration to natural baseflow provides a consistent regional framework within which more detailed models can be created without disrupting the regional water balance. The regional model then provides a constraint on groundwater discharges in sub-regional and local models of wellfields. As a result, model calibration to natural baseflows in streams has been emphasized over calibration to target heads. Relatively little effort has been made to develop a high-quality data set of target heads.

The insensitivity of model parameter values to calibration to observed heads has implications for sub-regional and local-scale modeling. While the regional water budget can be assessed, local conditions at wellfields, including induced recharge from surface waters, can only be characterized in a model with knowledge of local aquifer properties such as transmissivity and streambed resistance. This can be addressed by local field studies such as those described in Appendix E.

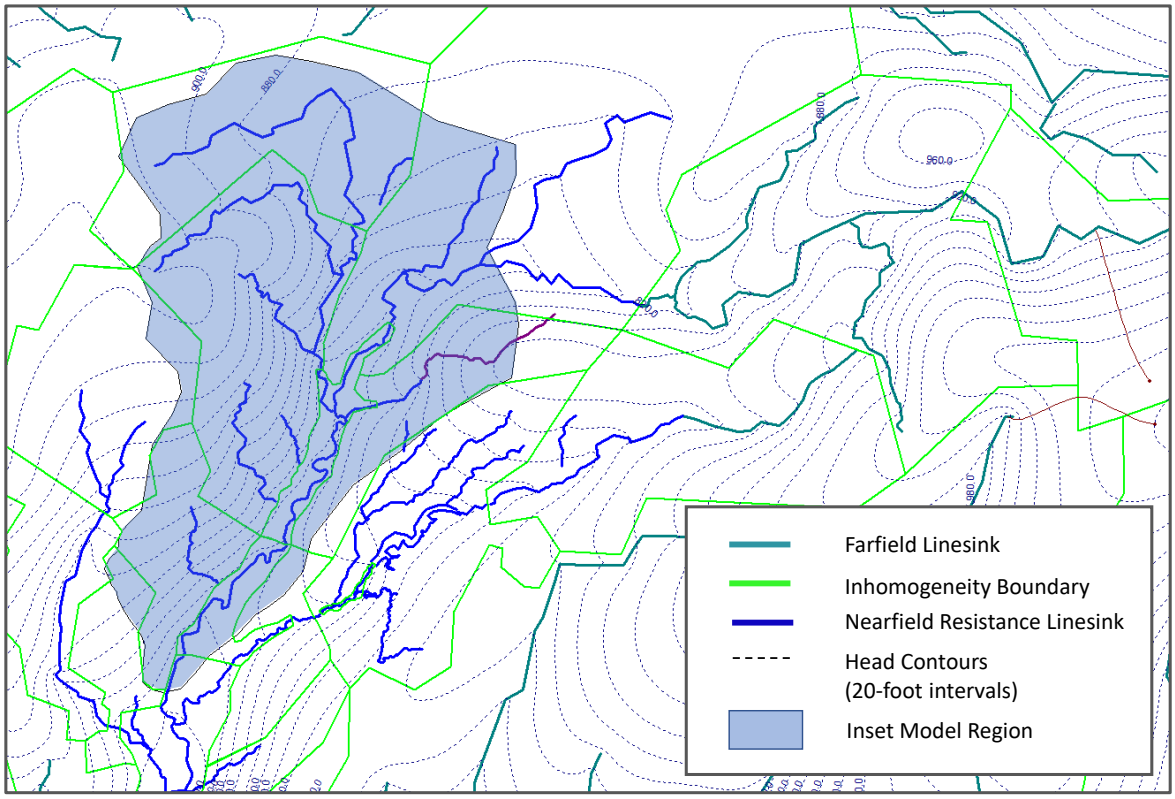

Figure 15.16: Refinements to surface waters and inhomogeneity boundaries in the sub-regional models.

15 Sub-Regional Flow Models

The regional GFLOW model of the White River and tributaries drainage system was refined in Sub-basins 3 through 11 to better define conditions in regions of large groundwater withdrawals for public supply. Figure 15.16 illustrates the region where the geometry of the nearfield resistance-linesinks and outwash inhomogenetiy boundaries are refined. Two sub-regional models are developed within this area: in the first model, refinement is focused around Fall Creek and the inset model region, illustrated in Figure 15.16. This model is used to extract a MODFLOW inset model that is used as a basis for a detailed, three-dimensional model of groundwater flow in the region of fasted growth in water withdrawals. The second sub-regional model focuses on the region between Geist Reservoir and Eagle Reservoir and is used to evaluate groundwater accessibility in the outwash region downstream of Geist Reservoir and in the Town of Speedway wellfield along the downstream reaches of Eagle Creek.

15.1 Data and Calibration

Surface water features in the sub-regional model are refined both by increasing the number of linesinks used to define the major rivers in the regional model, and by including secondary

Table 15.11: Summary of calibration statistics for targeted heads in the sub-regional model used to extract the inset model.

	Units	Sub-regional Model
No. of target points	–	2,242
Maximum residual	feet	131
Minimum residual	feet	-86
Average residual	feet	2.8
Median residual	feet	3.2
MAD	feet	16
RMSE	feet	21
Range of target values	feet	425
MAD (% of range)	%	3.8
RMSE (% of range)	%	4.9

Notes: MAD = mean absolute difference.

RMSE = root mean squared error.

Residual = simulated minus target head.

surface-water features. The secondary features are defined by NHD (USGS, 2020c) line-features describing surface-water geometry, with water levels obtained from the National Map Viewer (USGS, 2020a). Secondary features included in the model were tested and removed if model results indicated that they were largely recharge rather than discharge features. This is consistent with the model being designed to represent critical drought conditions. Many mapped perennial streams were removed from the model in this way. Inhomogeneity boundaries representing outwash were refined along the White River by increasing the number of line elements defining the boundaries. Inhomogeneity boundaries are added to represent the outwash downstream of Geist Reservoir and near the Town of Speedway wellfield. Recharge rates remain unchanged in the sub-regional models.

A subset of target head data covering the extent of the sub-regional model used for extracting the inset model, is used to assess simulated heads. The spatial distribution of target points is illustrated in Figure 15.17. The calibration statistics for model heads are presented graphically in Figure 15.18, and summarized in Table 15.11. Both the MAD and RMSE are reduced below 5% of the range of target values.

A MODFLOW data set covering the shaded region in Figure 15.16 was automatically generated from the sub-regional model, using GFLOW tools. The MODFLOW inset model was subsequently refined and calibrated, and used to investigate groundwater accessibility in Hamilton County. Development and use of the inset model is described in Section 16.

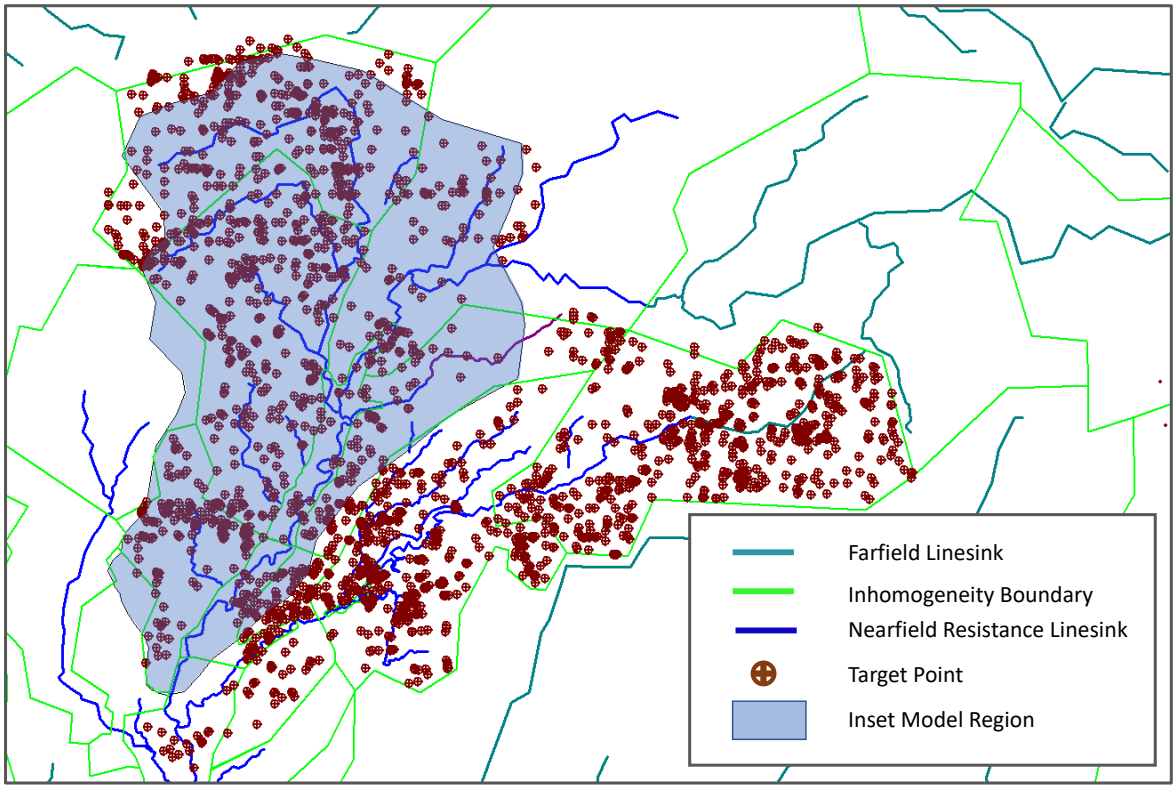

Figure 15.17: Distribution of head target points in the sub-regional model used to extract the inset model.

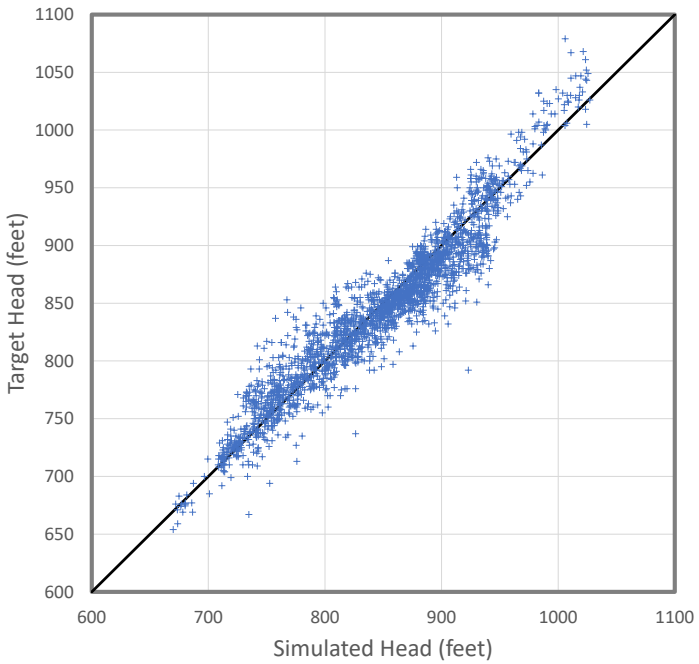

Figure 15.18: Simulated and target heads in the sub-regional model used to extract the inset model.

Table 15.12: Summary of calibration statistics for targeted heads in the sub-regional model used to assess groundwater accessibility .

	Units	GW Accessibility Model
No. of target points	–	1,391
Maximum residual	feet	+89
Minimum residual	feet	-87
Average residual	feet	-4.5
Median residual	feet	-4.2
MAD	feet	16
RMSE	feet	21
Range of target values	feet	433
MAD (% of range)	%	3.7
RMSE (% of range)	%	4.8

Notes: MAD = mean absolute difference.

RMSE = root mean squared error.

Residual = simulated minus target head.

15.2 Accessibility Models

We refine a second sub-regional model to investigate groundwater accessibility in a region containing major groundwater pumping. The region of interest is illustrated in Figure 15.19, with locations of two representative geologic sections shown. The sections are illustrated in Figures 15.20 and 15.21. Public supply wells near section A-A' are operated by Citizens Water and the Town of Lawrence; the Town of Speedway operates a wellfield just north of section B-B'. Groundwater accessibility is evaluated with the groundwater flow model at these wellfields. Refinements to surface water features and inhomogeneities in this region yields the calibration results presented in Figures 15.22 and 15.23, and Table 15.12. Successive refnements to surface water features have reduced the calibration error below 5% of the range of observed heads.

15.2.1 City of Lawrence and Citizens Geist Wellfields

The Geist wellfield, operated by Citizens Water, and the City of Lawrence wellfield both lie in a narrow strip of outwash and sand and gravel adjacent to Fall Creek, downstream from Geist Reservoir (Figure 15.20). Based on the analysis presented in Section 6, demand at Citizens Geist wellfield is projected to triple by 2070, while demand at the City of Lawrence wellfield is projected to increase by a factor of 1.5. Operation of the Citizens Reservoir (Section 4.5) in the near future will increase excess water availability in Fall Creek up to 20 MGD during dry periods, potentially providing a source for the increased wellfield demand. We investigate the

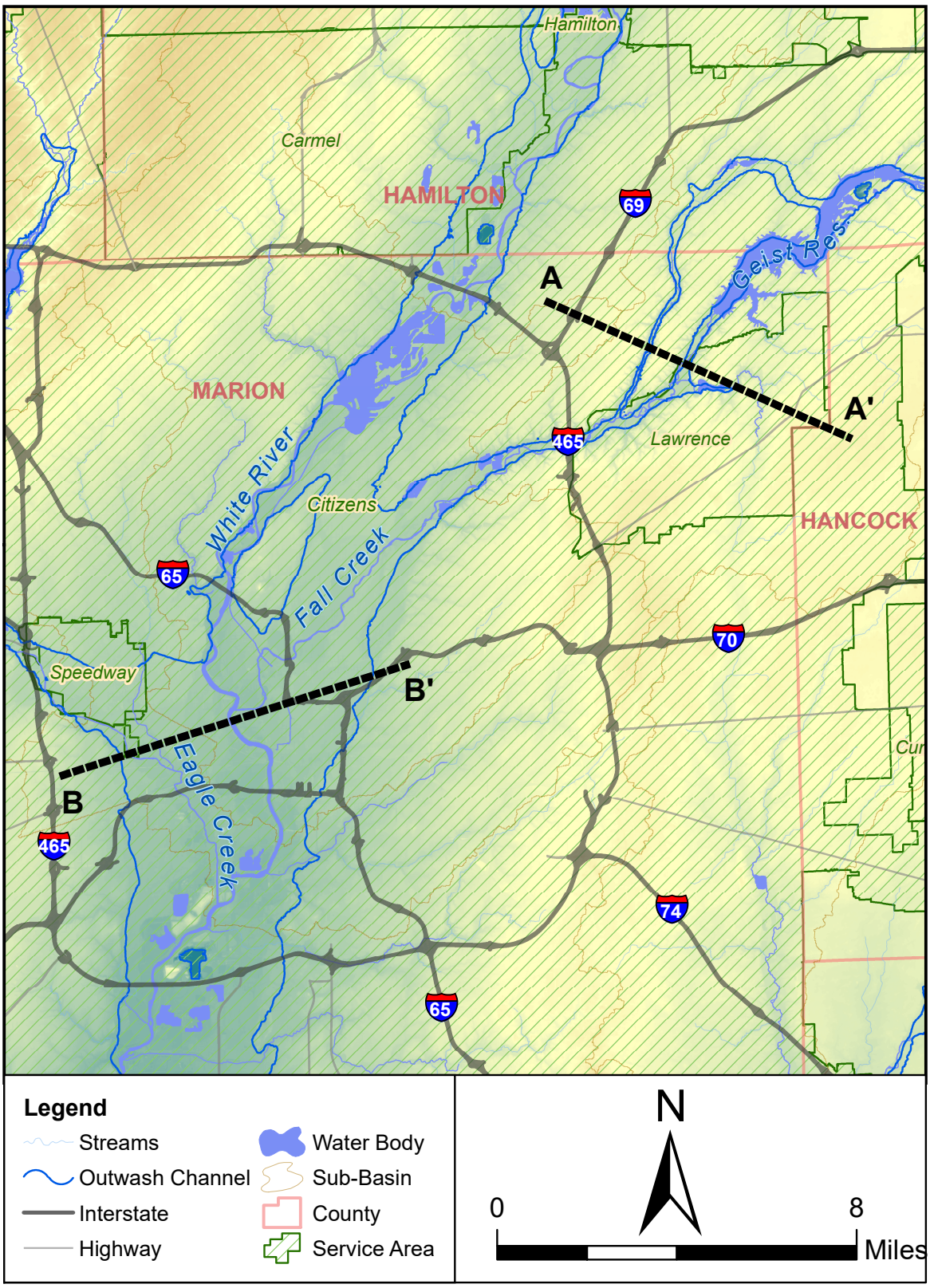

Figure 15.19: Region investigated with the groundwater accessibility models.

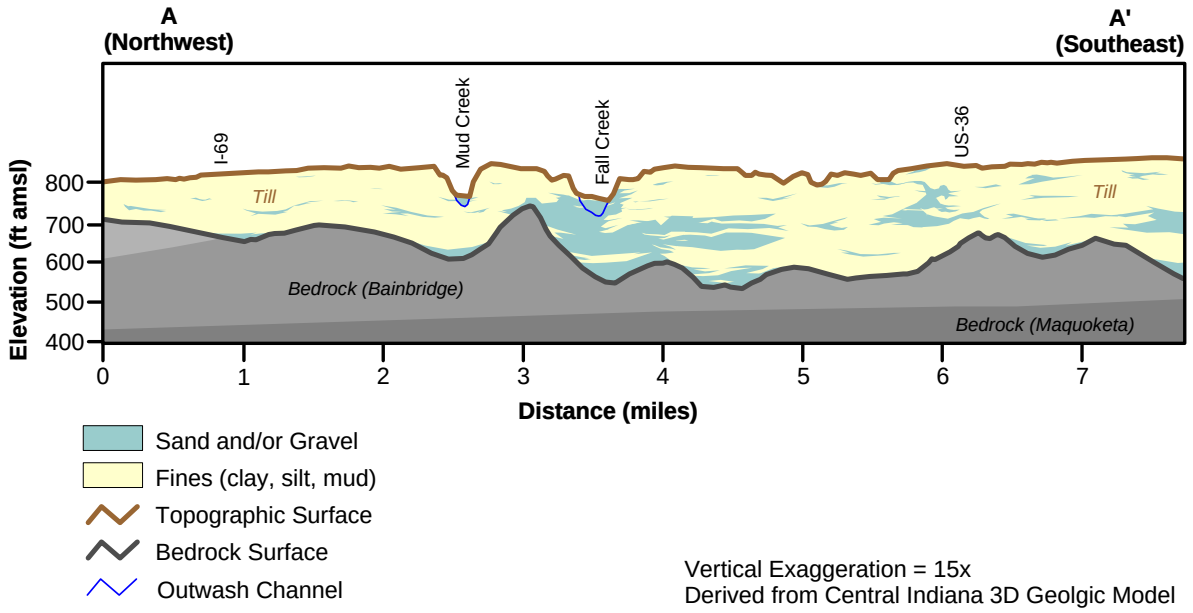

Figure 15.20: Geologic section through the unconsolidated material downstream from Geist Reservoir.

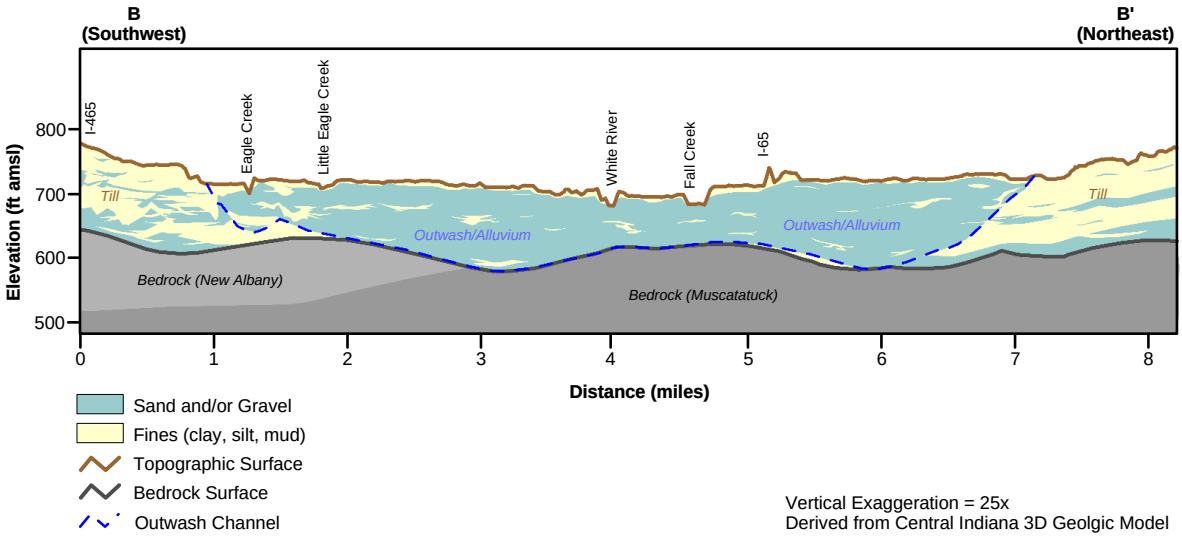

Figure 15.21: Geologic section through the unconsolidated material between Eagle Creek and Fall Creek.

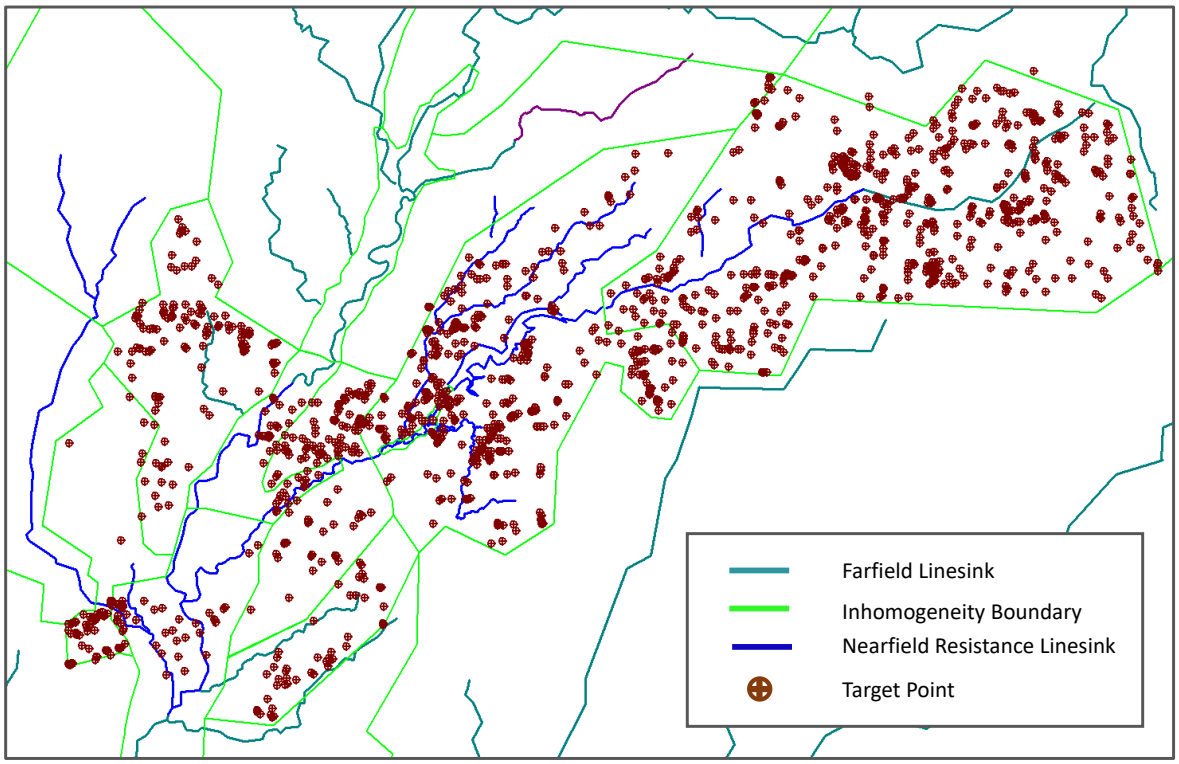

Figure 15.22: Distribution of head target points in the sub-regional model used to assess groundwater accessibility .

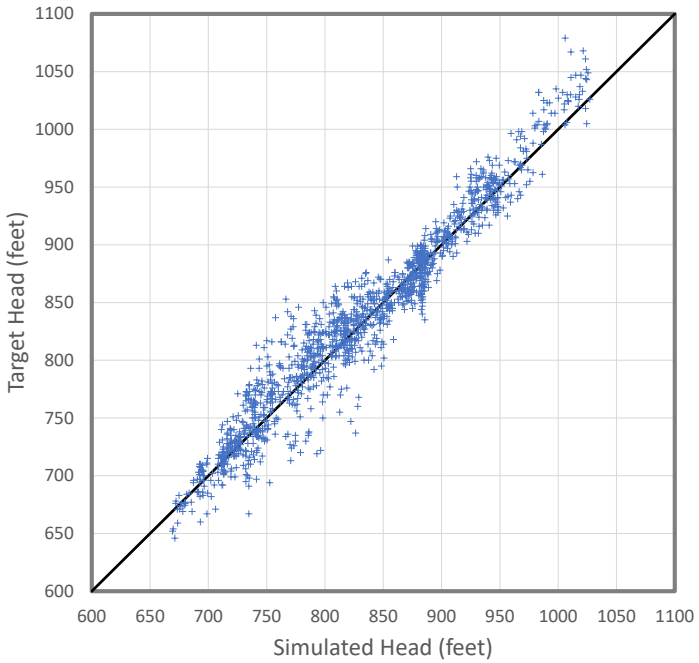

Figure 15.23: Simulated and target heads in the sub-regional model used to assess groundwater accessibility.

Geist and City of Lawrence wellfields to determine if water available in Fall Creek is accessible by the pumping wells, and whether the local outwash aquifer can supply future demands with increased flow in Fall Creek.

Table 15.13 summarizes the characteristics of the wells in the two wellfields, along with average annual and Quarter 3 pumping rates for 2014-2018. In addition, the projected 2070 Quarter 3 demand is presented. The well capacity listed in the table is obtained from the SWWF database, and is likely based on a short-term pumping test conducted after each well was installed. While it provides an estimate of the potential yield of a single well operating, the actual capacity is likely much less with all wells operating. From Table 15.13, the total capacity of the two wellfields is 24 MGD, while current Q3 demand is 5.3 MGD and future demand is 12.3 MGD.

The groundwater accessibility model is used to estimate the impacts of current and increased demand at the wellfields. Figure 15.24 illustrates static water levels in the wellfields without pumping occuring, with the locations of the wells identified. Figure 15.25 illustrates simulated drawdown in the aquifer under actual Quarter 3 pumping rates on the left and projected 2070 pumping rates on the right. Table 15.14 summarizes the drawdown in the aquifer just outside the well bores for the two pumping scenarios. In both simulations, the hydraulic conductivity of the outwash is specifed to be 100 feet/day, resulting in an average transmissivity of 10,000 ft^2/day, and the resistance of the streambed is specified as 1 day. This value of resistance corresponds to a 3-foot thick layer of sediment at the streambed with a vertical hydraulic conductivity of 3 feet/day.

Some of the simulated aquifer drawdowns in the Citizens wellfield for 2070 demands exceed 40 feet (40% of the aquifer thickness). These drawdowns are excessive and this suggests that the 2070 demand may not be accessible at this wellfield despite the increase in availability. To evaluate the maximum, combined potential yield of the two wellfields, the head at wells are fixed, and the discharge for each well is computed with the model. During development and testing of the groundwater accessibility model, it was observed that when drawdowns at wells approached the elevation of 725 feet, the groundwater would become detatched or disconnected from the streambed. This reflects a limiting condition on wellfield yield; if pumping rates increase further and the stream becomes disconnected, the drawdown at the wells increases quickly without an increase in yield. An elevation of 725 feet represents a 25-foot drawdown in the aquifer at each well. Within the wells, the drawdown will be greater due to well losses and well inefficiency.

Figure 15.26 presents an analysis of the total combined wellfield yield, including all of the Citizens and City of Lawrence wells. Individual well yields are based on fixing aquifer heads at the wells at an elevation of 725 feet. There is no known field testing at the site that would provide reliable estimates of aquifer hydraulic conductivity and streambed resistance, so a range of parameter values must be considered with the model. Model parameters were varied to test the sensitivity of the total yield. The hydraulic conductivity of the outwash aquifer is varied from

Table 15.13: Well characteristics with actual and projected demands for the Citizens Geist and City of Lawrence wellfields.

Well ID	Depth* (ft)	Diameter* (inches)	Screen length** (ft)	Approx. elevation, top of screen** (ft)	Aquifer*	Capacity* (gpm)	2014-2018 Actual Annual average demand (gpm)	2014-2018 Actual Q3 average demand (gpm)	2070 Projected Q3 average demand (gpm)
Citizens Geist									
5A	86	24	25	709	SG	1231	0	0	458
4	99	18	24	687	SG	1000	106	26	496
1A	96	24	25	687	SG	1231	254	404	1,044
2A	96	24	25	685	SG	1059	188	256	829
3A	101	24	25	679	SG	1059	120	141	662
6	115	24	–	–	SG	1400	197	263	840
8	90	24	–	–	SG	1800	143	394	1030
7	90	24	25	690	SG	1899	199	191	734
City of Lawrence									
15	82	16	–	–	SG	1000	327	451	496
14	86	16	23	–	SG	1000	202	191	211
16	87	20	18	–	SG	1400	410	375	413
9	106	36	–	–	SG	500	179	167	184
10	84	18	–	–	SG	1000	202	191	449
8	95	24	–	–	SG	1200	517	616	678
					Total (gpm)	16,779	3,044	3,666	8,526
					Total (MGD)	24.1	4.4	5.3	12.3

Notes: ft = feet. gpm = gallons per minute. MGD = million gallons per day. SG = sand and gravel.

* Data obtained from the SWWF database.

** Data obtained from the IDNR Water Well database.

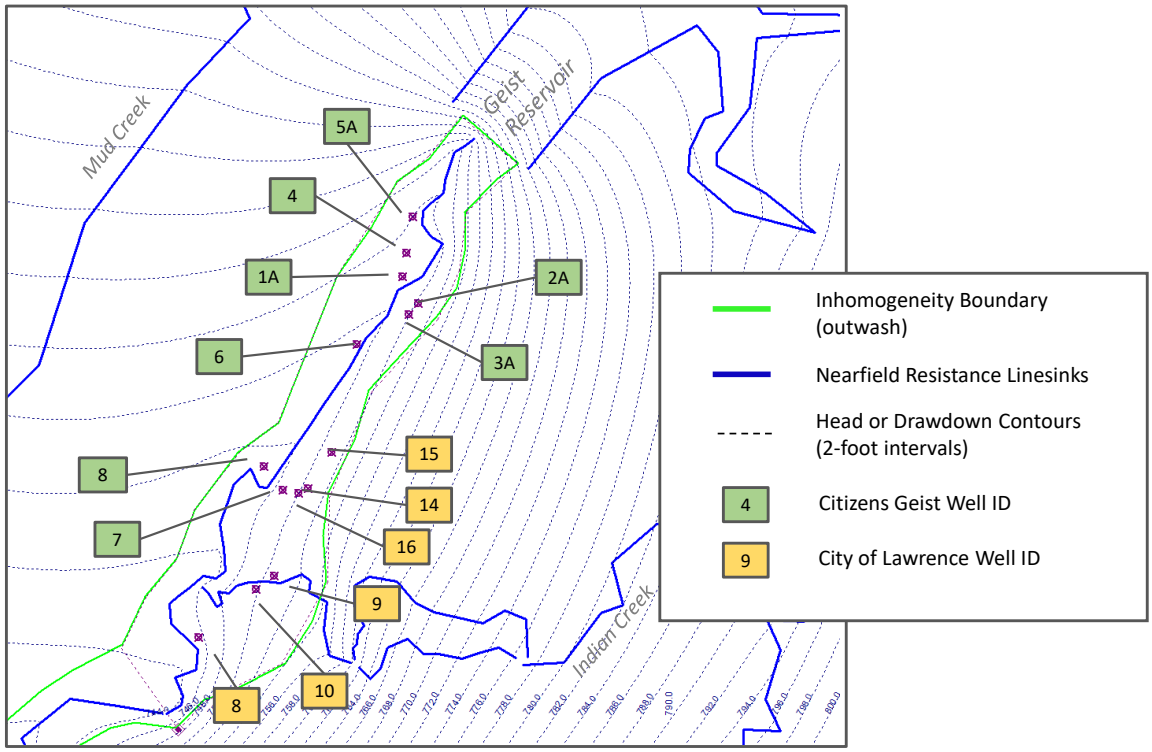

Figure 15.24: Simulated static heads near the Geist wellfield. *Simulation results with outwash hydraulic conductivity of 100 ft/day and streambed resistance of 1 day.*

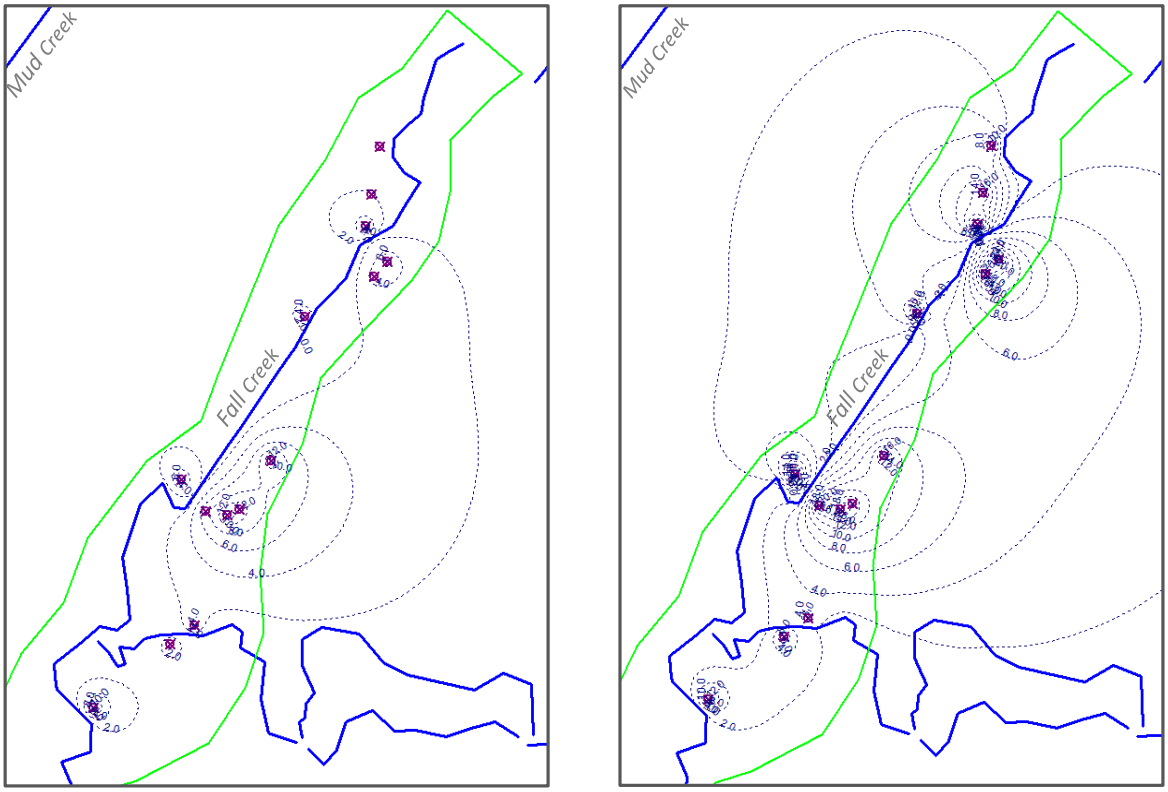

Figure 15.25: Simulated dawdown in the Geist wellfield. *2014-2018 average Q3 rates (left) and projected 2070 Q3 rates (right).*

Table 15.14: Aquifer drawdown at wells under average actual demand and 2070 projected demand. *Simulation results with outwash hydraulic conductivity of 100 ft/day and streambed resistance of 1 day.*

Wellfield	Well ID	2014-2018 Actual Average Q3 demands (ft)	2070 Projected Average Q3 demands (ft)
Citizens Geist	5A	0.5	19.7
	4	2.7	26.0
	1A	15.6	42.8
	2A	12.2	40.8
	3A	8.2	34.8
	6	9.5	30.3
	8	12.1	34.6
	7	15.4	39.8
City of Lawrence	15	23.3	27.0
	14	16.4	21.1
	16	21.8	28.1
	9	6.5	8.3
	10	7.9	18.6
	8	23.0	25.4

Notes: ft = feet.

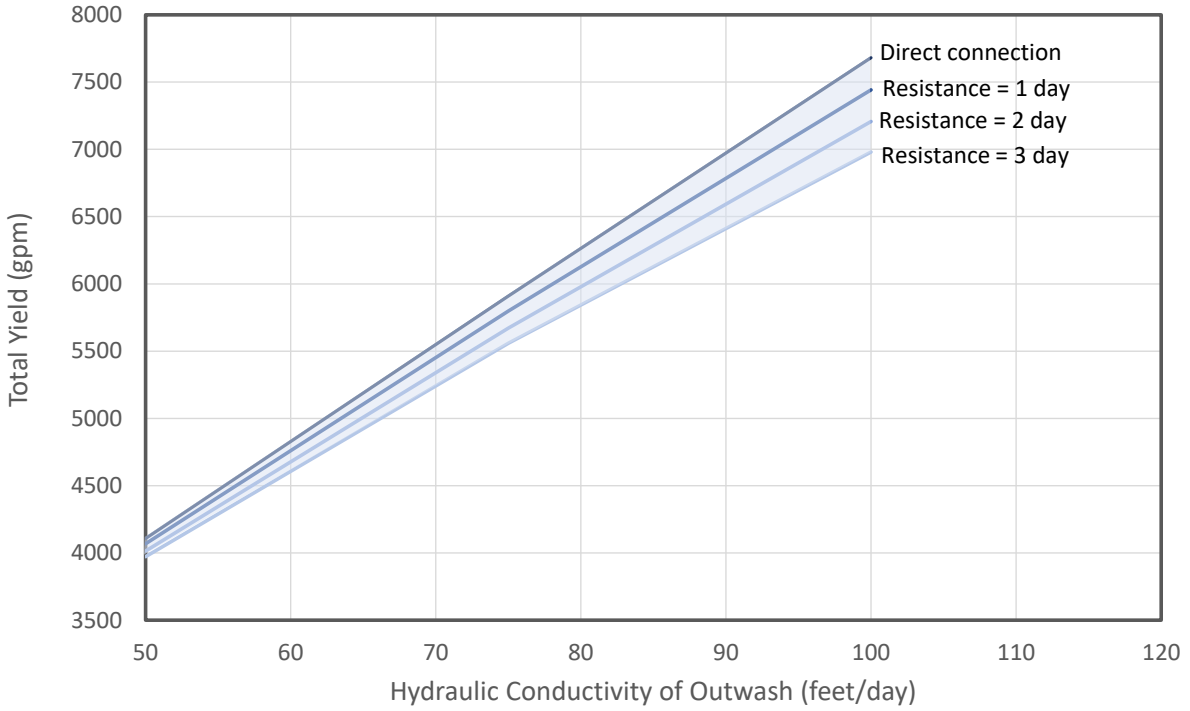

Figure 15.26: Sensitivity of wellfield yield to variations in outwash hydraulic conductivity and resistance of the Fall Creek bed.

50 to 100 feet/day, while the resistance of the Fall Creek streambed was varied over an order of magnitude. In the figure, ***direct connection*** refers to the case where the streambed resistance, c, is equal to $0.2kH$, where k is the hydraulic conductivity of the outwash in feet/day and H is the thickness of the aquifer beneath the streambed in feet (Anderson, 2005). The results show the total yield of this wellfield to be much more sensitive to the hydraulic conductivity of the outwash than the streambed resistance. The range in the potential total yield of the wellfield is from 4,000 gpm, for low hydraulic conductivity and high resistance, to 7,700 gpm for high hydraulic conductivity and low resistance. An accurate determination of both parameters can only be obtained by a carefully planned field testing program at the well site. However, using a typical range of values, it appears unlikely that the projected future demand of 8,526 gpm will be accessible from the streambed with the existing infrastructure at the wellfield.

15.2.2 Town of Speedway Wellfield

The Town of Speedway wellfield has a lower demand than the Geist wellfield, but like Geist, it is operated with support from surface water releases from an upstream reservoir. Well logs obtained from the IDNR water well database (IDNR, 2020b) indicate several clay lenses over the depth, and likely a poor connection to Eagle Creek. The bottom of the outwash and sand

and gravel in the wellfield is at an elevation of 650 feet; an inhomogeneity was included in the model to represent the local base elevation and hydraulic conductivity. Table 15.15 summarizes characteristics of the Speedway wells and the average annual and Quarter 3 demand from 2014-2018, and the projected Quarter 3 demand in 2070.

The groundwater accessibility model is used to estimate the impacts of current and increased demand at the wellfield. Figure 15.27 presents simulated static water levels in the wellfield, and Figure 15.28 presents simulated heads when pumping at the projected 2017 rates. Table 15.16 summarizes the static and pumping aquifer head levels under current and projected demand. Results indicate that the small increase in demand only lowers aquifer water levels slightly. To estimate the total wellfield yield and sensitivity to model parameters, a fixed head of 690 feet is specified at each well and the discharge of each well is computed by the model. Based on the well characteristics in Table 15.15, a minimum head level of 690 allows for additional head losses in the well due to inefficiency, and maintains submergence of the well screens. Figure 15.29 illustrates the sensitivity of total wellfield yield to variations in the local model parameters. The results indicate that the future total demand of 933 gpm is likely accessible by the existing wells.

15.3 Summary

Groundwater accessibility modeling was performed for the Citizens Geist and City of Lawrence wellfields along Fall Creek. The site was chosen as it is a location where future water availability is expected to increase due to operation of Citizens Reservoir. Model simulations indicate that groundwater accessibility using the existing wells in the outwash aquifer will not meet projected 2070 demands. Howerer, there appears to be potential for greater accessibility than required for the current demand. The potential increased yield can be achieved by cooperation between Citizens Water and the City of Lawrence in managing their combined wellfields. Modeling was also performed for the Town of Speedway wellfield along Eagle Creek, where current and future demands are significantly smaller than at the Geist wellfield. Simulations indicate that the existing Speedway wells will be adequate to meet future demands, and that the outwash aquifer may support additional withdrawals beyond the 2070 demand. In the cases examined here, the accessibility models were based on refinements to regional models, and publicly available information regarding well characteristics. Site-specific field testing to evaluate aquifer and streambed properties and detailed construction information for the wells and pumping systems are necessary to refine the predictive modeling presented here.

Table 15.15: Well characteristics with actual and projected demands for the Town of Speedway wellfield.

Well ID	Depth* (ft)	Diameter* (inches)	Screen length** (ft)	Approx. elevation, top of screen** (ft)	Aquifer*	Capacity* (gpm)	2014-2018 Actual Annual average demand (gpm)	2014-2018 Actual Q3 average demand (gpm)	2070 Projected Q3 average demand (gpm)
10R	64	16	10	669	SG	300	44	34	50
11R	55	16	9	678	SG	375	78	55	74
12	72	36	8	–	SG	500	56	39	56
13	59	16	8	673	SG	503	82	57	77
14R	62	30	9	674	SG	500	75	55	75
15	54	16	10	676	SG	326	63	44	62
2	78	50	30	676	SG	800	180	123	153
3	63	42	10	672	SG	400	79	58	78
4	69	42	10	670	SG	350	64	42	60
6	71	42	20	673	SG	500	117	82	106
7R	69	16	–	–	SG	300	37	27	42
8R	57	16	10	673	SG	225	47	33	49
9	64	36	12	676	SG	305	49	35	51
					Total (gpm)	5384	971	683	933
					Total (MGD)	7.8	1.4	1.0	1.3

Notes: ft = feet. gpm = gallons per minute. MGD = million gallons per day. SG = sand and gravel.

* Data obtained from the SWWF database.

** Data obtained from the IDNR Water Well database.

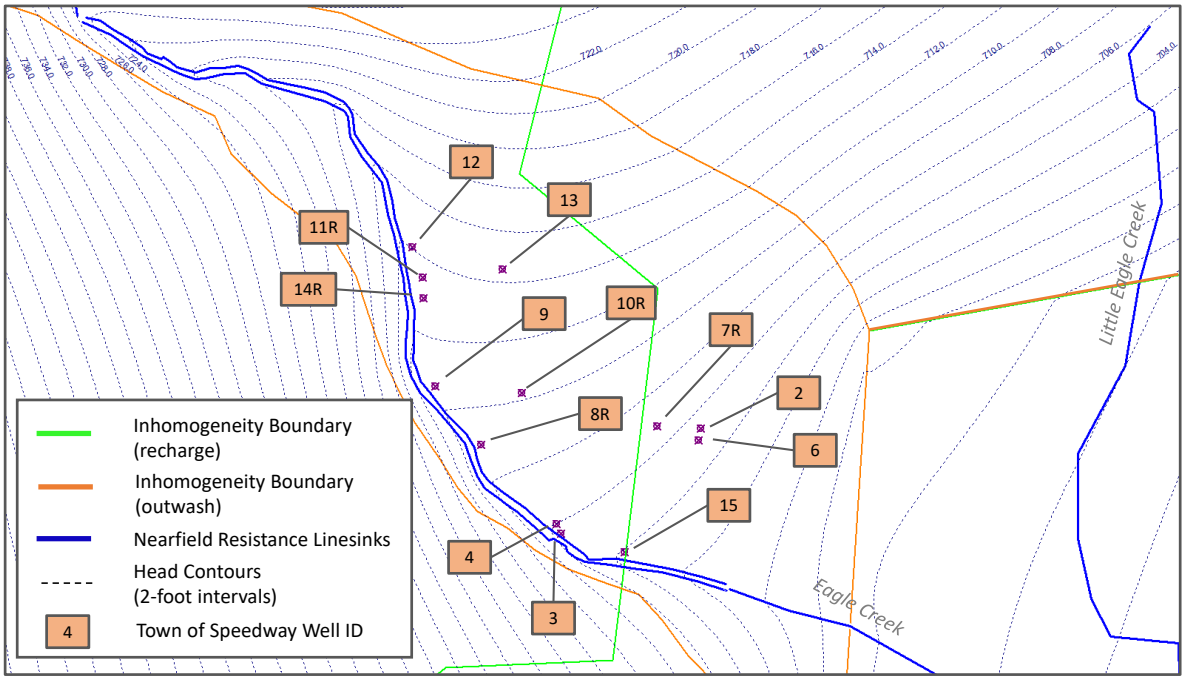

Figure 15.27: Simulated static heads at the Town of Speedway wellfield. *Simulation results with outwash hydraulic conductivity of 50 ft/day, streambed resistance of 5 days, and Q3 hydrologic conditions.*

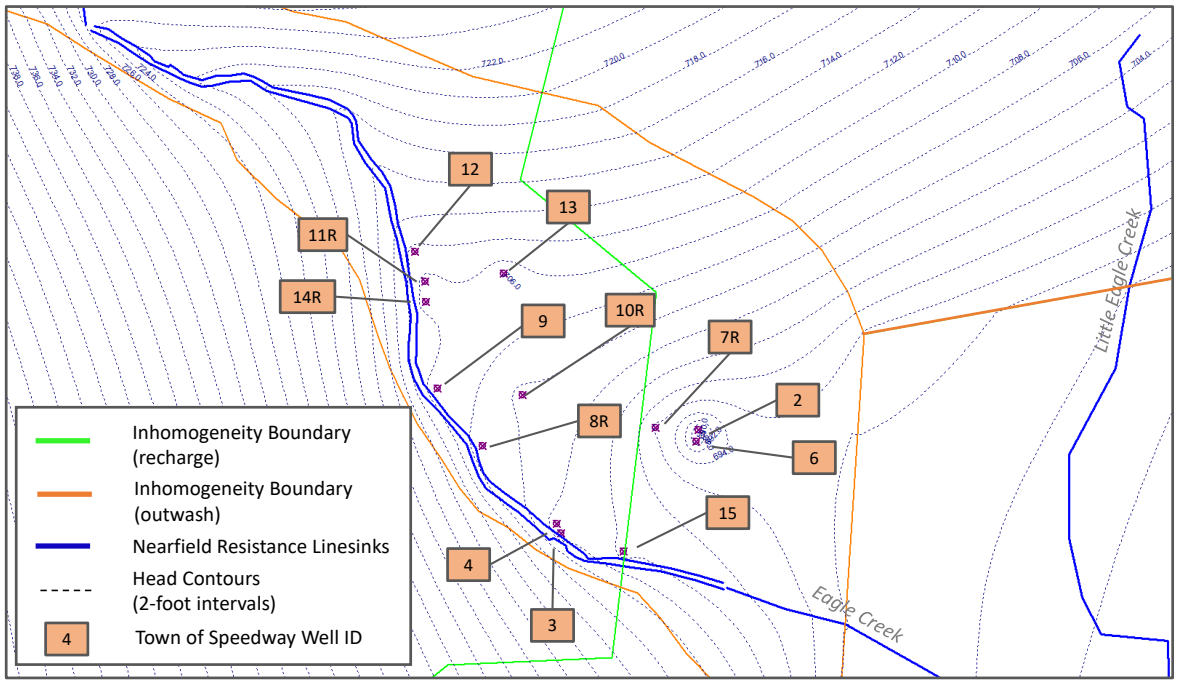

Figure 15.28: Head contours at the Town of Speedway wellfield under projected 2070 Q3 demand. *Simulation results with outwash hydraulic conductivity of 50 ft/day, streambed resistance of 5 days, and Q3 hydrologic conditions.*

Table 15.16: Aquifer heads at wells under average actual demand and 2070 projected demand.
Simulation results with outwash hydraulic conductivity of 50 ft/day and streambed resistance of 5 day.

Well ID	Approx. elevation, top of screen* (ft)	Static head at wells (ft)	2014-2018 Actual Average Q3 demands (ft)	2070 Projected Average Q3 demands (ft)
10R	669	708.2	702.8	700.4
11R	678	711.4	705.2	703.0
12	–	712.0	708.3	706.7
13	673	712.5	704.7	702.0
14R	674	710.8	705.3	703.3
15	676	701.9	697.5	695.6
2	676	703.3	685.9	679.4
3	672	703.6	699.0	697.3
4	670	704.0	699.8	698.1
6	673	703.1	688.5	683.0
7R	–	704.8	696.7	693.3
8R	673	706.8	703.4	701.9
9	676	708.9	705.8	704.5

Notes: ft = feet.

* Data obtained from the IDNR Water Well database.

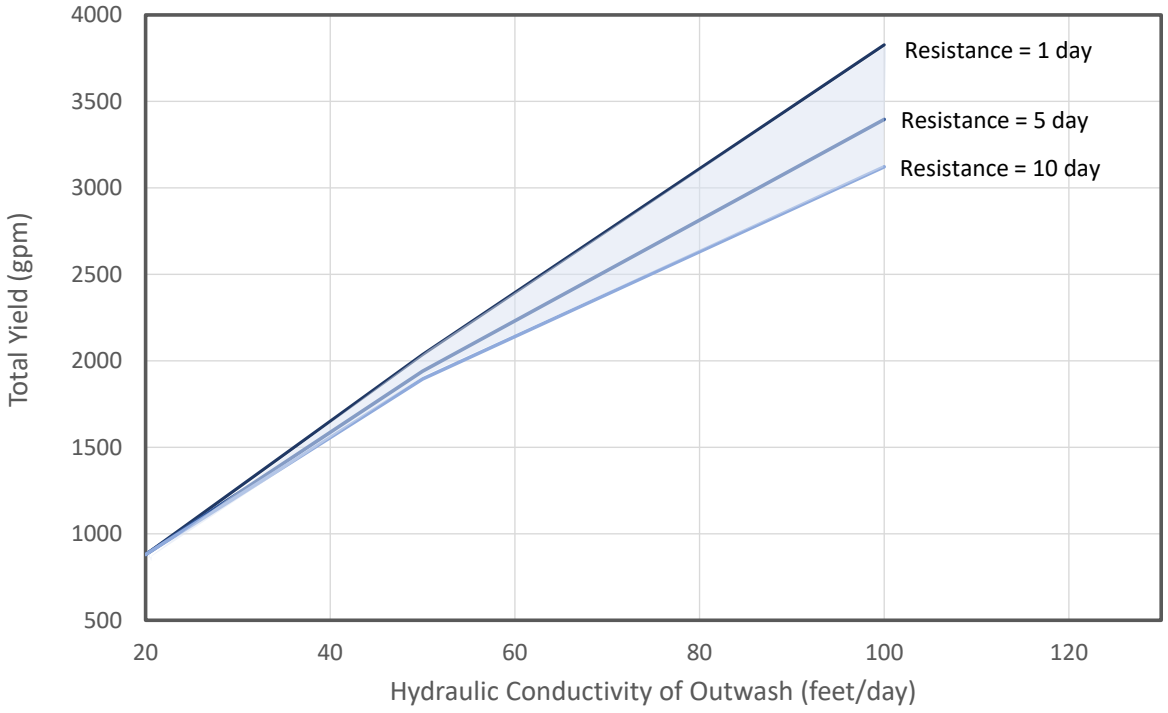

Figure 15.29: Sensitivity of wellfield yield to hydraulic conductivity and resistance of the Eagle Creek bed.

16 Inset Model

The Outwash Aquifer along the White River in Hamilton County has become an increasingly important source of water for public supply. The glacial deposits are highly productive in the southern portion of Hamilton County. Specifically, the river reach between State Road 32 and I-465 supports mining aggregate operations and high-capacity production for Carmel, Citizens Westfield, Citizens Water, and Indiana American Water Company (INAWC).

The objectives in developing the inset model are to demonstrate the transition from a regional GFLOW model of the comprehensive aquifer system to a detailed three-dimensional MODFLOW model, and to conduct an in-depth investigation of a critical area with a deficit in current and future excess water availability. The inset model is used to examine groundwater conditions and future excess water availability, to test impacts due to increased withdrawals at existing water supply wells, and assess the need for additional groundwater infrastructure to support expansion of the water supply system. Given the objectives, we created a regional model with natural boundaries, approximating the boundaries as a groundwater divide up-gradient of the corridor of production wells in Hamilton County. The divide was inferred by connecting stagnation points in the potentiometric contours predicted by the steady-state, regional GFLOW model. Figure 16.30 illustrates the extent of the model domain and the no-flow boundaries along the groundwater divides.

16.1 Expanding Water Use

Between State Road 32 and I-465, groundwater supports high-capacity production for Carmel, Citizens Westfield, Citizens Water, and Indiana American Water Company (INAWC) (Study Area). Figure 16.30 illustrates the locations of high-capacity wells within the model domain. The City of Carmel extracts essentially all of its public supply from the southern portion of this productive reach. Farther north, Citizens-Westfield operates a large public water-supply wellfield along River Road for the City of Westfield. The River Road wells are scattered within the Outwash Aquifer between a number of large aggregate operations. Mining withdrawals are discussed in Section 16.2. In 2006-2007, Citizens Water constructed six wells in the same region, three wells adjacent to the Westfield operations, and three wells located adjacent to Cicero Creek. Farther north, INAWC operates multiple wells along the White River in support of their Noblesville operations. Other high-capacity wells in the reach include irrigation wells and wells used for mining and for energy production.

Growth in the Study Area has resulted in a significant increase in groundwater use since the IDNR started tracking withdrawals statewide, increasing from a total of approximately 7 MGD in 1985 to over 32 MGD in 2018 (Figure 16.31). Most of this additional groundwater use is pumped from the outwash aquifer and is used for public supply. Carmel, Citizens, Westfield, and INAWC's production has increased steadily since the mid-1990's to support new customers (Figure 16.32). This growth and the addition of the Citizens Water River Road Wellfield have

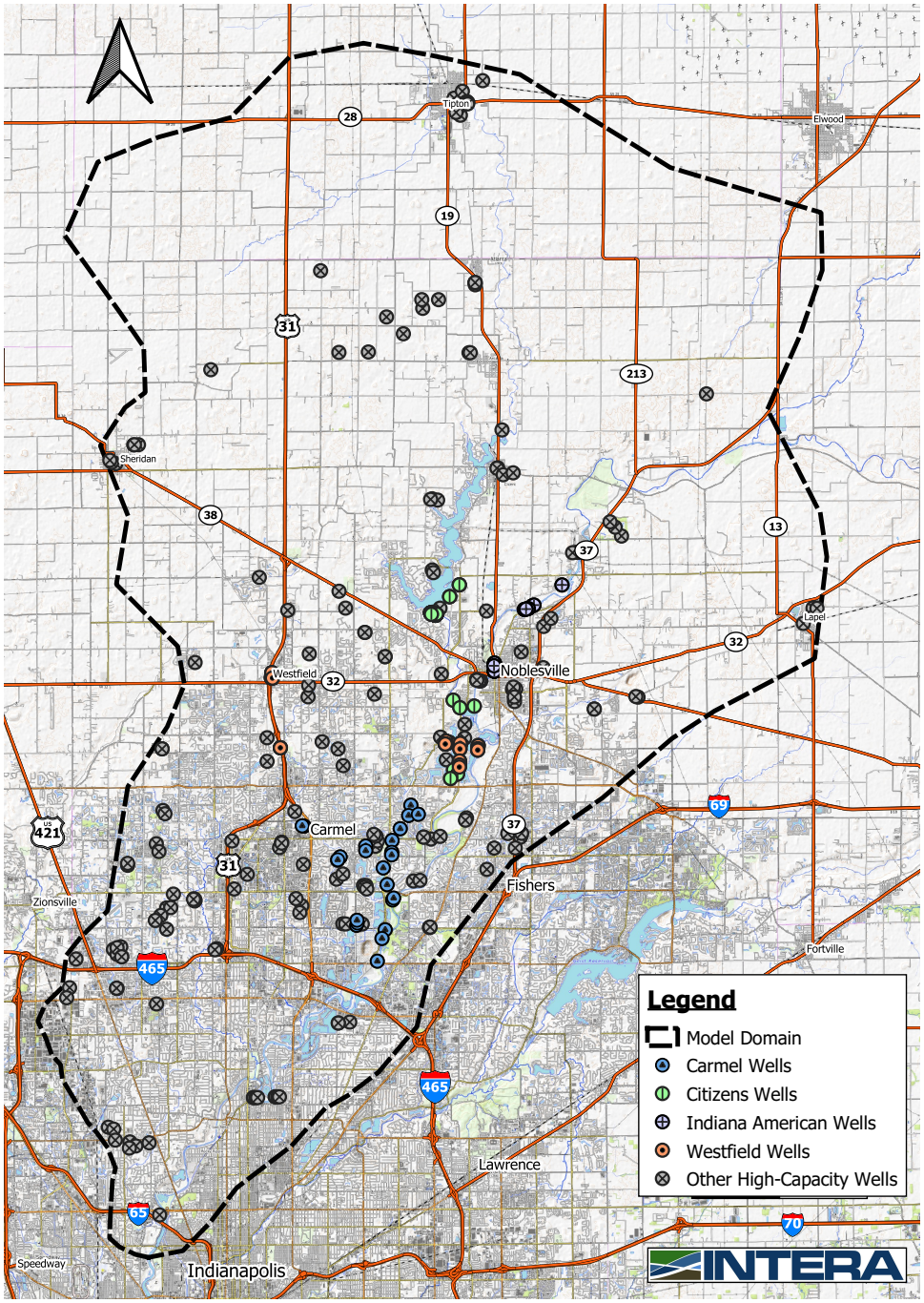

Figure 16.30: Inset model domain and locations of high-capacity wells currently registered as significant water withdrawal facilities in the Study Area (IDNR, 2020a).

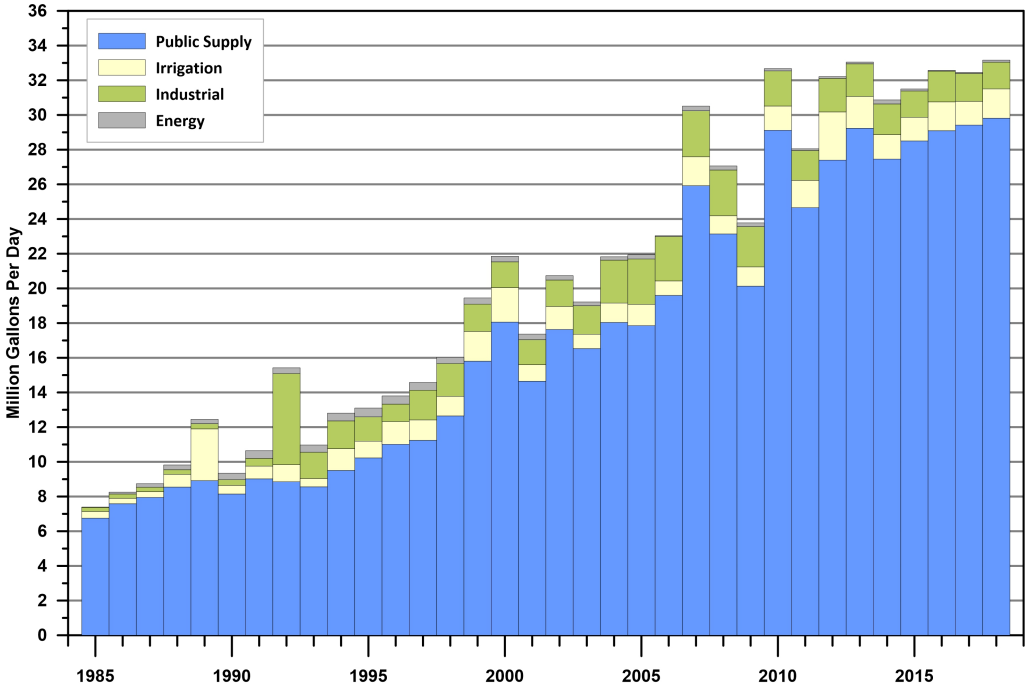

Figure 16.31: Significant water withdrawals from wells, by sector, in the model domain, 1985-2018 (IDNR, 2020a). Note that mine withdrawals are not included.

resulted in total groundwater withdrawals approaching 30 MGD in 2018.

16.2 Mining Withdrawals

For decades, both the outwash deposits and the bedrock have been a significant source of aggregate for the region. Within the model domain, Martin Marietta operates three mines, the Indianapolis North Mine, Carmel Sand and Gravel, and the Noblesville Mine (Figure 16.33). These operations produce aggregate from the unconsolidated deposits via surface pits and from the limestone bedrock via underground tunnels. The Noblesville Mine is located along River Road, north of 146th Street. The Indianapolis North Mine and Carmel Sand and Gravel are located along Hazel Dell Parkway, between 96th Street and 116th Street. For the purpose of this report, these two operations will be referred to as Indianapolis North. The Indianapolis North operation includes an open pit that has been excavated well below the overlying outwash formation and into the bedrock.

At both mines, a significant amount of water is pumped from the subsurface to maintain dry conditions in the tunnels. Leakage into the mine from the limestone and overlying outwash deposits is collected in sumps and pumped away from the mine. Water is also pumped between surface pits to maintain operational water levels, to supply water for washing operations, and to discharge excess water to the White River. We assume that net withdrawals from the sites are equal to reported average NPDES discharges (EPA, 2020) and that the difference between

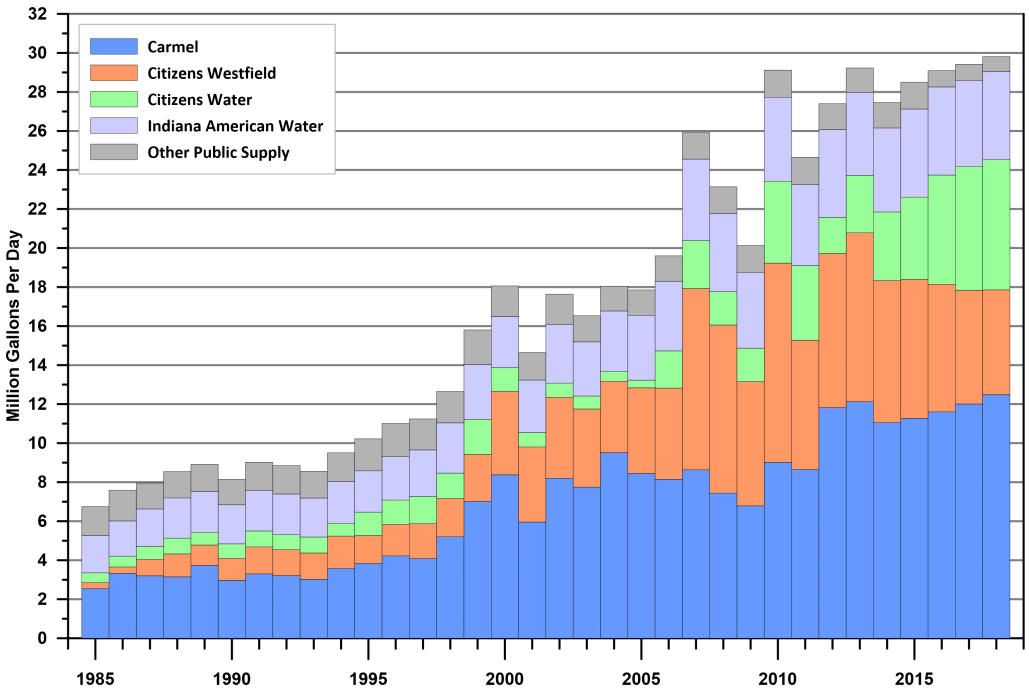

Figure 16.32: Significant water withdrawals from public-supply wells in the model domain, 1985-2018 (IDNR, 2020a).

the reported SWWF rates and the NPDES discharge represents water that has been moved between the pits or from the underground works and surface pits, and that this water is lost to evaporation or infiltrates into the surficial deposits.

To understand reported water use, we analyzed withdrawals registered with the mines in the IDNR SWWF database and reported discharges associated with the mines in the USEPA ECHO database . Multiple intakes are registered in the SWWF database at both the Indianapolis North Mine (Registration # 02025 and 4326) and the Noblesville Mine (Registration # 02981). The NPDES discharges are reported as part of respective permits for Total Suspended Solids at the Indianapolis North Mine (Facility ID: ING490012) and the Noblesville Mine (Facility ID: ING490026). The reported rates are summarized in Figure 4.6 in Section 4.4.2. Note that total withdrawals reported in the SWWF database for the two facilities in 2017 is nearly 32 MGD. This exceeds the combined withdrawals for the Public Supply sector, illustrated in Figure 16.32.

16.3 Hydrogeologic Framework

The framework presented here, combined with an analysis of existing information, was used to develop a conceptual model of the aquifer system and to parameterize and calibrate the groundwater flow model. The 3D geologic solid model (Appendix D) was used to guide development of the conceptual model. Below, we make reference to the original studies incorporated in the solid model.

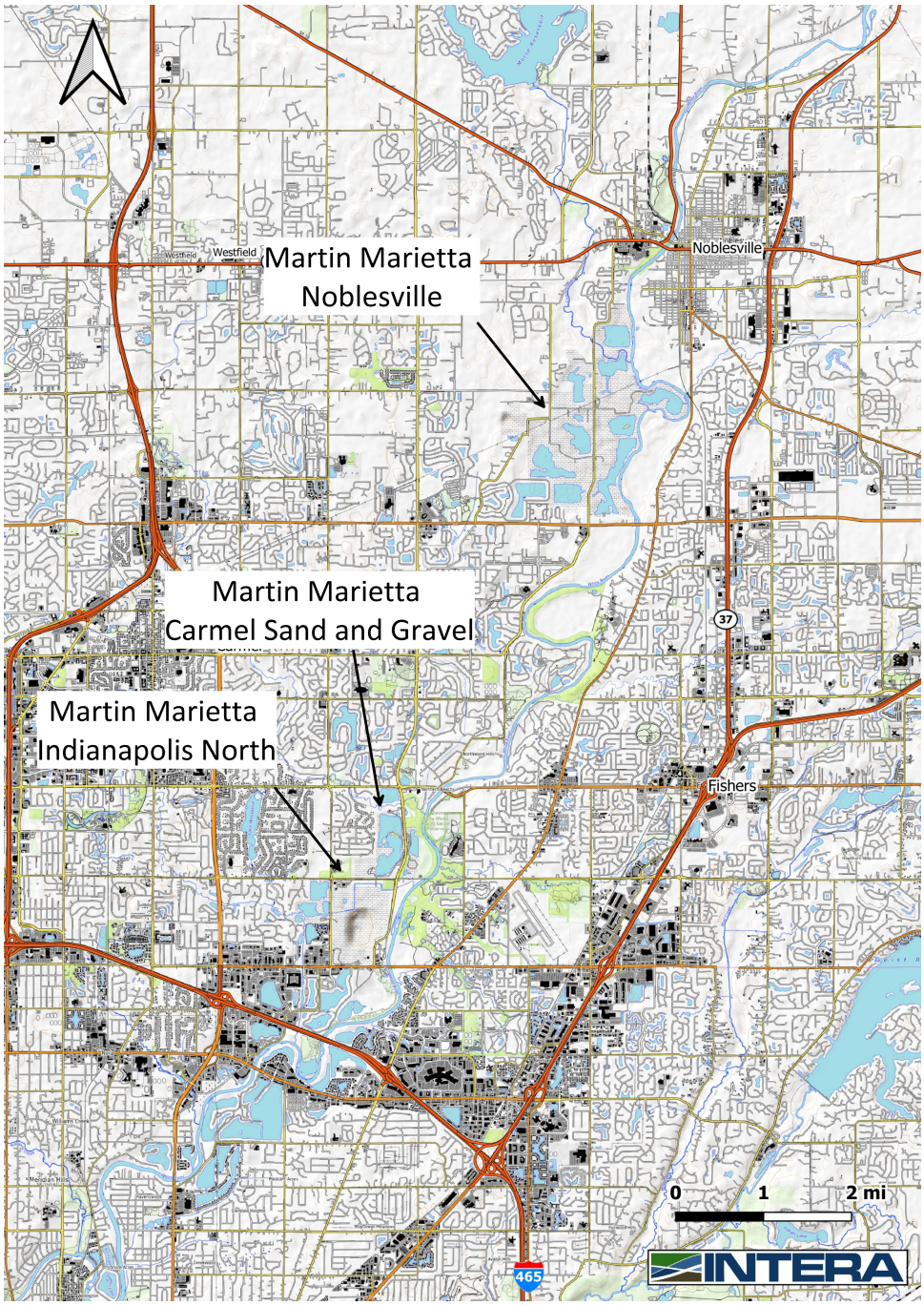

Figure 16.33: Locations of Martin Marietta mines within the model domain.

In Hamilton County, the most significant groundwater resources are associated with unconsolidated sand and gravel deposited by receding glaciers (Figure 16.34). A bedrock aquifer is present throughout the area but is infrequently utilized as a resource because yields are highly variable and are rarely sufficient for high-capacity wells. The overlying unconsolidated deposits consist of two general types:

1. Outwash deposits – sand and gravel deposited by rapidly moving melt water, and
2. Clay-rich, loamy, tills inter-bedded with stratified sand and gravel.

The outwash deposits are mapped as two distinct aquifer systems in Hamilton County, the White River Outwash Aquifer System and the White River Outwash Aquifer *Subsystem* (Figure 16.34). The White River Outwash Aquifer System forms the most productive aquifer in the county and is heavily used as a source of supply (Scott, 2010a). This aquifer system can be found along major rivers and near the land surface and is comprised of saturated permeable deposits that are capped by a layer of silt and clay (Scott, 2010a).

The boundary of the Outwash Aquifer System roughly coincides with the West Fork White River flood plain while the Outwash Aquifer *Subsystem* is mapped as a transitional zone between the Outwash Aquifer System and the Till. The Outwash Aquifer *Subsystem* is generally thinner, confined by a thicker cap of clay and silt at the land surface, and is less productive (Scott, 2010a).

16.3.1 Outwash Aquifer System

The outwash aquifer varies in thickness, extent, and lithology. In Hamilton County, the outwash deposits consist of a 1-3 mile wide channel of permeable deposits in an irregularly-shaped valley. Figure 16.35 shows the transect for the geologic cross section A-A' shown in Figure 16.36). The transect runs along the river from north of Noblesville to south of I-465. In areas where glacial meltwater carved valleys in the bedrock or filled pre-glacial bedrock valleys, the glacial deposits are thicker (Figure 16.36). In general, the grain size of the outwash deposits range from fine sands to coarse gravel to cobbles, but primarily consists of well-sorted, coarse-grained sand and gravel (Gillies, 1976). Well logs indicate that these unconsolidated deposits can reach a thickness up to 200 ft, but are typically 100 ft thick in the Carmel area. Sand and gravel thickness ranges from 0 to 100 ft.

Based on well log data and production well data, there is a highly prolific zone in the aquifer that extends from the River Road area south to 126th Street. The gravel thins both east and west of the pre-glacial bedrock valley trough and may be absent, particularly in areas where subsurface bedrock highs exist. While unconfined conditions prevail in the outwash, semi-confined to confined conditions do occur where surficial clay layers and/or significant subsurface clay layers are present.

The hydraulic conductivity (k) of the Outwash Aquifer System along the West Fork White River has been estimated at over 340 ft/day in some areas based on pumping test results (Bailey and Imbrigiotta, 1982). The transmissivity (T) of the aquifer, by definition, is highest

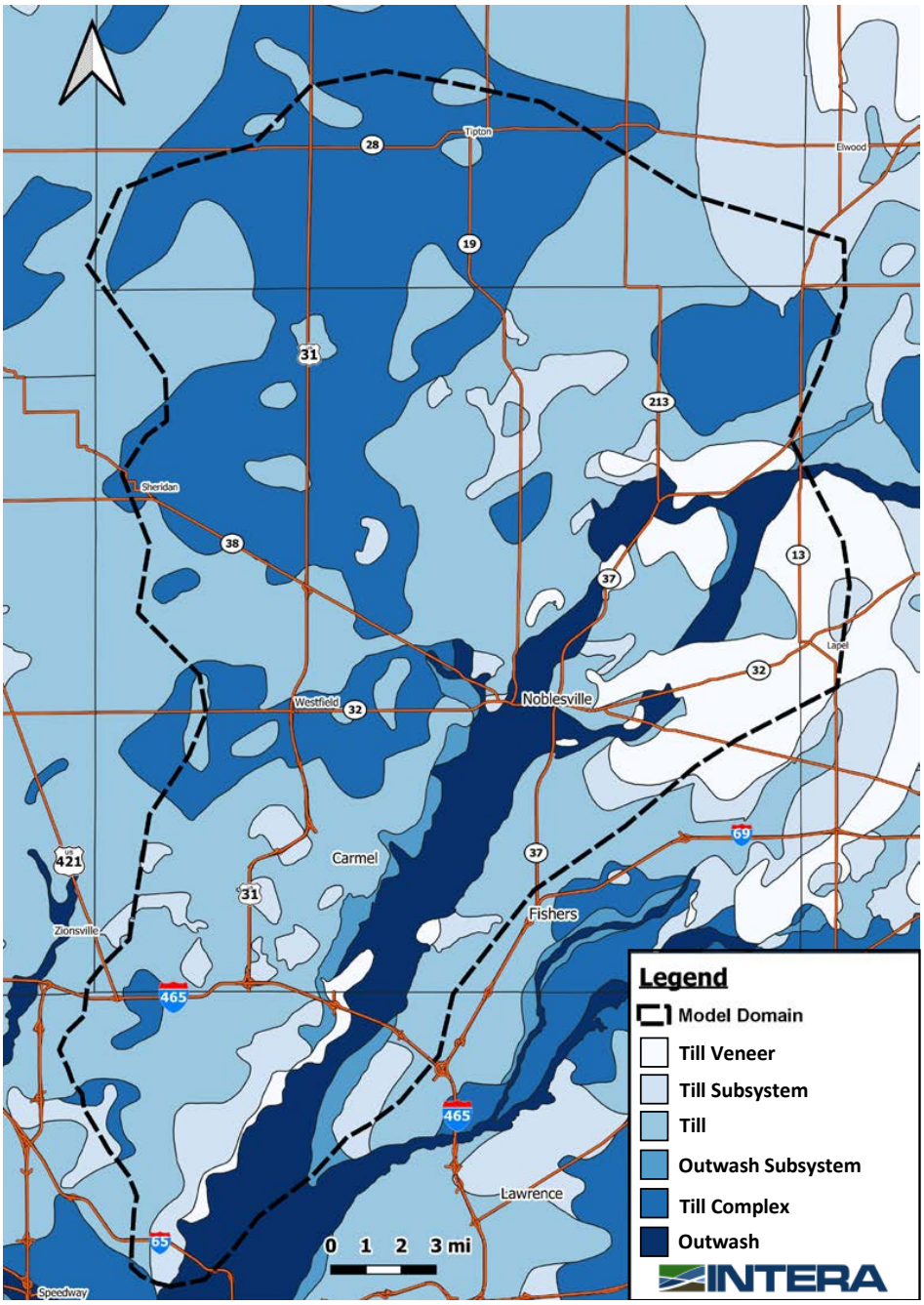

Figure 16.34: Unconsolidated deposits in the model domain. *Modified from Scott 2008, 2009, 2010a,b; Schmidt 2011; Grove 2008.*

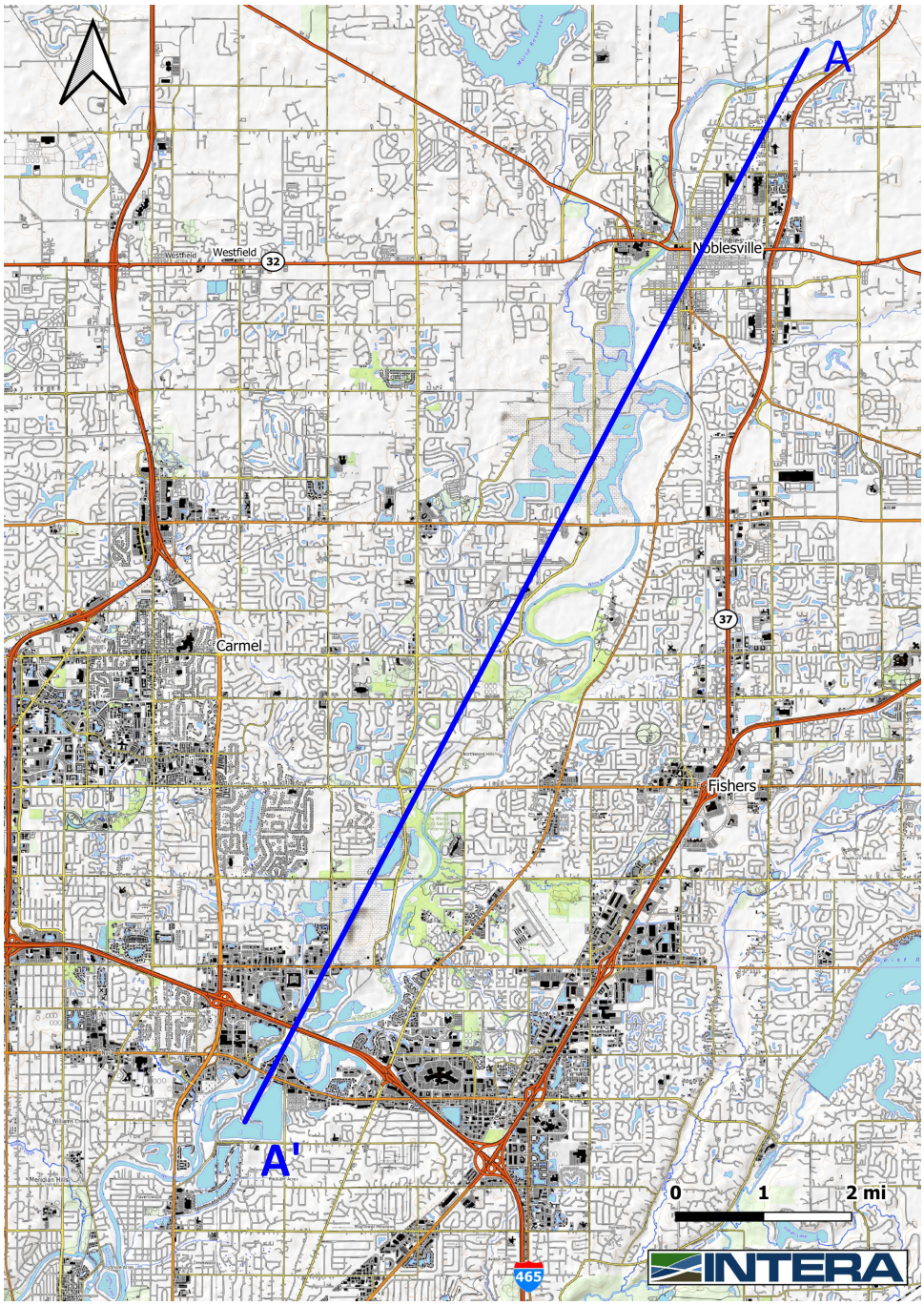

Figure 16.35: Transect for geologic cross section A-A shown in Figure 16.36.

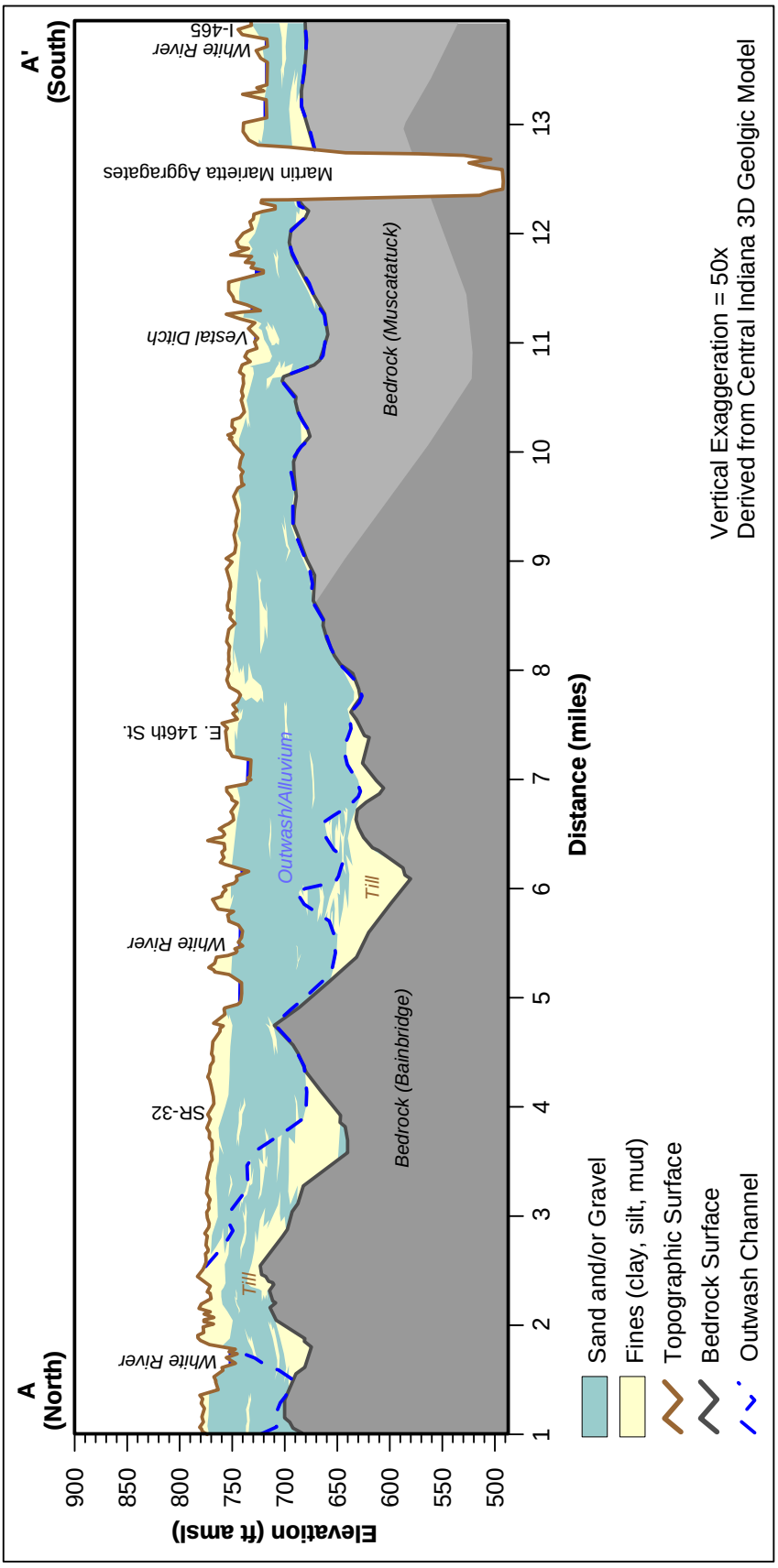

Figure 16.36: Geologic cross section A-A'.

where the saturated sand and gravel are thickest (Cable, 1971). Arihood (1982) reports a range of k values for the outwash aquifer (based on aquifer material) to be from 40-415 ft/day, with corresponding values for T ranging from 1,000-28,000 ft^2/day. (Herring, 1976) reports T values for the outwash in Marion County in the range of 7,000-28,000 ft^2/day. IDNR (2002) reports a T range of 2,000-20,100 ft^2/day for the Outwash Aquifer System in the West Fork White River Basin. Based on aquifer test pumping results from Carmel production wells that are completed in the outwash deposits, estimated k values range from 190-865 ft/day, corresponding to T values from 17,500- 38,000 ft^2/day (WHPA, 2003).

Aquifer properties of the Outwash Aquifer Subsystem, a transitional zone, are generally lower. IDNR (2002) reports a T range of 260-7,300 ft^2/day for the Outwash Subsystem in the West Fork White River Basin.

16.3.2 Till Aquifer System

Away from the river, sand and gravel deposits buried within the glacial till form aquifers suitable for domestic supply. These intra-till aquifers are often discontinuous. Most of Hamilton County is mapped as two distinct aquifer systems, the New Castle/Tipton Till Aquifer System and the New Castle/Tipton Complex Aquifer System (mapped as “Till” and “Complex”, respectively in Figure 3). The sand and gravel layers that comprise viable intra-till aquifers are similar between the two till aquifer systems, but the aquifers associated Tipton Complex Aquifer System are generally deeper and exhibit greater variation in depth, thickness, and lateral extent (Scott, 2010a).

The thickness, extent, and potential yields from the till aquifer systems are highly variable. Where present in the Study Area, sand and gravel aquifers within the till are confined and are commonly thin, with average thicknesses ranging from 5 to 20 ft (Scott, 2010a). Locally, yields can be large enough for high-capacity wells (Scott, 2010a). In most places, the till aquifers are capable of yields sufficient for most domestic purposes.

Hydrogeologic investigations by the Indiana Geological Survey have provided insight on these till aquifer systems (Brown et al., 1995). Based on water-level data, geometry, and the inferred origin of aquifers and confining units, sand and gravel units along the pre-Wisconsin surface and within the overlying late Wisconsin sequences collectively form an interconnected aquifer system (Brown and Laudick, 2003).

While reported k values for clays in glacial till systems range from 10-25 ft/day (Driscoll, 1986), the inter-bedded sand and gravel aquifers that occur within the till are much more transmissive. These more permeable sand and gravel layers may be regionally continuous, but are locally variable. Previous work in the area indicates that there are several “zones” including the average or "regional" value of k for the till aquifer system, that account for transmissivity of both glacial till and discontinuous, inter-bedded sand and gravel.

Arihood (1982) reports a range of k values for the confined inter-bedded sand and gravel aquifers in Hamilton County to be from 200-433 ft/day. Assuming an average aquifer thicknesses

ranging from 5-20 ft, the corresponding range for transmissivity is 1,000-8,660 ft^2/day.

16.3.3 Bedrock Aquifer System

Regionally, the area sits on top of the Cincinnati Arch, a northwest-to-southeast trending axis of bedrock high that dips down in both directions away from the axis. Bedrock dips gently to the southwest towards the southern boundary of Hamilton County, and to the northeast toward Tipton County. Based on well log data, the bedrock is occasionally in direct contact with overlying outwash deposits but may also be separated from the overlying outwash aquifer by relatively thin clay layers.

Hydraulic parameters of the bedrock are not as available as the unconsolidated deposits because of high local variability and a lack of quality pumping tests. Within the bedrock, well drillers report some variability of hardness, fracturing, and solution features but overall, it is relatively impermeable and does not appear to be an important water resource (Gillies, 1976). Herring (1976) reports T values for the Silurian-Devonian aquifer in Marion County in the range of 60-1,300 ft^2/day. IDNR (2002) reports a T range of 15-150 ft^2/day for the Silurian Devonian aquifer system in the West Fork White River Basin.

16.3.4 Recharge from Precipitation

In general, precipitation that does not runoff as surface water percolates through the unconsolidated sediments or lost through evapotranspiration percolates through the soil and recharges groundwater. The Outwash Aquifer System is recharged by precipitation and by inflow from till aquifers east and west along the perimeter. Water budget studies done by the USGS suggest that infiltration rates into the outwash system along the White River may be up to 12 in/yr (Meyer, 1978). More recently, IDNR estimated a range of recharge to the outwash aquifer of 10.5-14.7 in/yr (IDNR, 2002).

Lapham (1981) reports an average annual groundwater recharge rate to the till of approximately 2 in/yr, while Arihood (1982) suggests a range of 2-4.5 in/yr. IDNR (2002) reports an estimated range of 3.15-4.73 in/yr.

16.3.5 Surface Water/Groundwater Interaction

The degree of hydraulic connection between surface streams and groundwater can have a significant effect on yields. Under natural flow conditions, recharge to the regional aquifer ultimately discharges into surface waters, specifically the White River and its tributaries. There have been a few studies of the hydraulic connection between the sand and gravel aquifers and the streams south of the Study Area in Marion County (Meyer, 1978; Saul and Robinson, 2002). The general conclusion of these investigations is that the hydraulic connection varies locally depending on the grain size of the riverbed materials and the presence of intervening clay layers in the aquifer.

Results from the field investigation (Appendix E) and the geologic solid model (Appendix D) were used to parameterize conductance values for the RIVER cells representing the White River. Figure 16.37 shows River Mile (RM) designations along the White River as reference for Figure 16.38, which shows the total thickness of non-aquifer materials along the thalweg of the White River. Conductance values (C) representing the White River model cells were set based on the field investigation results at Carmel Well 30 (RM 251.7), Carmel Well 27 (RM 253.1), and the INAWC North Well Field (RM 265.9).

The observed fluxes at the three sites were used to derive site-specific values for conductance. These site specific values were then related to the entire river reach within the model domain by relating them to the total thickness of non-aquifer materials. To accomplish this, the White River was divided into eleven representative reaches as shown in Figure 16.39. The reaches are of variable length, with short lengths chosen for the field investigation sites.

16.4 Inset Groundwater Flow Model

The inset groundwater model was extracted from the GFLOW sub-regional model and refined using the USGS code MODFLOW-2005 (Harbaugh, 2005) facilitated by the use of the pre- and post-processing package Model Muse (Winston, 2009). The model was calibrated to steady state (i.e., average) conditions representative of 2009-2013. This time period was chosen to make use of the most recent water levels reported on well logs to IDNR that have been field located by the agency. To investigate groundwater accessibility with existing infrastructure, we created a scenario representative of 2016-2018 to make use of the most most current withdrawal information.

16.4.1 Model Grid and Layering

Grid cell sizes in the model were set at 1,000 ft in the far field. Cell sizes were reduced to 200 ft in the corridor of production wells between the Indiana American North Well Field in Noblesville and 96th Street to provide sufficient detail in the local flow patterns (Figure 16.40. The total number of active cells in the model domain is 78,314.

The regional model was vertically subdivided into two layers. Figure 16.41 shows an east-west cross section of the MODFLOW model looking north at the general location of 146th Street. The upper layer (Layer 1) represents the aquifers of interest, the Outwash and Till Aquifer Systems. Given the large regional scale of the aquifer system and observed water levels, the Outwash and Till Aquifer Systems is considered a single, regional aquifer. The elevation of the top of Layer 1 was defined with a USGS digital elevation model (DEM) (USGS, 2017). The bottom layer, Layer 2, represents the Bedrock Aquifer System. The top of Layer 2 was defined by a DEM of the bedrock surface (IGWS, 2015) and is modeled with a constant thickness of 100 ft thick.

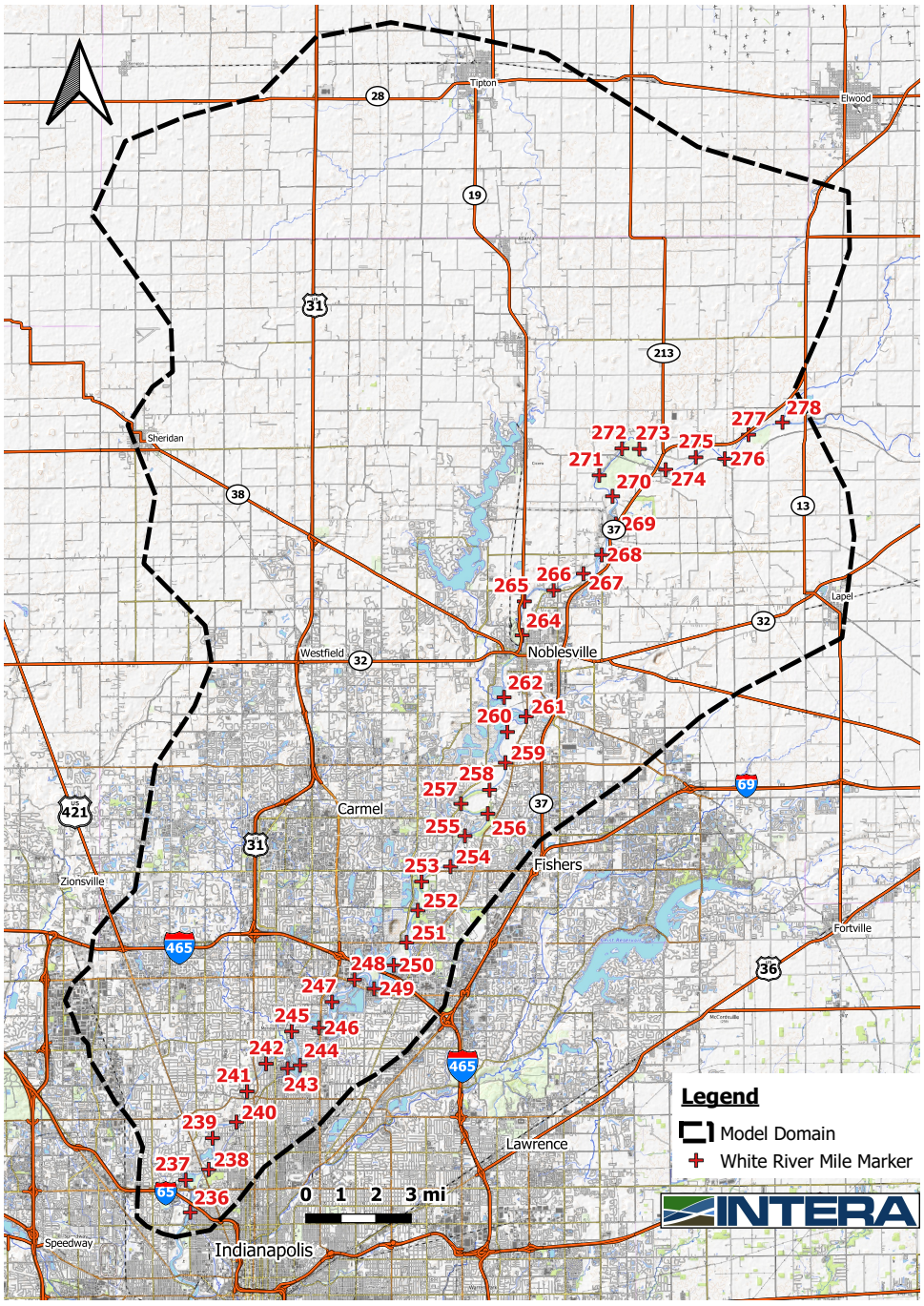

Figure 16.37: River mile designations along the White River (IDNR, 2016).

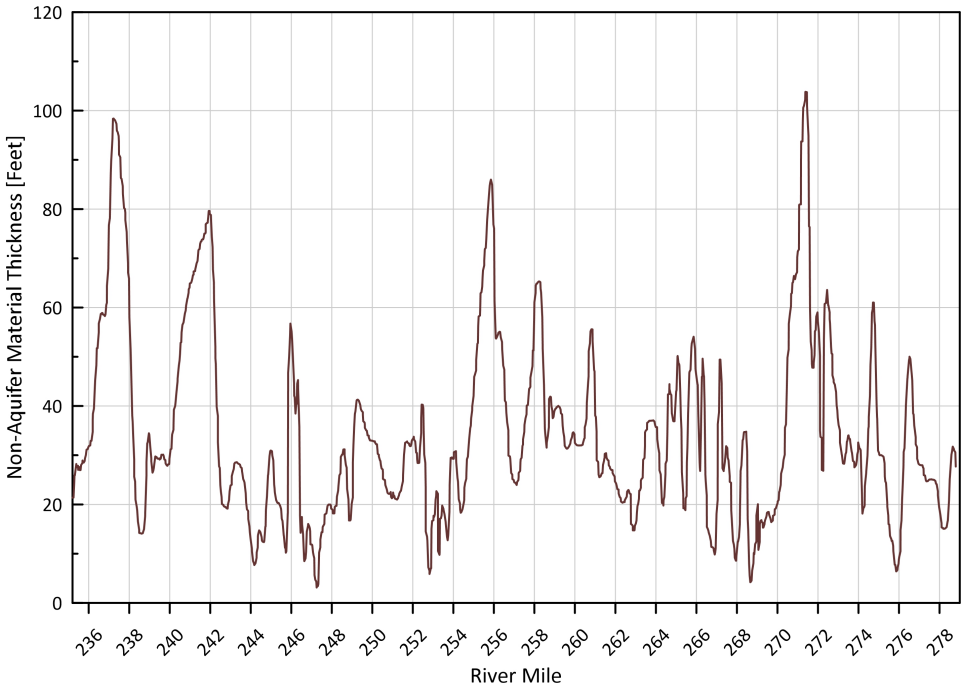

Figure 16.38: Thickness of non-aquifer material along the thalweg of the White River.

16.4.2 Aquifer Properties

Aquifer properties for Layer 1 were assigned based on a simplified version of the IDNR map of unconsolidated deposits (Figure 16.34). For model calibration, we simplified the layout of the regions into four primary zones as shown in Figure 16.42:

1. An Outwash zone as mapped through the central portion of the model domain.
2. A Till Veneer zone in the central eastern portion of the model domain.
3. A zone called Upland Till in the northern and northwestern portions of the model domain, which combines the Till, Till Complex, and Till Subsystems.
4. A zone called Till, which combines Outwash Subsystem with the units generally mapped as till in the central and southern portion of the model domain.

The hydraulic conductivity field for Layer 1 was set by assigning a single conductivity value for each zone. The value for k_x and k_y for each cell was set equal to the zone conductivity value (K_{zone}) multiplied by the proportion of permeable deposits at that location (k_x=k_y= $K_{zone}(\frac{sand/gravel\,thickness}{layer\,thickness})$. The K_{zone} values were adjusted during calibration, as described in Section 16.5.

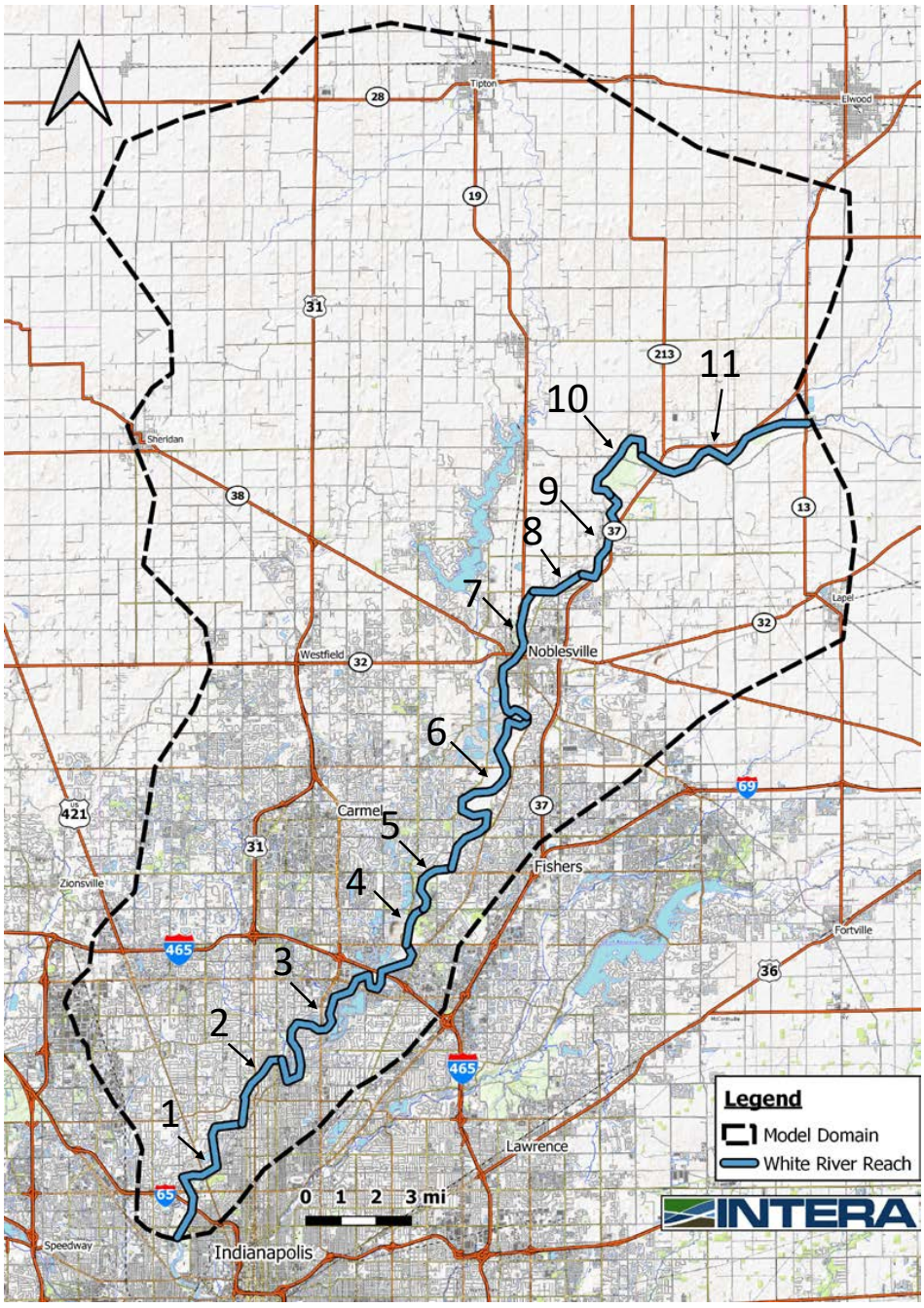

Figure 16.39: Representative reaches of the White River for assigning conductance values.

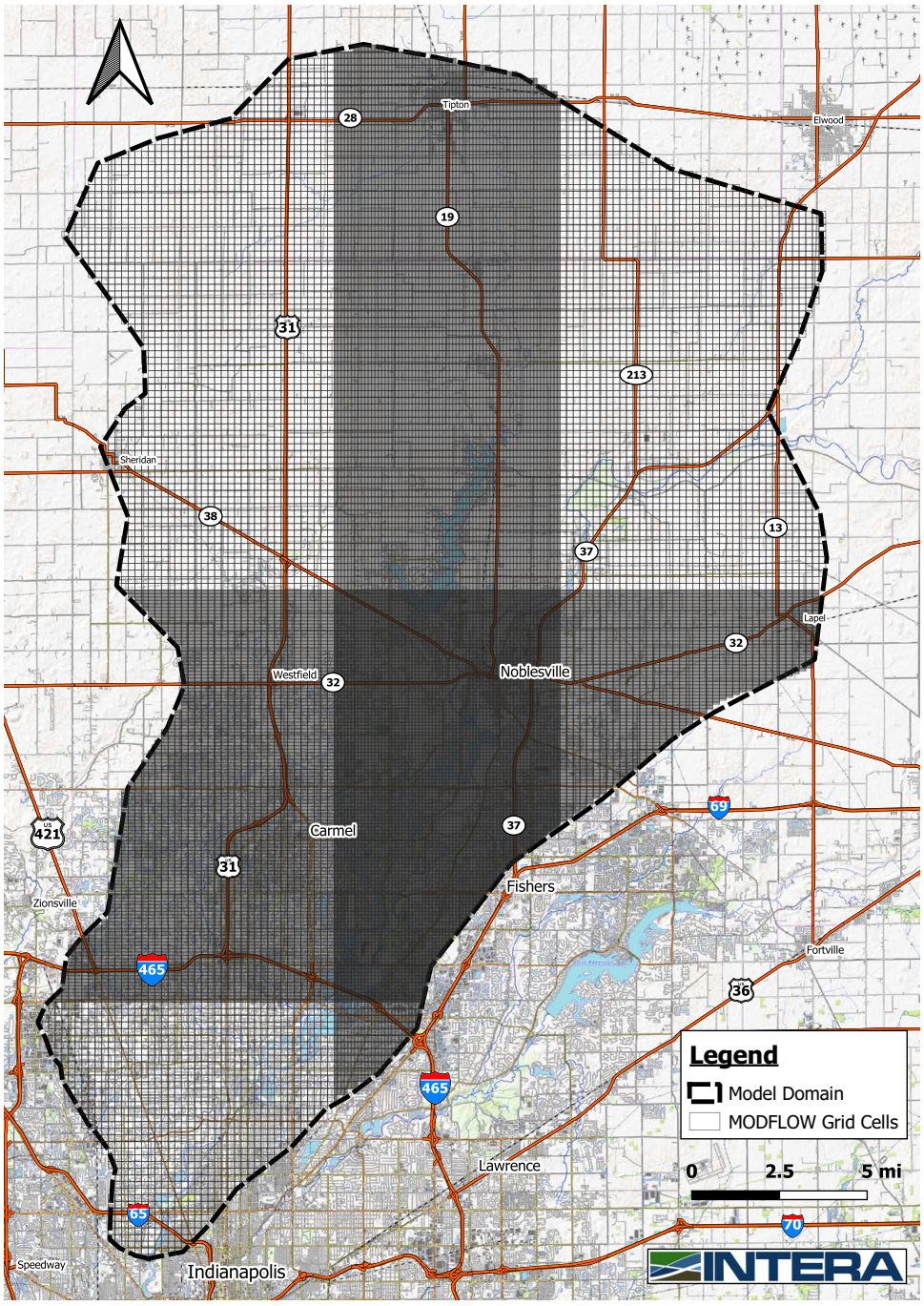

Figure 16.40: Model grid.

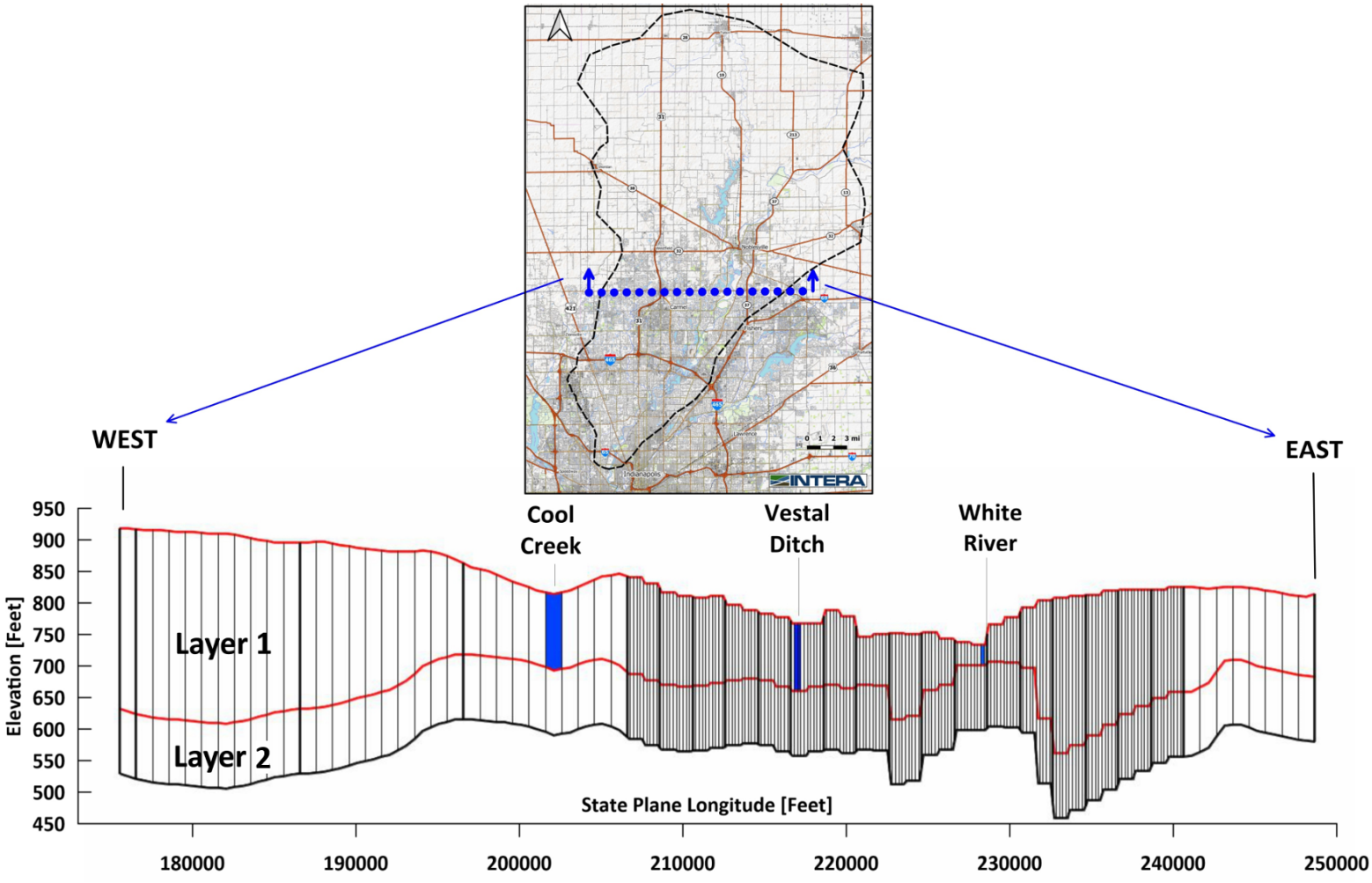

Figure 16.41: Cross section of MODLFOW model. Vertical exaggeration = 40.

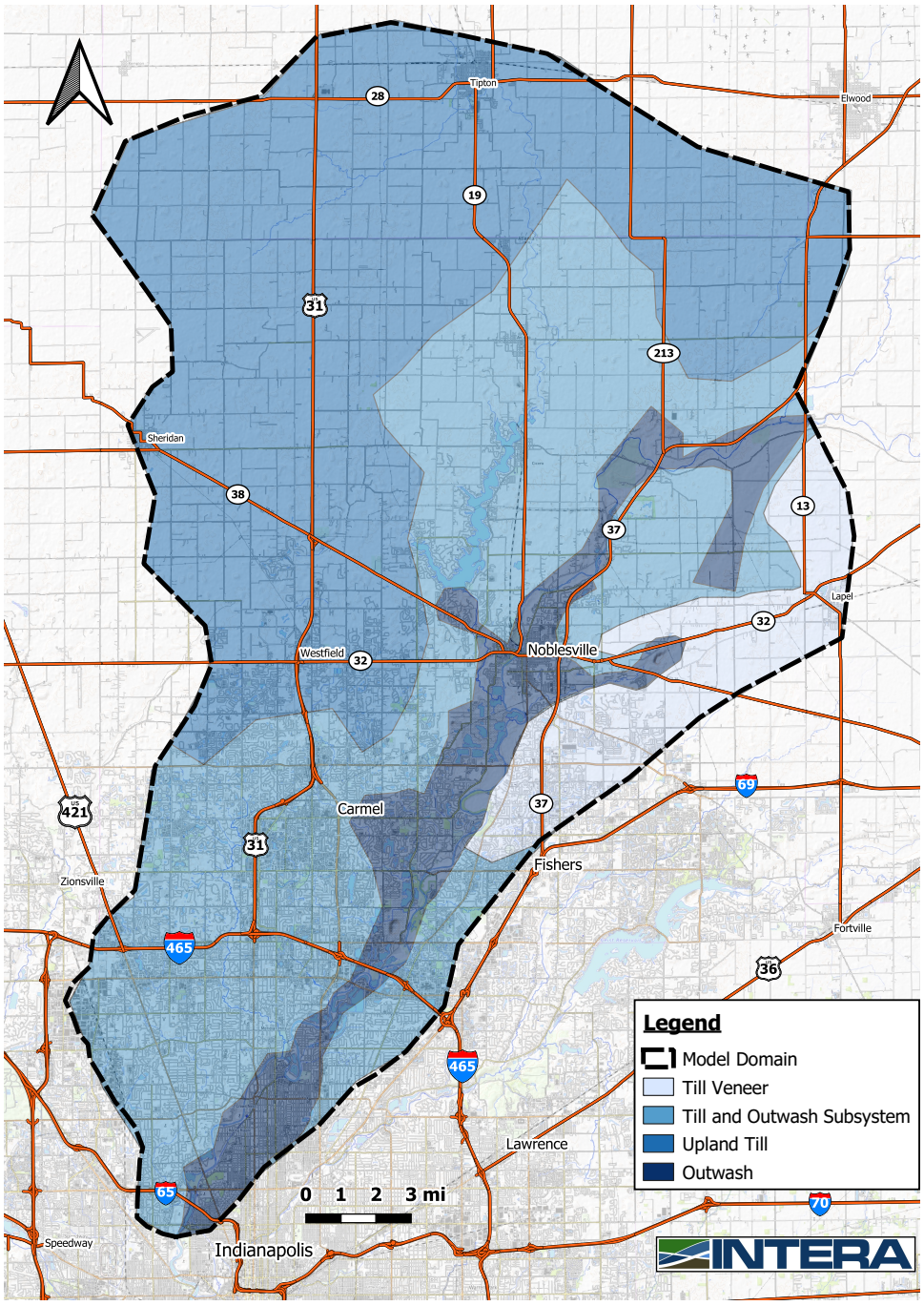

Figure 16.42: Generalized hydraulic conductivity zones.

16.4.3 Recharge

Areal recharge in the regional model was applied based on the conductivity zones defined above. A recharge rate of 14 inches/year was applied to the Outwash, while a rate of 1.0 in/yr was applied to the Upland Till, and 4.0 in/yr was applied to the Till/Outwash Subsystem and the Till Veneer.

The average recharge rate over the model domain is 3.8 in/yr. This average rate is equal to the critical Quarter 3 natural baseflow, presented in Table 14.2, prorated by the proportional area of the sub-basins that compose the inset model domain (Table 16.17).

16.4.4 Surface Water

Rivers and streams were simulated with the MODFLOW RIV (river) package. Water levels along the streams were derived from a United States Geological Survey (USGS) Digital Elevation Model (DEM) (USGS, 2020a). The streams that were included in the model are shown in Figure 16.43. Similarly, Morse Reservoir was simulated using the RIV package.

16.4.5 Mine Withdrawals

Mine withdrawals were approximated based on available information. In reality, the location and extent of the underground tunnels at both mines is unknown. Also, it is not known where water is removed and how much water is derived from the bedrock system and how much water is leaking from the overlying surficial system. Because excess water is collected in sumps from underground tunnels and an open pit for the case of the Indianapolis North operation, we assume that withdrawals are spread out over a large area.

Mine withdrawals were simulated with the MODFLOW recharge package by assuming that net withdrawals from the sites are equal to reported average NPDES discharges. The average 2009-2013 discharges for the Noblesville and North Indianapolis operations were 1.5 and 6.3 MGD, respectively. The average 2016-2018 discharges for the Noblesville and North Indianapolis operations were 4.2 and 6.1 MGD, respectively. For the Indianapolis North operation, the extent of the recharge zone was set equal to the open pit area at the site. For the Noblesville operation, the recharge zone was set equal to an area of approximately one-half square mile.

16.4.6 High-Capacity Wells

The locations and historical water withdrawals for high-capacity wells were obtained from the IDNR SWWF database (Figure 16.30) . The total combined rates for major sectors and utilities for the base and predictive scenarios are summarized in Table 16.18. The model was calibrated using the reported average annual withdrawal rate for each well active over the period 2009-2013 IDNR (2020a). The total combined rate for all high-capacity wells was 30.0 MGD, with a major portion, 26.1 MGD, being pumped by public water suppliers. Total withdrawals for the 2009-2013 base scenario, including mine withdrawals, was 37.8 MGD. The predictive scenario

Table 16.17: Aquifer recharge per sub-basin: Quarter 3, critical conditions, White River system.

Sub-Basin ID	USGS Station at outlet of Sub-Basin	Recharge rate (inch/month)	Recharge rate (inch/year)	Percentage of area in Model Domain (mi^2)	Sub-basin recharge contribution (inch/year)
White River System					
3	03349000 White River at Noblesville, IN	0.025	0.30	17.6	0.053
4	03349510 Cicero Creek at Arcadia, IN	0.000	0.00	19.9	0.000
5	03351000 White River near Nora, IN	0.612	7.34	43.9	3.226
7	03352500 Fall Creek at Millersville, IN	0.252	3.02	0.2	0.006
8	03353000 White River at Indianapolis, IN	0.252	3.02	14.1	0.426
9	03353200 Eagle Creek at Zionsville, IN	0.000	0.00	3.0	0.000
10	03353500 Eagle Creek at Indianapolis, IN	0.360	4.32	0.1	0.002
11	03353611 White R. at Stout Gen. Stn., Ind., IN	0.252	3.02	1.1	0.034
Wabash River System					
2	03339500 Sugar Creek at Crawfordsville	0.036	0.047	0.1	0.003
				Total	3.8

Notes: mi^2 = square miles.

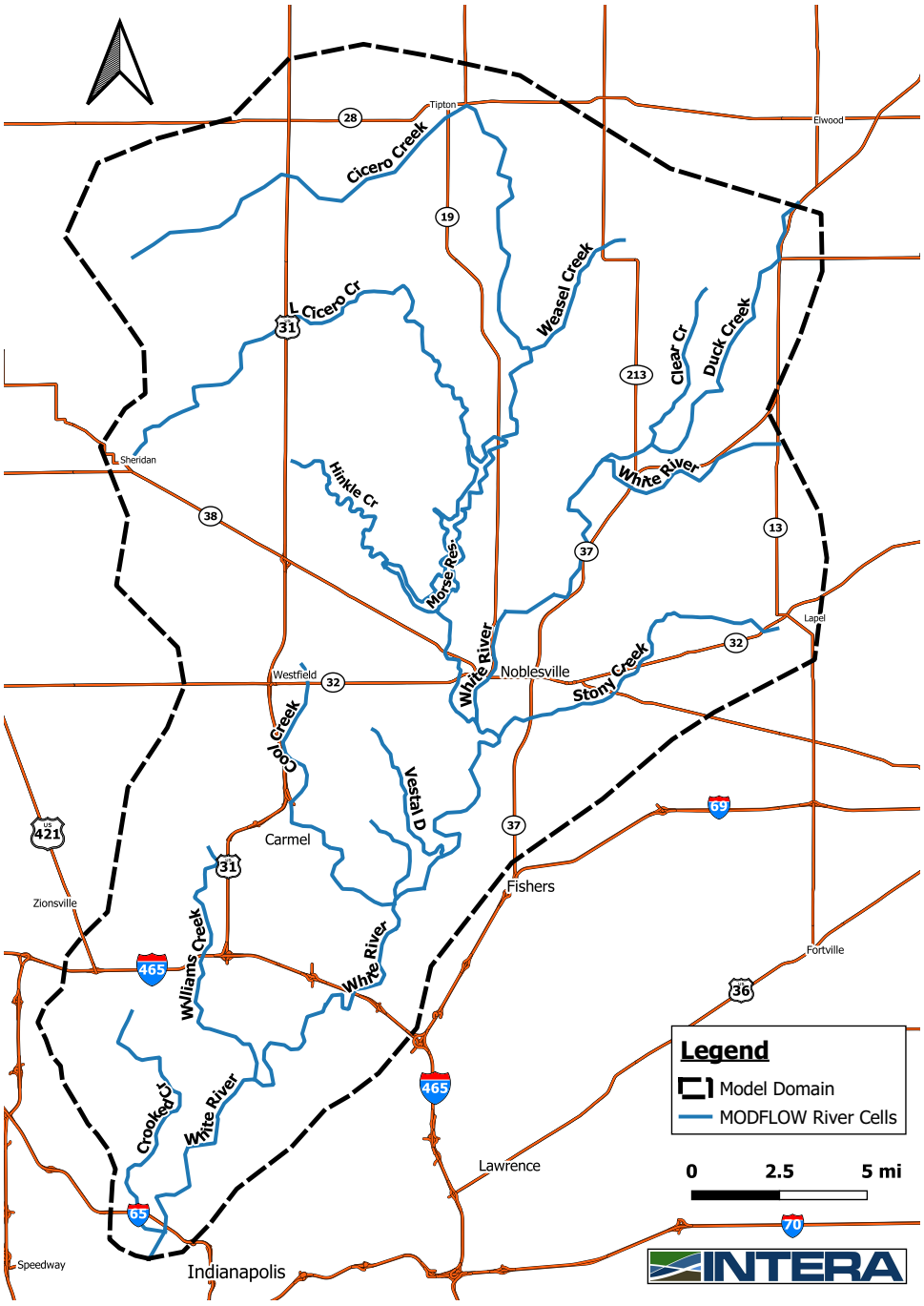

Figure 16.43: Streams represented as MODFLOW RIV cells.

Table 16.18: Withdrawal rates for high-capacity wells and mines in the base model (average 2009-2013) and the predictive scenario (average 2016-2018) .

Sector	Utility	Base Scenario 2009-2013 (MGD)	Predictive Scenario 2016-2018 (MGD)
Public Supply			
	Carmel	9.7	12.0
	Citizens Westfield	8.0	5.9
	Citizens Water	2.9	6.2
	Indiana American Water	4.2	4.5
	Other Public Supply	1.4	0.6
	Total Public Supply	**26.1**	**29.3**
Irrigation/ Industry/Energy		3.9	3.3
Mining		7.8	10.3
	Grand Total	**37.8**	**42.8**

Notes: MGD = million gallons per day.

representing 2016-2018 average conditions included a high-capacity well total of 32.6 MGD, with 29.3 MGD being pumped by public water suppliers. Total withdrawals for the 2016-2018 predictive scenario, including mine withdrawals, was 42.8 MGD.

16.4.7 Observations

Layer 1 was calibrated to water levels reported on well logs for wells drilled in the model domain between 2009 and 2013 in the IDNR Water Well Database (IDNR, 2020b) and USGS monitoring wells (USGS, 2020b) (Figure 16.44). The quality of the water-level data reported by the USGS is excellent, but is mostly limited to the river reach between 146th Street and 96th Street. Well logs submitted after 2013 have not been field verified in the IDNR database, so the 2009-2013 data set provides the most current water levels with a spatial distribution that includes the entire model domain. By contrast, the quality of the water level data from the IDNR database is poor.

The IDNR well log dataset is derived from water levels that are reported when a well is drilled. The data is reported by various drillers, using different methods, and representing different times of the year when water levels may naturally vary. Unlike the USGS data, the IDNR data are not based on strict vertical control of the measuring point elevation. Despite the uncertainties, the IDNR data is the only data available for calibration outside of the corridor

covered by USGS wells. Our objective in incorporating these data into calibration was to estimate model parameters that resulted in a fit of modeled results "somewhere in the middle" of the observed data; this was achieved as described in Section 16.5.

Layer 2 parameters were adjusted to generally match bedrock water levels published by IDNR (Figure 16.45).

16.5 Model Calibration

The model was calibrated manually by adjusting the hydraulic conductivity values in the various zones, and the streambed conductance along surface streams. The model was calibrated by trial and error so that it adequately simulates the behavior of the system in the domain. Figure 16.46 shows simulated head values plotted against observed heads. The Root Mean Square Error (RMSE) was 13.9 feet for all observations. The range of observed values is 250 feet, resulting an RMSE of 5.6% of the observed range. Potentiometric contours for the calibrated base model are shown in Figure 16.47.

16.6 Model Parameters

The final, calibrated aquifer properties are summarized in Table 16.19. Because the Bedrock Aquifer System was modeled as a single layer with constant thickness, we report a single value for Layer 2 transmissivity. The spatial distribution of Layer 1 transmissivity is shown in Figure 16.48.

Conductance values for the eleven White River reaches shown in Figure 16.39 are presented in Table 16.20. Conductance values for all other surface water features simulated as MODLFOW RIVER cells are presented in Table 16.21. Conductance is a lumped term that governs the modeled exchange between ground water and surface water. Specifically, conductance (C) is a factor that relates the difference in head in a river cell to the rate of flow. In MODFLOW, C generally has units of L^2/T and is equal to $k \times L \times W/M$, where:

k = the hydraulic conductivity of the sediment in the boundary condition such as a river or drain,

L = the length of the boundary condition in the cell,

W = the width of the boundary condition, and

M = the thickness of the sediment in the boundary condition perpendicular to flow between the boundary and the cell.

Model Muse provides a function that can automatically calculate the length term above. In this case, C is treated as $k \times W/M$ instead of $k \times L \times W/M$, making the units L/T. These are the units of the conductance terms reported below in Section 16.5.

Seepage inflow rates along the White River were assessed to compare to historic measurements. Table 16.20 shows the modeled seepage rate for each White River Reach as a result of running the calibrated model with no well or mine withdrawals. The resulting average rate of 2.37 cfs/mile, which compares well with seepage studies conducted by the USGS in Hamilton

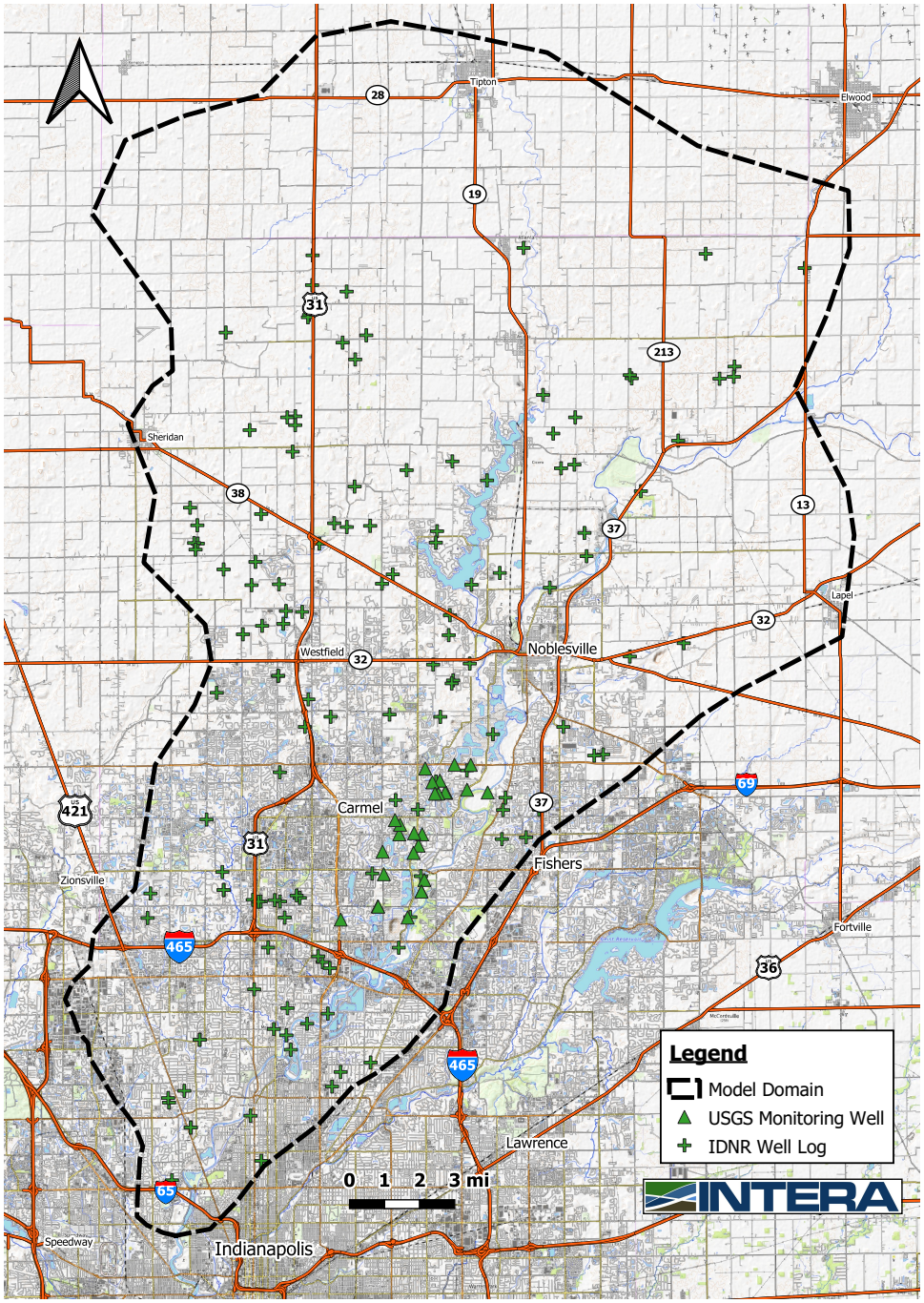

Figure 16.44: Location of water level observations used in model calibration (IDNR, 2020b; USGS, 2020b).

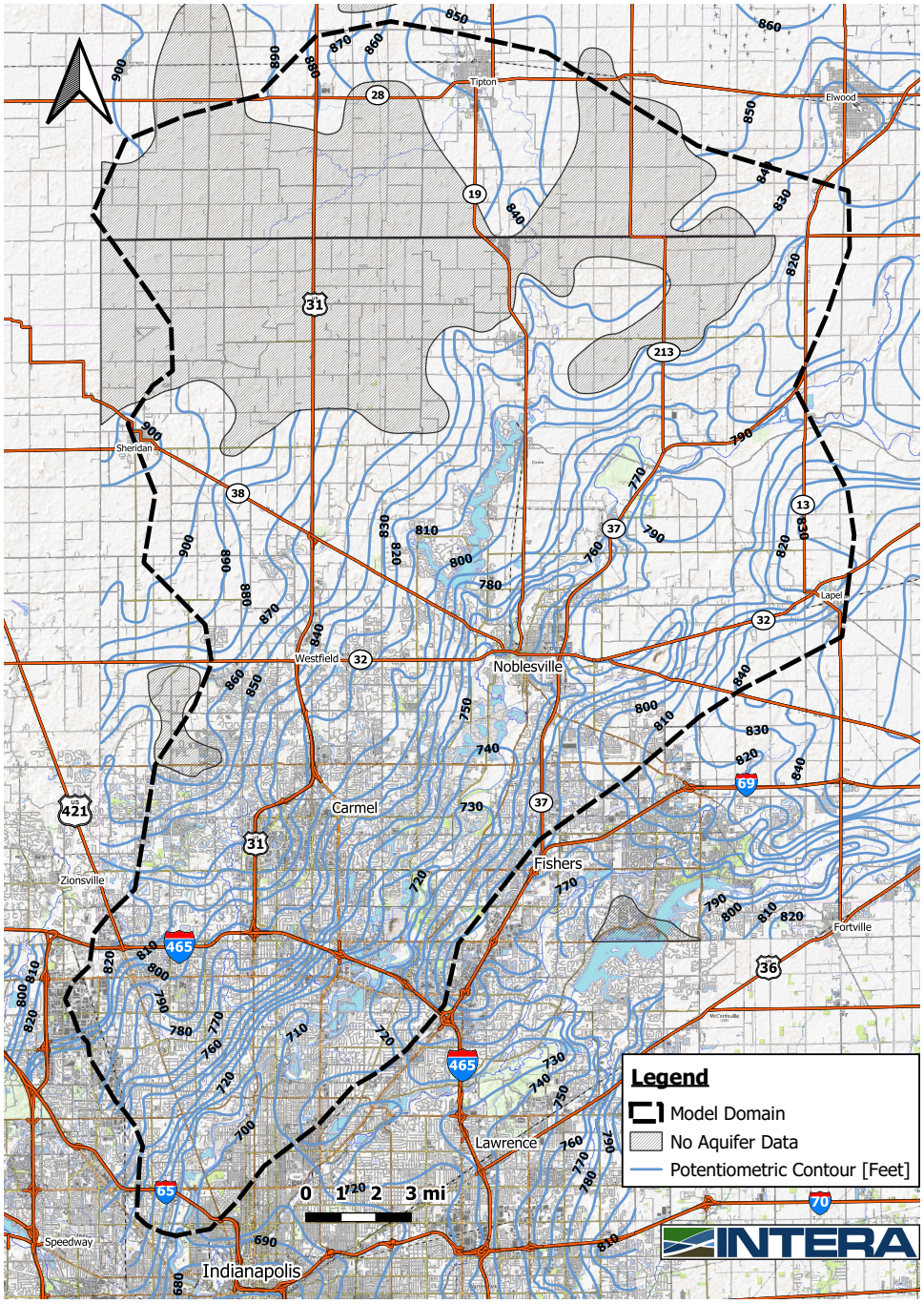

Figure 16.45: Potentiometric contour map of bedrock aquifers systems in the model domain. *Compiled from Grove (2012a,b); Korinek (2013); Schmidt (2014).*

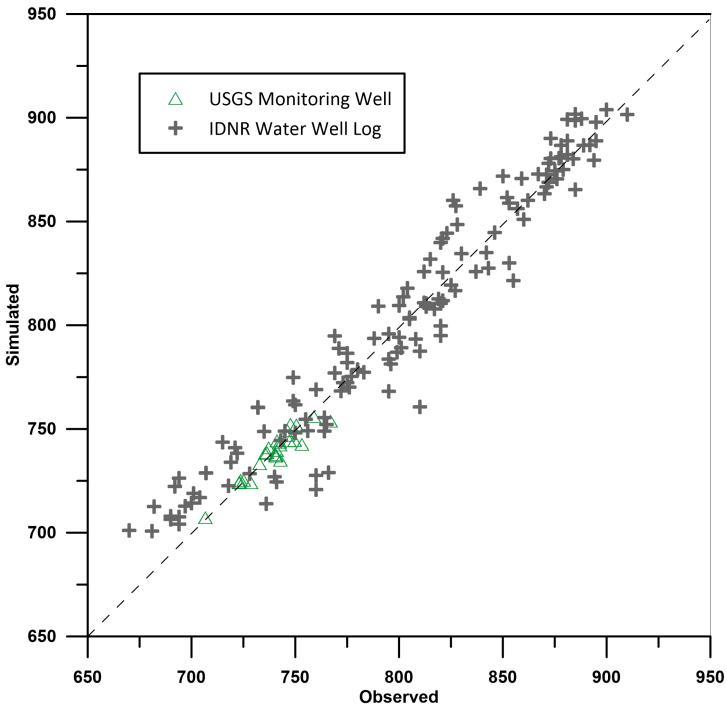

Figure 16.46: Simulated versus observed head values for the calibrated base model.

County in an area not affected by significant ground water withdrawals. Seepage rates are reduced where groundwater withdraws intercepts water that would otherwise discharge to the river. Meyer (1978) calculated a seepage inflow rate of 2.6 cfs/mile based on measurements in Hamilton County in October 1973 when the flow duration was 66% at the Nora gage. Meyer et al. (1975) calculated a seepage inflow rate of 2.5 cfs/mile over a longer reach of the river in November, 1974, when the flow duration was 69% at the Nora gage.

16.7 Water Budget

The model water budget for the base model is shown in Table 16.22. The water budget for the 2016-2018 predictive model is shown in Table 16.23. Background pumping includes pumping from significant water withdrawal facilities as discussed in Section 16.4.6. Mine withdrawals are represented as outflow from the recharge package, as described in Section 16.4.5.

16.8 Groundwater Accessibility

To estimate the amount of water than can be produced from existing public-supply wells, we performed a drawdown analysis based on the predictive scenario using the average 2016-2018 pumping rates (Section 16.4.6). The analysis accounts for available drawdown at each individual well combined with the aquifer drawdown predicted by the 2016-2018 scenario.

Aquifer drawdown was estimated at each public-supply well included in the scenario (Figure

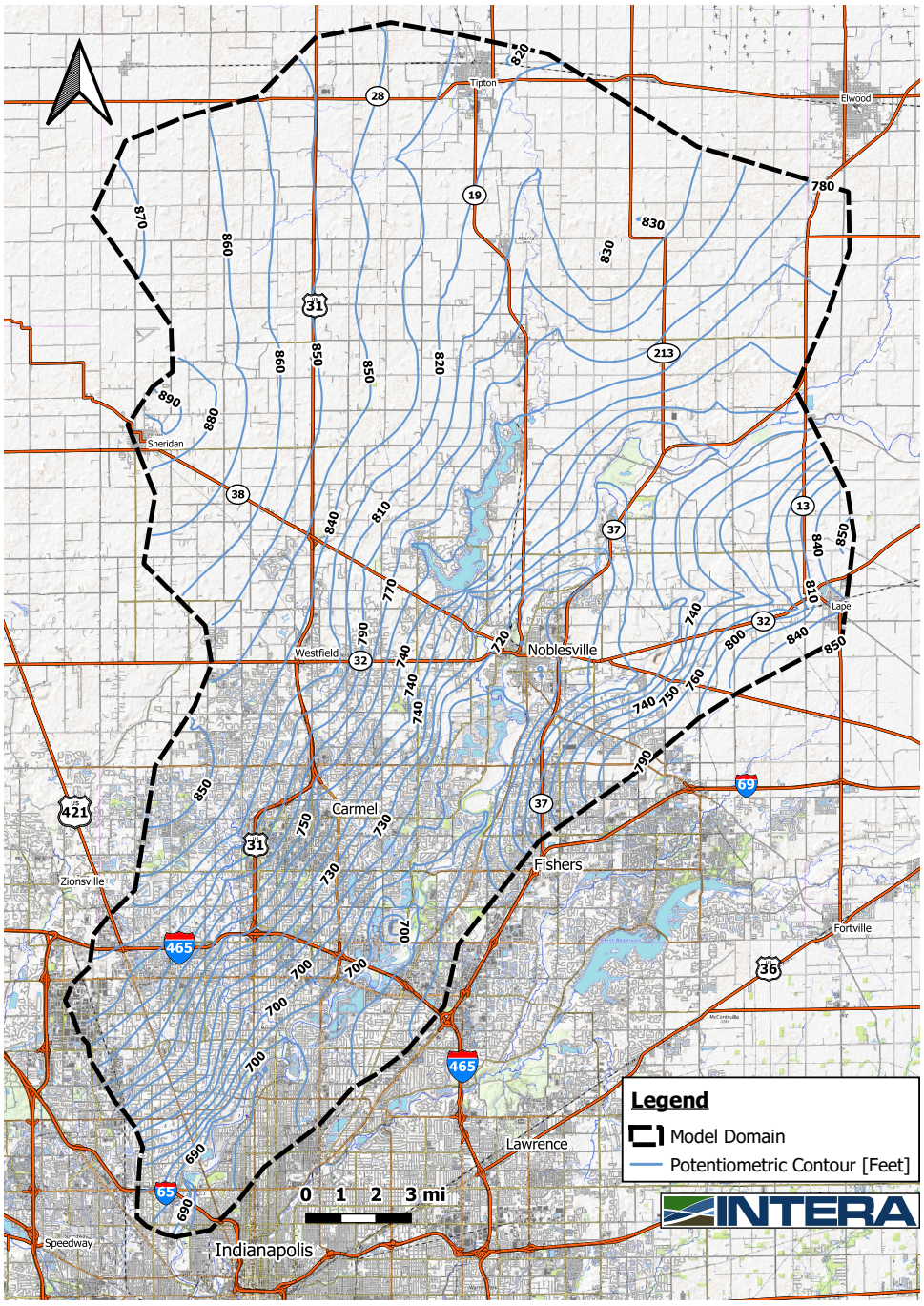

Figure 16.47: Predicted contours of hydraulic head from the calibrated base model.

Table 16.19: Summary of aquifer properties in the calibrated model.

Layer	Description	K_{zone} multiplier (–)	Transmissivity range (ft^2/day)	Median value (ft^2/day)
1	Outwash	150	343-21,650	7,140
1	Upland Till	100	630-6,000	3,020
1	Till	75	190-10,700	2,330
1	Till Veneer	15	161-1,160	420
2	Bedrock	5	500	-

Notes: ft^2/day = square feet per day.

Table 16.20: Conductivity values for eleven White River Reaches and modeled inflow seepage rates with no withdrawals.

Segment Name	Segment Reach (River Miles)	RIV Conductivity (ft/day)	Modeled Seepage Rate with No Withdrawals (cfs/mile)
White River 1	235.2-240.1	26	2.26
White River 2	240.1-242.5	16	3.26
White River 3	242.5-251.0	64	1.38
White River 4	251-252.1	28	2.61
White River 5	252.1-253.5	70	3.89
White River 6	253.5-261	19	2.27
White River 7	261-265.4	40	2.18
White River 8	265.4-266.95	48	3.12
White River 9	266.95-270.1	54	1.79
White River 10	270.1-273.15	20	1.56
White River 11	273.15-278.8	47	1.76

Notes: ft/day = feet per day. cfs = cubic feet per second

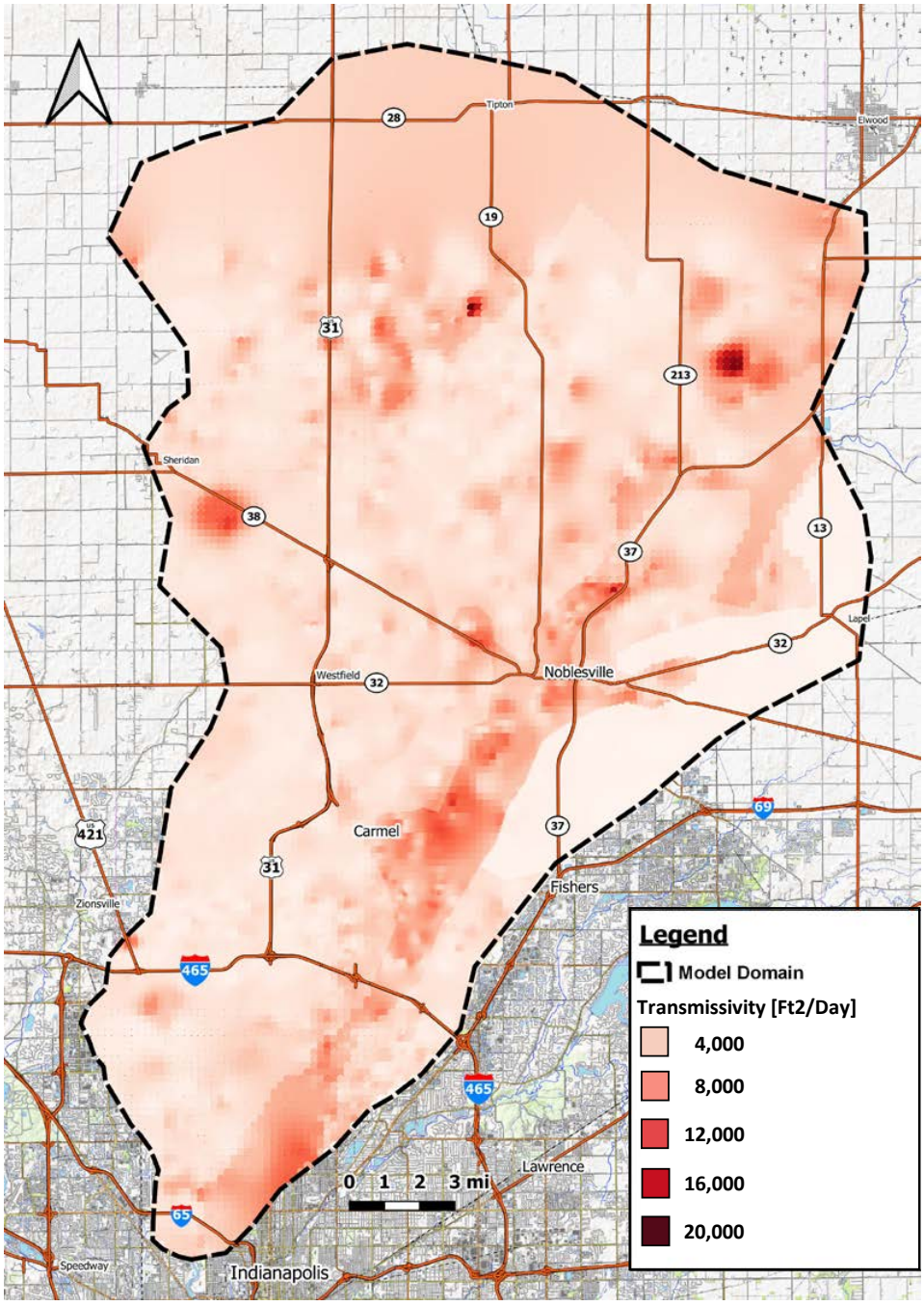

Figure 16.48: Distribution of transmissivity in model Layer 1.

Table 16.21: Conductivity values for other surface water features simulated as MODFLOW RIV cells.

Stream	Conductivity (ft/day)
Bear Creek	1
Cool Creek	10
Cool Creek	10
Crooked Creek	5
Cicero Creek	10
Duck Creek	25
Hinkle Ditch	0.5
Little Cicero	10
Mitchner Ditch	5
Morse Reservoir	10
Stony Creek	10
Vestal Ditch	5
Weasel Creek	10
Williams Creek	20

Notes: ft/day = feet per day.

Table 16.22: Water balance for calibrated model representing average 2009-2013 pumping rates.

	INFLOW (ft^3/day)	INFLOW (MGD)	OUTFLOW (ft^3/day)	OUTFLOW (MGD)
Wells	–	–	4,009,172	30.0
Recharge	11,453,665.	85.7	1,033,920.	7.7
River Leakage	3,902,865.	29.2	9,784,360.	73.2
Total	15,356,531.	114.9	15,343,773.	114.8

Notes: ft^3/day = cubic feet per day. MGD = million gallons per day.

INFLOW - OUTFLOW = 12,578 ft^3/day; Error = 0.08%

Table 16.23: Water balance for predictive scenario representing average 2016-2018 pumping rates.

	INFLOW (ft^3/day)	INFLOW (MGD)	OUTFLOW (ft^3/day)	OUTFLOW (MGD)
Wells	–	–	4,355,510	32.6
Recharge	11,453,665.	85.7	1,352,640.	10.1
River Leakage	4,493,281.	33.6	10,226,038.	76.5
Total	15,946,946.	119.3	15,343,773.	119.2

Notes: ft^3/day = cubic feet per day. MGD = million gallons per day.

INFLOW - OUTFLOW = 12,759 ft^3/day; Error = 0.09%

16.49). Drawdown is highest in the middle of the model domain between State Road 32 and I-465, where mining and public withdraws are concentrated. Note that drawdown at the Lapel public-supply wells near the eastern boundary is overestimated based on model construction. For simplicity, the boundary was derived from stagnation points predicted by the regional model and implemented as no-flow boundaries. In reality, pumping will induce flow across the boundary by moving the stagnation point. However, for the purpose of the drawdown analysis, this simplification is conservative.

Individual well characteristics were compiled to define an available drawdown at each well. The well characteristics shown in Table 16.24 are based on several sources. In general, the information was derived from well logs in the IDNR database (IDNR, 2020b), with land surface elevations derived from a USGS Digital Elevation Model (USGS, 2017). Where possible, IDNR database entries were supplemented with information supplied by the utilities, which was considered more accurate and up-to-date than the IDNR database. Carmel (Carmel, 2019) and INAWC (INAWC, 2019) provided characteristics for their wells, including surface elevation. Existing reports were used to supplement information on the Citizens and Westfield Wells, including reports related to the River Road (CEG, 2013) and Harbour Well Fields (Layne, 2014).

Due to lack of information, some characteristics were estimated based on surrounding wells, as noted in Table 16.24.

Additional capacity was conservatively estimated based on an accounting of available drawdown at each active well (Table 16.25). Remaining available drawdown was estimated by subtracting the predicted aquifer drawdown and the well drawdown from the available drawdown. The well drawdown calculation assumes that the well is operating at 80% of the reported design capacity and with the specific capacity degraded to 80% of the original. It is normal for the specific capacity to decrease through time as the screen and gravel pack foul and clog. Industry practice is generally to rehabilitate a well before the specific capacity degrades below 80% of the original. Wells with less than 20 ft of remaining available drawdown were not considered for additional production. Also, wells with reported average pumping rates that were greater than the reported capacity were not considered for additional production. Available capacity from the remaining wells was calculated from the remaining capacity, defined as the difference between the average 2016-2018 rates and 60% of the design rate. Using a higher rate than 60%, resulted in excessive interference and additional drawdown greater than 10 ft at nearby wells with limited available drawdown.

The estimated additional capacity is summarized in Table 16.26 and compared to the average 2016-2018 rates. The estimated increase in average production from active public-supply wells is 14.3 MGD, resulting in a total production of 43.5 MGD. This value can be compared to the projected demand for groundwater production in the model domain. The estimated total average production from public-supply wells is comparable to the projected average demand for 2035 (41.6 MGD) (Table 16.27). However, the average total production is far short of the average Quarter 3 projected demand of 61.9 MGD and below the average projected demand in 2070.

16.9 Meeting the future demand for groundwater

Based on the drawdown analysis, new well sites will be needed to meet projected demand in the region defined by the model domain. New well sites will need to be strategically placed and should induce recharge of White River water, if possible. Induced recharge is the only way to significantly increase production from the wells in the heavily used corridor between Noblesville and I-465. Table 16.28 shows the modeled water budget for the 2016-2018 conditions for three reaches of the White River (Figure 16.50):

- Reach 1 – From the State Road 32 at the top of the model domain to Noblesville
- Reach 2 – From Noblesville to I-465
- Reach 3 – From I-465 to the bottom of the model domain just below I-65

Based on a comparison of the modeled water budgets for the White River for a no-pumping scenario and the predictive scenario using average 2016-2018 withdrawal rates, a majority of

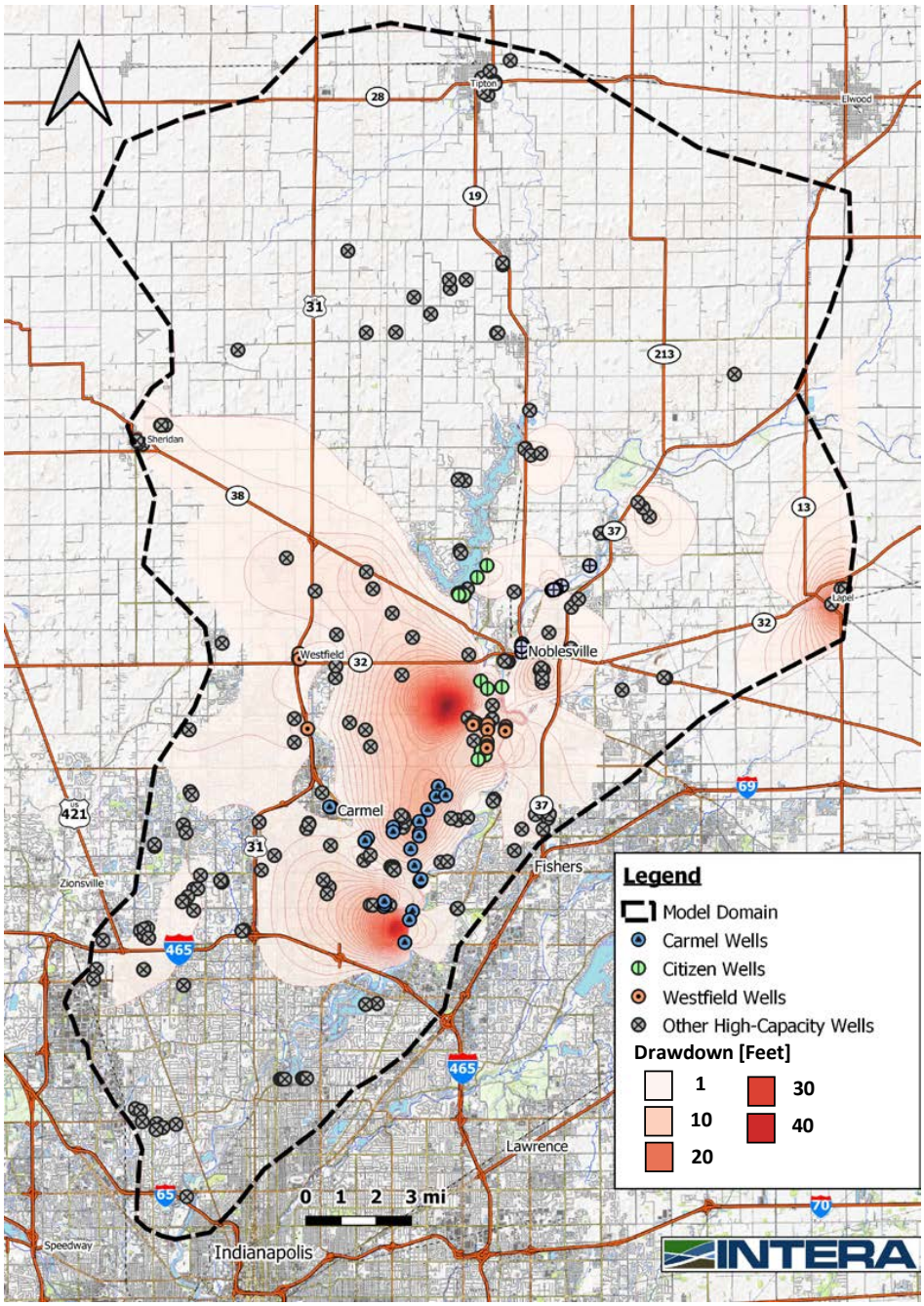

Figure 16.49: Drawdown based on the predictive scenario using average 2016-2018 rates.

the water withdrawn in Reach 2 is intercepted groundwater, approximately 14 MGD, with approximately 8 MGD being induced from the White River. The water budget suggests that the potential for intercepting significantly more ground water on its way to the river is limited.

16.10 Summary

The MODFLOW inset model was constructed to examine groundwater conditions in a critical resource area and assess the need for additional groundwater infrastructure to support expansion of the water supply system. Additional capacity was conservatively estimated based on an accounting of available drawdown at each active public supply well. Based on model development and the results of the drawdown analysis, we conclude:

- The USGS monitoring well network that it operates with cooperators in the Hamilton County is extremely valuable for monitoring and assessing the resource. However, the network is spatially limited. More monitoring sites with a greater spatial distribution are needed for informed resource management.
- The current state for reporting mine withdrawals and discharges creates uncertainty regarding the source aquifer, the location of withdrawals, and how much water is consumed.
- The drawdown analysis results suggest that existing infrastructure has limited capacity to meet future projected demands. New well sites will be needed to increase production from wells.
- New well sites in the corridor between Noblesville and I-465 are limited by what can ultimately be intercepted on its way to river. Strategies to increase production from wells in this reach must include induced infiltration of river water, where possible. A suitable radial collector well site located near the river between 146th street and 116th street could maximize any increase in production from wells in this reach.

Table 16.24: Characteristics of public-supply wells.

Facility	Well Source ID	Aquifer	Elevation (feet)	Total Depth (feet)	Screen Depth (feet)	Static Water Level (feet)	Available Drawdown (feet)	Specific Capacity (gpm/ft)	Capacity (gpm)
CMW	5	SG	770.0	63	47	5	42	37.7	753
CMW	6	SG	775.0	60	47	4	43	82.3	987
CMW	7	SG	790.5	92	46	28	18	119.8	1078
CMW	8	SG	791.6	90	48	30	18	65.0	812
CMW	9	SG	754.1	83	48	6	42	129.6	920
CMW	27	LS	729.0	78	53	14.7	38.3	66.5	1,808
CMW	28	LS	727.0	76.5	51.5	12.3	39.2	97.3	2,850
CMW	10	SG	744.3	58	38	13	25	127.8	703
CMW	22	SG	745.0	68	55	15	40	60.6	1,400
CMW	30	SG	735.0	92	68	13.3	54.7	78.1	2,500
CMW	13	SG	757.0	84	67	7	60	83.9	1,300
CMW	14	SG	767.0	110	73	6	67	88.0	1,500
CMW	15	SG	757.0	94	71	10	61	50[E]	200
CMW	16	SG	752.0	100	81	14	67	45.2	1,250
CMW	17	SG	768.0	117	88	17	71	87.1	1,500
CMW	18	SG	757.0	93	65	13	52	101.8	3,002
CMW	19	SG	755.0	78	62	13	49	37	1,803
CMW	20	SG	733.0	101	70	16	54	131	2,778
CMW	21	SG	770.0	107	82	16	66	50[E]	2,000
CMW	23	SG	735.0	96	70	29	41	111	2,448
CEG	1	SG	771.6	80	60	32	28	20[E]	300
CEG	7	SG	808.5	117	67	15[E]	52[E]	21.4	900
CEG	10	SG	769.0	66	68	14.5	53.5	20[E]	400
CEG	11	SG	817.2	65	142	15[E]	127[E]	20[E]	900
CEG	5R	SG	763.1	63	46	15[E]	31[E]	20[E]	600
CEG	WRN 1	SG	749.5	130	93	14.8	78.2	45	1,600
CEG	WRN 2	SG	759.3	130	106.5	22.9	83.6	45	1,500
CEG	WRN 3	SG	755.2	131.5	96	23.75	72.25	75	1,500

gpm = gallons per minute; SG = Sand and Gravel; LS = Limestone

CMW = Carmel Municipal Water; CEG = Citizens Energy Group; CWW = Citizens Water Westfield

INAWC = Indiana American Water Company; LMU = Lapel Municipal Utility; TCU =Town of Cicero Utilities

AWD = Arcadia Water Department; AtWD = Atlanta Water Department

Table 16.24: Characteristics of public-supply wells.

Facility	Well Source ID	Aquifer	Elevation (feet)	Total Depth (feet)	Screen Depth (feet)	Static Water Level (feet)	Available Drawdown (feet)	Specific Capacity (gpm/ft)	Capacity (gpm)
CEG	WRN 4	SG	750.1	127	76	17.2	58.8	44	1,145
CEG	WRN 5	SG	752.5	106.5	187	21	166	19	1,210
CEG	WRN 6	SG	759.7	206	81.7	26	55.7	7	400
CEG	WRN 7	SG	742.5	181	150[E]	25[E]	125[E]	7	1,400
CWW	5	SG	765.1	78	55	16.5	38.5	63	1,400
CWW	6	SG	765.8	75.5	52	17.5	34.5	63	1,400
CWW	7	SG	764.7	72	50	17.5	32.5	56	1,400
CWW	8	SG	754.4	98	48	8.9	39.1	90	2,100
CWW	9	SG	750.8	92	62	11.8	50.2	117	2,100
CWW	10	SG	750.4	97	55	9	46	76	2,100
CWW	11	SG	769.4	84	62	25.3	36.7	59	1,800
CWW	12	SG	764.6	78	56	23.3	32.7	41	1,200
CWW	13	SG	759.9	85	60.5	14.7	45.8	27	1,000
CWW	14	SG	748.1	76	56	12.1	43.9	77	1,000
CWW	15	SG	752.6	76	56[E]	12[E]	44[E]	77[E]	1,397
CWW	16	SG	750.9	76	56[E]	12[E]	44[E]	77[E]	1147
CWW	4	SG	898.1	127	125[E]	28.1	96.9[E]	4.3[E]	175
INAWC	2	SG	756.1	61	50[E]	11.1	38.9[E]	20[E]	486
INAWC	4	SG	948.6	158	158	45	113	15[E]	500
INAWC	5	SG	937.2	117.5	117.5	32	85.5	17.3	500
INAWC	6	SG	947.6	137	137	51	86	15[E]	500
INAWC	1	SG	758.0	71	71	21	50	142	2,000
INAWC	2	SG	758.6	80	49	6	43	51.7	880
INAWC	3	SG	756.9	78	64	21.7	42.3	68.8	726
INAWC	4	SG	758.7	103	68	18.3	49.7	34.2	760
INAWC	5	SG	757.5	72	62.3	18.7	43.63	31.8	700
LMU	FORD	LS	858.1	201	150[E]	25[E]	125[E]	5[E]	220
TCU	1	SG	838.5	115	98[E]	25[E]	73[E]	20[E]	500

gpm = gallons per minute; SG = Sand and Gravel; LS = Limestone

CMW = Carmel Municipal Water; CEG = Citizens Energy Group; CWW = Citizens Water Westfield

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Table 16.24: Characteristics of public-supply wells.

Facility	Well Source ID	Aquifer	Elevation (feet)	Total Depth (feet)	Screen Depth (feet)	Static Water Level (feet)	Available Drawdown (feet)	Specific Capacity (gpm/ft)	Capacity (gpm)
TCU	2	SG	838.6	107	98[E]	25[E]	73[E]	20[E]	480
TCU	3	SG	832.1	108	98	25.5	72.5	20[E]	600
TCU	4	SG	827.7	115	98	21	77	20[E]	500
AWD	1	LS	865.3	250	137	27	110	7.21	300
AWD	2	LS	866.9	250	137	30[E]	107[E]	6.60	300
AtWD	2	SG	857.5	90	81	12	69	20[E]	80
AtWD	4	SG	857.1	130	112	11	101	5[E]	225

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AWD = Arcadia Water Department; AtWD = Atlanta Water Department

Table 16.25: Drawdown Analysis.

Facility	Well Source ID	Average '16-'18 Rate	Well Draw-down at Capacity	Aquifer Drawdow-nat '16-18 Rates	Remaining Available Draw-down	Remaining Capacity assuming 60% Usage	Additional Pumpage
		(gpm)	(feet)	(feet)	(feet)	(gpm)	(gpm)
CMW	5	170.8	20.0	6.1	<20	281	0
CMW	6	320.6	12.0	6.3	24.7	272	272
CMW	7	175.0	9.0	10.5	<20	472	0
CMW	8	66.1	12.5	10.3	<20	421	0
CMW	9	105.0	7.1	14.7	20.2	447	447
CMW	27	780.7	27.2	4.3	<20	304	0
CMW	28	578.7	29.3	5.0	<20	1131	0
CMW	10	286.8	5.5	19.8	<20	135	0
CMW	22	478.1	23.1	18.8	<20	362	0
CMW	30	740.9	32.0	10.4	<20	759	0
CMW	13	782.5	15.5	15.9	28.6	0	0
CMW	14	499.2	17.0	14.6	35.4	401	401
CMW	15	133.4	4.0	9.7	47.3	0	0
CMW	16	56.2	27.7	5.3	34.1	694	694
CMW	17	590.6	17.2	15.4	38.4	309	309
CMW	18	614.9	29.5	16.3	<20	1186	0
CMW	19	234.0	48.7	11.9	<20	848	0
CMW	20	481.2	21.2	7.1	25.7	1186	1186
CMW	21	343.0	40.0	13.6	<20	857	0
CMW	23	917.2	22.1	18.8	<20	552	0
CEG	1	47.5	15.0	1.1	<20	133	0
CEG	7	448.5	42.1	4.6	<20	91	0
CEG	10	20.0	20.0	1.2	32.3	220	220
CEG	11	506.1	45.0	7.3	74.7	34	34
CEG	5R	167.8	30.0	1.8	<20	192	0
CEG	WRN 1	804.1	35.6	8.2	34.5	156	156

gpm = gallons per minute; SG = Sand and Gravel; LS = Limestone

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[1] *Assumes 80% design capacity, 60% specific capacity;* [2] *Assumes 60% design capacity*

Table 16.25: Drawdown Analysis.

Facility	Well Source ID	Average '16-'18 Rate	Well Draw-down at Capacity	Aquifer Drawdow-nat '16-18 Rates	Remaining Available Draw-down	Remaining Capacity assuming 60% Usage	Additional Pumpage
		(gpm)	(feet)	(feet)	(feet)	(gpm)	(gpm)
CEG	WRN 2	892.5	33.3	8.2	42.1	7	7
CEG	WRN 3	777.7	20.0	8.3	44.0	122	122
CEG	WRN 4	283.1	26.0	5.8	27.0	404	404
CEG	WRN 5	104.5	63.7	4.3	98.0	622	622
CEG	WRN 6	30.2	57.1	1.6	<20	210	0
CEG	WRN 7	225.6	70.0	7.3	47.7	614	614
CWW	5	259.9	22.2	8.1	<20	580	0
CWW	6	264.7	22.2	10.0	<20	575	0
CWW	7	389.1	25.0	9.7	<20	451	0
CWW	8	485.2	23.3	8.0	<20	775	0
CWW	9	660.6	17.9	8.1	24.1	599	599
CWW	10	503.5	27.6	8.1	<20	757	0
CWW	11	371.7	30.5	7.7	<20	708	0
CWW	12	223.7	29.3	7.6	<20	496	0
CWW	13	144.4	37.0	7.6	<20	456	0
CWW	14	215.8	13.0	7.0	23.9	384	384
CWW	15	220.2	18.1	7.0	<20	618	0
CWW	16	163.1	14.9	6.3	22.8	525	525
CWW	4	205.9	41.0	4.4	51.5	0	0
INAWC	2	686.1	24.3	4.6	<20	0	0
INAWC	4	2.6	33.3	4.5	75.2	297	297
INAWC	5	101.7	28.9	4.5	52.1	198	198
INAWC	6	52.2	33.3	4.5	48.2	248	248
INAWC	1	1903.9	14.1	9.9	26.0	0	0
INAWC	2	55.5	17.0	9.6	<20	472	0
INAWC	3	118.5	10.6	4.6	27.1	317	317

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[1] *Assumes 80% design capacity, 60% specific capacity;* [2] *Assumes 60% design capacity*

Table 16.25: Drawdown Analysis.

Facility	Well Source ID	Average '16-'18 Rate	Well Draw-down at Capacity	Aquifer Drawdow-nat '16-18 Rates	Remaining Available Draw-down	Remaining Capacity assuming 60% Usage	Additional Pumpage
		(gpm)	(feet)	(feet)	(feet)	(gpm)	(gpm)
INAWC	4	103.1	22.2	2.4	25.1	353	353
INAWC	5	85.2	22.0	2.0	<20	335	0
LMU	FORD	138.2	44.0	25.1	55.9	0	0
TCU	1	53.4	25.0	3.1	44.9	247	247
TCU	2	59.0	24.0	2.9	46.1	229	229
TCU	3	120.1	30.0	3.9	38.6	240	240
TCU	4	66.2	25.0	3.1	48.9	234	234
AWD	1	0.0	41.6	0.8	67.6	180	180
AWD	2	0.1	45.5	0.8	60.7	180	180
AtWD	2	0.0	16.0	0.7	52.3	48	48
AtWD	4	0.0	45.0	0.7	55.3	135	135

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AWD = Arcadia Water Department; AtWD = Atlanta Water Department

[1] *Assumes 80% design capacity, 60% specific capacity;* [2] *Assumes 60% design capacity*

Table 16.26: Results of drawdown analysis and comparison to average 2016-2018 rates.

Utility	Average Pumping Rate 2016-2018 (MGD)	Potential Increase based on Drawdown Analysis (MGD)	Total Potential Rate (MGD)
Carmel	12.0	4.8	16.8
Citizens Westfield	5.9	3.1	9.3
Citizens Water	6.2	2.2	8.1
Indiana American Water	4.5	2.0	6.5
Other Public Supply	0.6	2.1	2.8
Total	**29.3**	**14.3**	**43.5**

Notes: MGD = million gallons per day.

Table 16.27: Projected demand for groundwater production within the model domain.

Scenario	Q1 Average (MGD)	Q2 Average (MGD)	Q3 Average (MGD)	Q4 Average (MGD)	Annual Average (MGD)
Projected 2035	29.2	42.4	61.9	33.0	**41.6**
Projected 2070	36.6	54.9	77.7	41.4	**52.7**

Notes: MGD = million gallons per day.

Table 16.28: Water balance for three main reaches of the White River in the model domain.

Reach	Description	No Withdrawals		Average 2016-2018 Rates	
		INFLOW (MGD)	OUTFLOW (MGD)	INFLOW (MGD)	OUTFLOW (MGD)
1	State Rd 13 to Noblesville	0.0	19.5	2.0	16.5
2	Noblesville to I-465	0.03	21.7	8.5	7.89
3	I-465 to I-65	0.14	16.7	0.14	16.9

Notes: MGD = million gallons per day.

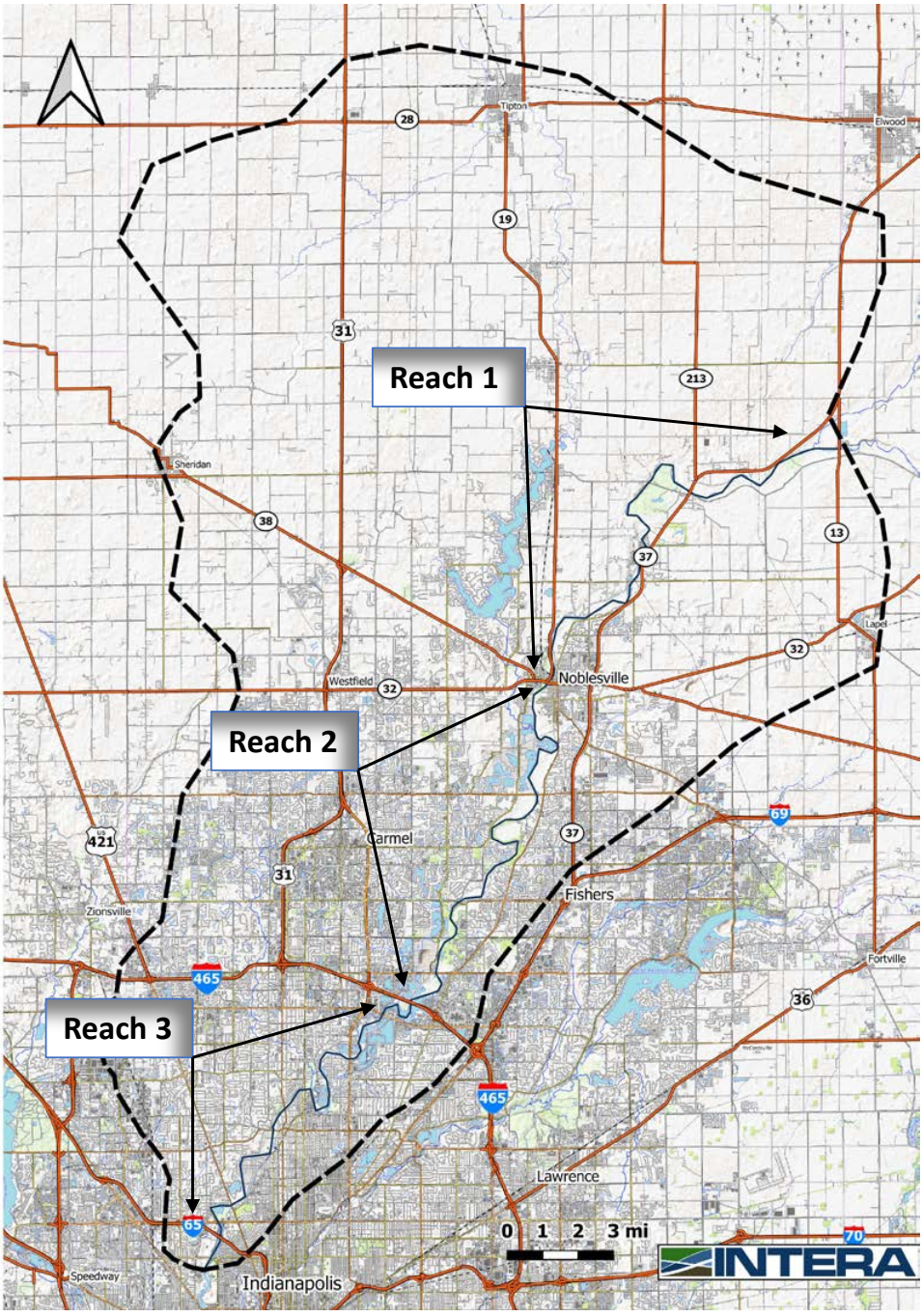


Figure 16.50: White River water balance reaches

17 Summary of Groundwater Modeling Results

A groundwater modeling study was conducted specifically to evaluate capacities of existing water supply wellfields, and assess the potential for increasing the yield of the wellfields to meet future, projected demands. The modeling followed a step-wise process consisting of the following steps:

1. **Regional flow modeling:** regional models were developed, and spatially-varying recharge rates were calibrated to match Quarter 3 natural streamflow, developed in Part I of this report. The regional models are developed with GFLOW software and represent steady state, low-flow conditions. The purpose of the regional models is to constrain the groundwater inputs to the sub-regional models to represent low-flow conditions.

2. **Sub-regional flow modeling:** the regional models were refined locally to assess groundwater accessibility at existing wellfields. The sub-regional models were developed with GFLOW software by refining surface water and outwash features in the regional model. Wellfields that were investigated include the Geist and City of Lawrence wellfields, and the Speedway wellfield. Individual water supply wells in each wellfield are tested under current and future Quarter 3 demands, using public information to define well characteristics.

3. **Inset modeling:** an inset model was extracted from a sub-regional GFLOW model. The inset model was then further refined using MODFLOW software. The inset model includes variable aquifer thickness, continuously varying aquifer transmissivities, and a model layer representing the bedrock. The inset model is focused in Hamilton County, where demand for water is growing rapidly. The inset model was used to investigate the effects of mining on groundwater accessibility and to project capacities of the existing groundwater infrastructure.

The regional flow modeling demonstrates that the hydrologic system in the Central Indiana region is dominated by surface-water features; model calibration to regional target heads obtained from well records is largely futile. In the regional model we instead focus on calibration of groundwater discharges to estimates of natural baseflow. Calibration to natural baseflow provides a consistent regional framework within which more detailed models can be created without disrupting the regional water balance.

Results of the sub-regional flow modeling at the Geist and Lawrence wellfields indicate that groundwater accessibility using the existing wells will not meet projected 2070 demands. However, there appears to be potential for greater accessibility than required for the current demand. The potential increased yield can be achieved by cooperation between Citizens Water and the City of Lawrence in managing their combined wellfields. Modeling results for the Town of Speedway wellfield along Eagle Creek, where current and future demands are significantly smaller than at the Geist wellfield, indicate that the existing Speedway wells will be adequate

to meet future demands, and that the outwash aquifer may support additional withdrawals beyond the 2070 demand. In the cases examined here, the accessibility models were based on refinements to regional models, and publicly available information regarding well characteristics. Site-specific field testing to evaluate aquifer and streambed properties and detailed construction information for the wells and pumping systems are necessary to refine the predictive modeling presented here.

The MODFLOW inset model was constructed to examine groundwater conditions in a critical resource area and assess the need for additional groundwater infrastructure to support expansion of the water supply system. Additional capacity was conservatively estimated based on an accounting of available drawdown at each active public supply well. Model results indicate that the existing infrastructure has limited capacity to meet future projected demands. New well sites will be needed to increase production from wells. Further, the capacities of water supply wells in the region are likely impacted by the large mines operating near the White River.

Part IV
Summary of Work and Findings

The major product of this study is the development of a water-availability model for the Central Indiana region. The model is data driven with a quarterly temporal resolution. This model was used to identify spatial and temporal variations in water availability in the Central Indiana region from 2007-2017. That period of record includes both years of high precipitation and streamflow (2011) and low precipitation and streamflow (2007, 2012) and provides a basis for investigating the natural variability in hydrologic conditions. The water-availability model was combined with the results of the Phase I Demand Study (IFA, 2020) and estimates of future return flows to project future water availability to 2070. Critical sub-basins with deficits in excess availability have been identified, and the effects of future demands on those deficits have been assessed.

The water-availability model is nuanced, and some terms with specific meaning were developed to help differentiate the components of the water budget. Each sub-basin has unique hydrologic features, both natural and man-made, that impact water availability, excess availability and cumulative availability. The sub-basin maps and graphs in Appendix B provide the most concise information for understanding the results of the availability assessment on the sub-basin scale. They present the relative magnitudes of the components of Quarter 3 excess availability and the temporal variation in excess availability in a sub-basin, as well as the cumulative excess availability for the period 2007-2017.

In addition to development of the water-availability model, a review of water quality in the region, based on existing data, has been made. The investigation considers water quality impacts on water availability.

Finally, an assessment of groundwater accessibility is made using groundwater flow models at various scales to investigate local and regional phenomena. The models are used, primarily, to investigate the adequacy of the existing groundwater infrastructure for meeting future demands during low-flow conditions.

Substantial field work, hydrologic analysis, geological analysis, and mapping was performed in support of the water-availability model and groundwater flow models. That work is presented in detail in the Appendices to this report. Appendix C presents the development and extension of a Soil-Water-Budget (SWB) model to investigate spatial and temporal variations in aquifer recharge. The SWB model was used as a tool in developing and validating components of the water-availability model.

Appendix D presents the development and use of a solids model of the geology of the Central Indiana region. The model is developed with Leapfrog software, by assembling existing geologic data sets into a single, consistent, three-dimensional framework. The model is particularly useful for exploring the local connectivity of unconsolidated sand and gravel lenses, and directing

field studies to collect new information. The geologic model was used to develop conceptual models for the regional groundwater flow models and more detailed conceptual models of the unconsolidated materials for the local-scale groundwater flow models.

Finally, Appendix E presents results of an extensive field study to investigate the local connections between groundwater and surface water. The study includes installation of 16 streambed piezometers instrumented with temperature and pressure probes. The instruments were monitored for a period of three months. Conditions at the monitors are driven by pumping of nearby water-supply wells and flow conditions in the rivers in which they are installed. The diurnal temperature variations recorded by the probes were analyzed to estimate infiltration or exfiltration rates at the streambed. The results provide valuable insights into local connections between groundwater and surface water, and hydraulic properties of streambed sediments.

18 Current Water Availability in Central Indiana

Water availability throughout the Central Indiana region is limited by seasonal low flows that usually occur in the late summer and fall. The natural hydrologic conditions are characterized by lower baseflow in Quarters 3 (July through September) and 4 (October through December); Quarters 1 (January through March) and 2 (April through June) are characterized by relatively large natural baseflow in streams, with net excess availability in most sub-basins. Temporal variations in water demand and returns at wastewater treatment plants are also characterized by relatively large withdrawals and relatively low returns during Quarter 3. Therefore, throughout this report, Quarter 3 is defined as the critical period for evaluating excess water availability. For the period of record (2007-2017), the critical year for excess water availability varies by sub-basin, with 2007, 2009 and 2012 being the most frequent critical years. 2012 represents the critical year for cumulative excess availability in the region.

Throughout the region, excess water availability in the driest months depends upon the discharges from permitted wastewater treatment plants upstream. The public water supply in Central Indiana relies on ***indirect water reuse***. Discharge from wastewater treatment plants is as important to maintaining availability as is the natural baseflow. This conclusion is consistent with recent studies of water re-use in the Wabash River watershed (Wiener et al., 2016, 2020), and has implications for projecting water availability into the future (Section 6): increases in future demand in the Public Supply sector are largely offset by increases in discharge from wastewater treatment plants.

Finally, availability of water in the state is not limited by any current regulation of instream flow levels. The IDNR recommends a minimum instream flow equal to the $Q_{7,10}$. In the White River drainage system, with large anthropogenic effects on streamflow, the $Q_{7,10}$ is more a reflection of past water withdrawal and returns than it is a measure of ecological health of the River. In this study, the annual Q_{90} is used as a default value for instream flow in Quarters 1 and 2, and the $Q_{7,10}$ is used in the critical Quarters 3 and 4. Increasing the instream flow

requirements will directly decrease excess water availability.

Variations in excess water availability occur in the three major drainage systems in the region. Characteristics of each drainage system are described below.

18.1 White River and Tributaries

The White River and tributaries drainage system is characterized by locally large water withdrawals for public supply and power generation, focused in Marion and Hamilton Counties. Similarly large return flows occur at major wastewater treatment plants, with large withdrawals and returns typically occurring in adjacent basins. Sub-basins with deficits in Quarter 3 excess availability include Sub-basin 5 (Noblesville through Nora region), Sub-Basin 7 (Geist Reservoir and downstream reaches of Fall Creek), Sub-basin 8 (Indianapolis region), Sub-basin 10 (Eagle Creek from the reservoir through Speedway) and Sub-basin 13 (South Indianapolis through Centerton).

Sub-basin 5 in Hamilton County has a deficit in excess availability, due primarily to extreme summer demands for public supply, low summer return flows at wastewater treatment plants, and dewatering of two quarries operated by Martin Marietta. Sub-Basin 8 in Marion County includes large withdrawals by Citizens Water for public supply; major return flows from the Belmont Advanced Wastewater Treatment Plant occur in the adjacent downstream sub-basin (11), which is characterized by large excess availability.

Results show that when full use of the available storage in Morse and Geist Reservoirs is made, deficits in Sub-basins 5 and 7 are greatly reduced, or eliminated.

18.2 Tributaries of the Wabash River

The tributaries of the Wabash River drainage system is characterized by small water withdrawals, small return flows, and large variation in natural baseflow. In the period 2007-2017, excess water availability has been very low in each sub-basin, but has not been negative. However, there is little room for increasing the water supply in this region due to frequent periods of low baseflow.

18.3 East Fork White River and tributaries

The East Fork of the White River and tributaries drainage system is also characterized by small water withdrawals, small return flows, and large variation in natural baseflow. In the period 2007-2017, excess water availability has been very low in each sub-basin, and has become negative in two downstream sub-basins. The negative values are due to periods of extremely low to zero natural baseflow, rather than excessive anthropogenic effects (withdrawals and returns). Sub-basins 5 and 8 (Greenfield through Columbus) in Shelby and Franklin Counties have negative excess availability, due primarily to the operation of irrigation wells in the downstream

reaches of each basin. In both cases, most withdrawals for public supply occur upstream in the basins.

18.4 Cumulative Excess Availability

Despite several sub-basins with deficits in excess availability, minimum Quarter 3 cumulative excess availability has been positive for the period of record, 2007-2017, in the entire Central Indiana region. This highlights the fact that informal transfers of excess water between sub-basins is an important feature of the regional water supply system, as it exists today. The water supply for both Hamilton and Marion Counties depends, in part, on excess water availability in upstream sub-basins.

19 Future Water Availability in Central Indiana

The evaluation of 2007-2017 excess water availability and cumulative excess availability presented in Section B is a well-defined problem with few assumptions; in contrast projecting excess water availability into the future requires many assumptions, each with potentially large impacts on results. The assumptions and limitations on projected availability discussed above must be fully understood to properly interpret the results presented in this report.

The Phase I Demand Study (IFA, 2020) predicts an increase in total water withdrawals in the Central Indiana region of 111 MGD over current levels by 2070. This does not result in an equal decrease in excess or cumulative excess water availability, as in most sub-basins, increased withdrawals are offset by increased returns. A major exception occurs in Sub-basin 5 of the White River drainage system in Hamilton County, where the relationship between public supply withdrawals and return flow at wastewater treatment plants is unique in the Central Indiana region. The average Quarter 3 ratio of return flows at wastewater treatment plants (23 MGD) to public supply withdrawals (50 MGD) is 0.46, which is significantly smaller than other regions. There is an average of 27 MGD in the third quarter that is withdrawn for public supply, but not returned at wastewater treatment plants, suggesting that it is used for lawn watering. Hamilton County is the fastest growing region in terms of water demand, so current excess availability deficits seen in the area are exacerbated by future demands. Large projected increases in withdrawals for public supply in Sub-basin 8 (Marion County) are offset by large increases in return flows at Belmont and Southport Advanced Wastewater Treatment Plants in Sub-basins 11 and 13. Minimal population growth and therefore small increases in withdrawals for public supply are expected in the other major drainage regions (tributaries of the Wabash River and East Fork White River and tributaries).

The proposed operation of Citizens Reservoir has a significant positive impact on water availability in the future, as seen as a net increase in availability in Sub-basin 7 of the White River drainage system during Quarter 3. This also increases the cumulative excess availability in Sub-basin 11.

Instream flows and natural baseflow are assumed to remain the same as the 2007-2017 period. Changes to either will directly impact the estimates of future water availability presented here. Climate change has the potential to have a much larger impact on water availability in the Central Indiana region than increasing demand. Increasing annual precipitation and increasing summer temperatures have been observed in climatological records, with trends expected to continue into the future. Translation into changes in watershed processes, however, is a problem that is unresolved. It is unclear whether utilities should plan for decreasing water availability or increasing availability due to climate change impacts on the Central Indiana region. Recent decades have seen increasing streamflow and baseflow in the region. The use of natural baseflows calculated for the 2007-2017 period in estimates of future water availability assumes that the observed increases in that period relative to long-term averages, continue into the future.

20 Water Quality Impacts on Current and Future Water Availability

The water quality issues faced in the Central Indiana region are typical of most suburban to urbanized settings. Ambient groundwater quality in the Central Indiana region is well-characterized by the ongoing statewide monitoring activities conducted by the Groundwater Section of IDEM. The assessment of regional groundwater quality, based on current IDEM data, does not limit the potential sources for groundwater supply for a large water utility. While several constituents occur at levels greater than the MCL, most can be removed by standard treatment to provide a potable water supply. The mapping of ambient groundwater quality prepared by IDEM (2016), and the mapping presented here, provide guidance for identifying or eliminating potential sources for smaller utilities and domestic supplies, where standard treatment costs may be prohibitive. These results provide a guide for groundwater quality only. Any natural, or ambient water quality issues must be dealt with on a case-by-case basis, with detailed site investigations, to determine the actual impacts on groundwater availability.

Groundwater contamination from historic contaminant releases poses a larger threat to groundwater supply, accessibility and availability in the Central Indiana region than ambient conditions. A potential contaminant source inventory was conducted here to address this concern. The inventory suggests that impacts to groundwater availability are primarily of concern in Marion County, where many potential and actual contamination sources exist. Contaminant plumes are monitored and tracked through individual state and federal enforcement actions, but there is currently no way to readily access and map all plume data to determine regional impacts to water availability. The potential contaminant source mapping alone accounts for over 11% of the surface area of the outwash deposits in Marion County, which are the primary source of groundwater supply in the county. Substantially more area is covered by known contaminant plumes, but those areas remain un-mapped on a regional scale. No changes in the water availability model were made to account for historic contaminant releases. Again, these

results provide a guide for groundwater quality only. Any historic contaminant releases must be dealt with on a case-by-case basis, with detailed site investigations, to determine the actual impacts on groundwater availability.

An overview of surface water quality in the region is provided by the current federal 303(d) listing of impaired waterways, which shows most major rivers and streams in the region to be impaired by a large range in chemical, bacterial, and biological parameters. Surface-water quality in the past has been impacted by combined sewer overflows; conditions in Marion County will improve significantly with the operation of the deep tunnel interceptor. In addition, major reductions in withdrawal and return of non-contact cooling water by the energy sector will result in improved water quality. As discussed in Section 3.4, wastewater treatment plant effluent is indirectly used for water supplies throughout the region. Compliance with water quality requirements for wastewater plant effluent is necessary for maintaining and improving surface water quality and providing downstream potable water supplies.

21 Groundwater Accessibility

Groundwater flow modeling confirms that groundwater production is limited by existing groundwater infrastructure, even in sub-basins where future excess availability exceeds projected demands. Modeling of the Geist wellfield suggests that locally, groundwater supplies can be increased significantly over current use, but more detailed field testing must be conducted to accurately assess the maximum yield from the outwash aquifer. At the Geist wellfield, maximizing the yield from the aquifer along with optimal releases from Citizens Reservoir, will requires collaboration between the two utilities using the aquifer to manage the resource. Detailed modeling in Hamilton County shows that existing infrastructure can support groundwater production at higher rates than currently demanded, but falls short of projected 2070 demands. This means that new wellfields will be required to meet future demands. The regional outwash aquifer is the only source for high-capacity wells, and in many areas it is already heavily used. Alternatives to expanding groundwater capacity include developing increased surface water intake capacity, and importing water from outside the Central Indiana region.

The detailed study of Hamilton County also confirms the importance of the Martin Marietta mines on water availability and groundwater accessibility. A more thorough understanding of the mining operations, active lifespan, and water use are needed to improve predictions of future groundwater conditions in the region.

22 Recommendations

Water resources and water availability in Central Indiana have been investigated on an irregular basis, beginning with a statewide inventory in 1980 (IDNR, 1980). This assessment was followed in 2002 with a groundwater availability study of the White River Basin (IDNR, 2002), and in 2010 with an investigation of Central Indiana's regional water supply (WHPA, 2010). The IDNR published a water shortage plan for the State of Indiana in 2009 and updated the plan in 2015 (IDNR, 2015). Each study furthers the understanding of the importance of water availability in the State. The current study shows that water withdrawals in the Central Indiana region are occurring near the limit of water availability. The occurrence of a significant regional drought, longer and more severe than the 2012 drought, may tax the existing system beyond its capacity. Measures to increase the resiliency of the regional public supply and to allow for growth are necessary.

The following recommendations focus on changes to the regulatory framework to monitor water availability and on methods for increasing the resiliency of the current water supply while allowing for growth in the region.

22.1 Changes to the Regulatory Framework

Changes to the regulation of water withdrawals are recommended to improve the State's ability to assess water availability regionally, and to focus monitoring on critical regions where water availability is known to be inadequate.

22.1.1 Data Management and Quality Control

Water withdrawal data and return flow data are managed by different State agencies, each with different reporting requirements and quality controls; the data sets are managed for very different purposes. Both the Indiana SWWF database and the EPA ECHO database require interpretation and significant effort to extract time series data. Quality control is an issue with both data sets, as identified in the report. Cooperation between IDNR and IDEM, aimed at using the two data sets for assessing water availability, could result in significant improvements in the understanding of water transfers within the State. Agency cooperation could include joint monitoring of water withdrawal and NPDES permits for facilities such as quarries, that are regulated under both programs. This effort would identify quality control issues with major facilities and identify gaps in the current reporting.

22.1.2 Annual Updating of Water Availability

A data-based framework for assessing excess water availability has been developed in this study. The workflow described in this report is tedious but could be automated. Improved data management and quality control, made possible by agency cooperation, would streamline the

workflow and allow for automatic updating of water availability estimates. Regular database updates and maintenance are necessary for this effort to be successful.

22.1.3 Additional Reporting Requirements for Major Water Users

Major water users, outside of the Public Supply sector, with withdrawals greater than a designated threshold level could be required to provide more stringent withdrawal and return reporting. Major quarries where reported withdrawals and returns are inconsistent, could be required to provide a facility water-budget report identifying withdrawals, diversions, and on-site discharges to ponds. Also, requiring water-supply utilities with reservoirs to report daily reservoir releases, inflows, stage and storage levels, would benefit future water availability assessments.

22.1.4 Define Instream Flows

As discussed in Section 2.9, instream flows are not regulated in Indiana, but are provided as recommendations in the State's water shortage plan (IDNR, 2015). That study focuses on water quality rather than ecological health of streams. The evaluation of natural streamflow and natural baseflow in this study provides a stronger basis for defining the ecological health of a stream than use of the $Q_{7,10}$ in a region with large anthropogenic impacts on streamflow. Many states have developed instream flow limits to regulate water withdrawal based on natural streamflow, following the concepts of Ecological Limits of Hydrologic Alteration (ELOHA) (NatureConservancy, 2020). Protection of instream flows requires action to determine impacts on future water availability, and assess future needs.

22.1.5 Develop a State Database of Known Groundwater Plumes

The extent and severity of groundwater contamination limit new sources for groundwater supply. Without readily accessible information on the extent of contamination, the impacts to groundwater availability cannot be assessed. A state database of known groundwater contamination and mapping of plumes would be of great utility to State planners, utilities, and the public.

22.2 Regional Collaboration of Public Water Suppliers and Sanitary Districts

We have shown in Section 3.3 that managing drought conditions in 2012 in the White River drainage system required excess upstream water to be available for use in downstream subbasins with water deficits. This represents an unofficial form of regional collaboration. While this approach has worked in past to maintain supplies regionally, it may not be reliable in the future. An organized regional collaboration of water users would strengthen the resiliency of the

regional water supply. Collaboration could include utilities sharing information regarding real-time water use and returns, short-term forecasts, transfers of water supplies between utilities, and system improvements. Collaborator input and regional impacts should be considered when planning and implementing any significant changes to a water supply system. Further it has been shown that return flows from wastewater treatments are an integral part of excess and cumulative water availability in the region. Organized collaboration between major wastewater treatment plants and water utilities would be beneficial in water-supply planning.

22.3 Water Conservation

The water deficit in the region along the White River extending from Noblesville to Nora (Sub-basin 5) is exacerbated by the relationship between Quarter 3 withdrawals and return flows in the sub-basin: the average ratio of return flows at wastewater treatment plants (23 MGD) to public supply withdrawals (50 MGD) is 0.46, which is significantly smaller than other regions. There is an average of 27 MGD that is withdrawn for public supply, but not returned at wastewater treatment plants, suggesting that it is used for lawn watering. Water conservation measures, either voluntary or mandatory, could be implemented within a Water Management District during a declared drought. In 2012, Citizens Water reduced demand by up to 31% (Citizens, 2013) using a combination of voluntary and mandatory restrictions on lawn watering.

22.4 Invest in Increasing Water Availability

Three methods are available for increasing water availability in the Central Indiana region. These include increasing surface water storage capacity, developing short-term emergency groundwater supplies that draw from groundwater storage, and importing a supply from outside the region.

22.4.1 Develop Surface-Water Storage

Increasing surface water storage capacity allows for collection of excess water in Quarters 1 and 2, with releases to supplement water availability during Quarters 3 and 4. Surface storage is used, for example, by Citizens Water at Morse and Geist Reservoirs. Problems with inline surface water reservoirs include sedimentation and water quality issues, and conflicts between water supply use and public recreational use. In addition, because of their large surface areas, high evaporative losses may occur during critical summer months. The most significant change to water availability in the region is the construction of Citizens Reservoir, which, when operational in 2021, will add up to 30 MGD of supply. In contrast to the Morse and Geist Reservoirs, Citizens Reservoir is developed in an abandoned quarry with a small surface area. Citizens Reservoir avoids many of the problems of an inline reservoir and provides a dedicated storage supply to enhance water availability.

The design of the Citizens Reservoir could be duplicated at other inactive quarries. The active Martin-Marietta quarries in Sub-basin 5 could be considered for conversion to surface water reservoirs at the end of mining operations. They are centrally located in the region of largest water deficit.

Alternatively, while the quarries are operational, water utilities could cooperate with Martin Marietta to use dewatering water directly for supply. This approach has been successful in the City of Burnsville, MN where operation of a limestone quarry had impacted both water supplies and sensitive wetlands for years. In 2008, the City entered into an agreement with the quarry to receive dewatering water at the City water treatment plant. The collaboration has proved mutually beneficial for the City and the quarry, and has improved conditions at nearby wetlands. The project has produced both economic and environmental benefits (MNDOH, 2020).

22.4.2 Improve Stormwater Management

Redirecting stormwater from surface outfalls to infiltration ponds is important for improving both water quality and quantity. This is a form of redirecting surface runoff to increase groundwater storage and baseflow to streams. However, this is commonly a local scale problem and the impacts to the regional study are not quantifiable. While the impacts of local stormwater management are not quantified in this study, they are important on a smaller watershed scale.

22.4.3 Develop Emergency Groundwater Supplies

Emergency groundwater supplies could be obtained by removing groundwater from aquifer storage during drought conditions. Emergency wells can be designed and located where there is a significant time lag between the start of pumping to when stream depletion affects streamflow. Emergency supplies would be for short-term use only, would likely have to be developed in buried sand and gravel lenses or bedrock, and have limited yield. Exploration and field testing is required to identify appropriate locations.

22.4.4 Import Water to the Central Region

The most direct solution to increasing water availability is to develop a drought-proof water supply outside of the Central Indiana region and construct a pipeline to import the water. This option provides both resiliency to the existing water supply and the possibility of growth.

22.5 Closely Monitor Climate Change

A major uncertainty about future water availability is the impact that climate change will have on streamflow and baseflow in the Central Indiana region. While increased precipitation in the last decade has resulted in increasing streamflow and baseflow, it is unclear whether this trend will continue into the future; available watershed studies that consider climate change provide

conflicting results. Natural streamflow and natural baseflow in the region should be monitored and evaluated annually for trends.

References

Alder, J. and Hostetler, S. (2013). USGS National Climate Change Viewer. Technical report, United States Geological Survey.

Anderson, E. (2005). Modeling groundwater - surface water interaction using the Dupuit approximation. *Advances in Water Resources*.

Arihood, L. (1982). Ground-Water Resources of the Upper White River Basin, Hamilton and Tipton Counties, Indiana. Water Resources Investigation Report 82-48, United States Geological Survey.

Bailey, Z. and Imbrigiotta, T. (1982). Ground-Water Resources of the Glacial Outwash along the White River, Johnson and Morgan Counties, Indiana. Water Resources Investigation 82-4016, United States Geological Survey.

Briggs, M. A., Lautz, L. K., McKenzie, J. M., Gordon, R. P., and Hare, D. K. (2012). Using High-Resolution Distributed Temperature Sensing to Quantify Spatial and Temporal Variability in Vertical Hyporheic Flux. *Water Resources Research*, 48: 1-16.

Brown, S., Bleuer, N., O'Neal, M., Olejnik, J., and Rupp, R. (2001). Glacial-terrain Explorer. *Indiana Geological Survey Open-File Study 00-08*.

Brown, S., Ferguson, V., and Flemming, A. (1995). Hydrologic Framework of Marion County, Indiana. Open File Report 93-5, Indiana Geological Survey, Environmental Geology Section.

Brown, S. and Laudick, A. (2003). Hydrogeologic framework of Marion County, Indiana: a digital atlas illustrating hydrogeologic terrain and sequence. Open-File Study 00-14, Indiana Geological Survey.

Burger, A. (1986). BEDROCK_GEOLOGY_RGM_250K_IN: Bedrock geology of Indiana from the regional geologic map series of the indiana geological survey. 1:250,000, Polygon Shapefile.

Cable, L. (1971). Hydrogeology of the Principal Aquifers in Vigo and Clay Counties,Indiana. Water Resources Bulletin 34, United States Geological Survey.

Carmel (2019). Data Summary for Production Wells. Excel Spreadhseet.

CEG (2013). River Road Wellhead Data. Binder of technical well information, Citizens Energy Group.

Citizens (2013). Citizens Water Drought Management Plan. Technical report.

Citizens (2020a). Citizens Reservoir–Project Summary. https://www.citizensenergygroup.com/Our-Company/Our-Projects/Citizens-Reservoir.

Citizens (2020b). Digindy Project Summary. https://www.citizensenergygroup.com/Our-Company/Our-Projects/Dig-Indy.

Citizens (2020c). Perry K Steam Plant conversion-Project Summary. https://www.citizensenergygroup.com/My-Business/Utility-Services/Thermal/History.

Constantz, J. (2008). Heat as a Tracer to Determine Streambed Water Exchanges. *Water Resources Research*, 44.

Cremeans, M. M., Devlin, J. F., Osorno, T. C., McKnight, U. S., and Bjerg, P. L. (2020). A Comparison of Tools and Methods for Estimating Groundwater-Surface Water Exchange. *Groundwater Monitoring and Remediation*, V40 (1): 24-34.

Dierauer, J. and Zhu, C. (2020). Drought in the twenty-first century in a water-rich region: modeling study of the Wabash River watershed, USA. *Water*, 12-181.

Driscoll, F. (1986). *Groundwater and Wells*. Johnson Screens, St. Paul Minnesota.

Droste, J. and Shaver, R. (1975). Jeffesonville Limestone (Middle Devonian) of Iindiana: Stratigraphy, Sedimentation, and relation to Silurian Reef-Bearing Rocks. *AAPG Bulletin*, 59(3):393–412.

Drum, R., Noel, J., Kovatch, J., Yeghiazarian, L., Stone, H., Stark, J., Kirshen, E., Best, E., Emery, J., Trimboli, J., and Raff, D. (2017). Ohio River Basin – Formulating Climate Change Mitigation/Adaptation Strategies through Regional Collaboration with the ORB Alliance. Technical report, U.S. Army Corps of Engineers, Institute for Water Resources: Alexandria, VA.

Eagon, H. B. (1995). Preliminary Evaluation Northeast Well Field Area. Prepared for Indiana American Water Company, Eagon and Associates, Inc.

Eagon, H. B. (1996). Aquifer Test Analysis and Evaluation of the Miller Well Field. Prepared for Indiana American Water Company, Eagon and Associates, Inc.

EPA (2020). ECHO Enforcement and Compliance History Online. https://echo.epa.gov/.

Falcone, J. (2011). GAGES II (Geospatial Attributes of Gages for Evaluating Streamflow) Summary Report. Technical report, United States Geological Survey.

Fenelon, J. (1998). Water Quality in the White River Basin, Indiana, 1992-1996. USGS Circular 1150, United States Geological Survey.

Fenelon, J. and Bobay, K. (1994). Hydrogeologic Atlas of Aquifers in Indiana. Water Resources Investigation Report 92-4142, United States Geological Survey.

Fowler, K. and Wilson, J. (2015). Low-flow characteristics for selected streams in Indiana. Scientific Investigation Report 2014-5242, United States Geological Survey.

Frankson, R. and Kunkel, K. (2015). NOAA National Centers for Environmental Information–State Summaries 149-IN. https://statesummaries.ncis.org/in.

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and Wickham, J. (2011). Completion of the 2006 National Land Cover Database for the Counterminous United States. Technical report.

Gillies, D. (1976). Availability of Ground Water Near Carmel, Hamilton County, Indiana. Water Resources Investigation Report 76-46, United States Geological Survey.

Gleeson, T. and Richter, B. (2017). How much groundwater can we pump and protect environmental flows through time? Presumptive standard for conjunctive management of aquifers and rivers. *River Research and Applications*.

Gray, H. (2002). SURFICIAL_GEOL_MM49_IN: Quaternary Geologic Map of Indiana. Indiana Geological Survey Miscellaneous Map 49 1:500,000, Polygon Shapefile.

Gray, H., Ault, C., and Keller, S. (1987). AQUIFER_SYSTEMS_BEDROCK_IDNR_IN: Bedrock Aquifer Systems of Indiana. 1:500,000, Polygon Shapefile.

Grove, G. (2008). Unconsolidated Aquifer Systems of Boon County, Indiana. Aquifer Systems Map 54-A, Indiana Depertment of Natural Resources, Division of Water.

Grove, G. (2012a). Potentiometric surface map of the bedrock Aquifers of Hamilton County, Indiana. Potentiometric Surface Map 21-B, Indiana Depertment of Natural Resources, Division of Water.

Grove, G. (2012b). Potentiometric surface map of the bedrock Aquifers of Marion County, Indiana. Potentiometric Surface Map 19-B, Indiana Depertment of Natural Resources, Division of Water.

Haitjema, H. M. (1995). *Analytic element modeling of groundwater flow*. Elsevier.

Hamlet, A., Byun, K., Robeson, S., Windhalm, M., and Baldwin, M. (2018). Impacts of climate change on the state of Indiana: ensemble future projections based on statistical downscaling. *Climate Change Publications*.

Harbaugh, A. (2005). MODFLOW 2005, the U.S. Geological Survey Modular Ground-Water Model-the Ground-Water Flow Process. Techniques and Methods 6-A16, United States Geological Survey.

Hatch, C. E., Fisher, A. T., Revenaugh, J. S., Constantz, J., and Ruehl, C. (2006). Quantifying Surface Water-Groundwater Interactions Using Time Series Analysis of Streambed Thermal Records: Method Development. *Water Resources Research*, 42:W10410.

Hatch, C. E., Fisher, A. T., Revenaugh, J. S., Constantz, J., and Ruehl, C. (2012). Automated Calculation of Vertical Pore-Water from Field Temperature Time Series Using VFLUX Method and Computer Program. *Journal of Hydrology*, 420-421:142-158.

Herring, B. (1976). Technical Atlas of the Ground-Water Resources of Marion County, Indiana. Technical report, Indiana Depertment of Natural Resources, Division of Water.

Homer, C., Dewitz, J., ans S. Jin, L. Y., Danielson, P., Xian, G., Coulston, J., Herold, N., Wickham, J., and Megown, K. (2015). Completion of the 2011 National Land Cover Database for the Counterminous United States: Representing a Decade of Land Cover Change Information. Technical report.

Homer, C., Dewitz, J., Fry, J., Coan, M., Hossain, N., Larson, C., Herold, N., McKerrow, A., VanDriel, J., and Wickham, J. (2007). Completion of the 2001 National Land Cover Database for the Counterminous United States. Technical report.

Hostetler, S. and Alder, J. (2016). Implementation and evaluation of a monthly water balance model over the US on an 800 m grid. *Water Resources Research*, 52:9600–9620.

Hudson, S. (2020). IDEM 2013-2018 Drinking Water Branch groundwater quality data for Central Indiana region. email transmittal.

IDEM (2016). Ground Water Monitoring Network Report 2016: Summary and Results. Technical report, Indiana Department of Environmentat Management.

IDEM (2020). 303(d) Impaired Waters List. https://www.in.gov/idem/nps/2647.htm.

IDNR (1980). The Indiana Water Resource: Recommendations for the Future. Technical report, Indiana Department of Natrual Resources, Governor's Water Resource Study Commission.

IDNR (2002). Groundwater Resources in the White and West Fork White River Basin, Indiana. Water Resources Assessment 2002-6, Indiana Depertment of Natural Resources, Division of Water.

IDNR (2011). AQUIFER_SYSTEMS_UNCONSOLIDATED_IDNR_IN: Unconsolidated Aquifer Systems of Indiana. 1:48,000, Polygon Shapefile.

IDNR (2015). Indiana's Water Shortage Plan. Technical report, Indiana Department of Natural Resources, Division of Water.

IDNR (2016). Stream Mileage Markers for Streams in Indiana. Raster digital data, Indiana Department of Natural Resources.

IDNR (2018). Significant Water Withdrawal Facility Data. https://www.in.gov/dnr/water/4841.htm.

IDNR (2020a). Significant Water Withdrawal Facilities.

IDNR (2020b). Water Well Record Database. Technical report, Indiana Department of Natural Resources.

IFA (2020). Central Indiana Water-Supply Needs 50-year Forecast. Technical report, Indiana Finance Authority.

IFA (2021). 2020 Status Report, Central Indiana's Water Supply, Future Demand, Availability, Options. Technical report, Indiana Finance Authority.

IGWS (2000). PHYSIOGRAPHY_SR61_IN: Physiographic Regions of Indiana. 1:500,000, Polygon Shapefile.

IGWS (2015). BEDROCK_SURFACE_DEM_100M_IGS_IN.TIF: Bedrock Surface Elevation DEM of Indiana. 100-Meter TIFF Image.

IGWS (2020a). Bedrock Geology of Indiana. https://igws.indiana.edu/Bedrock.

IGWS (2020b). Potential Contaminant Source Inventory. https://maps.indiana.edu/.

IGWS (2020c). Surficial Geology. https://igws.indiana.edu/Surficial.

IGWS (2020d). Trenton Field from A Brief Overview of the History of the Petroleum Industry in Indiana. https://igws.indiana.edu/OilGas/Indiana

INAWC (2019). GIS coverage for Production Wells. Vector Shapefile.

IPL (2020a). Eagle Valley conversion–Project Summary. https://www.iplpower.com/About_IPL/Power_Generation/Combined_Cycle_Gas_Turbine/.

IPL (2020b). Harding Street Station conversion–Project Summary. https://www.iplpower.com/About_IPL/Newsroom/News_archives/2016/IPL_burns_coal_for_the_last_time_at_Harding_Street_Station/.

Irvine, D. J., Briggs, M. A., Lautz, L. K., Gordon, R. P., McKenzie, J. M., and Cartwright, I. (2017). Using Diurnal Temperature Signals to Infer Vertical Groundwater-Surface Water Exchange. *Groundwater*, V55 (1):10-26.

Irvine, D. J., Lautz, L. K., Briggs, M. A., Gordon, R. P., and McKenzie, J. M. (2015). Documentation for VFLUX 2: Vertical Fluid Heat Transport Solver.

JHE (2007). Aquifer Evaluation in the Vicinity of Well 20. Technical report, Jones and Henry Engineers, Ltd. Prepared for City of Carmel.

JHE (2010). Northern Beach Park Groundwater Exploration. Technical report, Jones and Henry Engineers, Ltd. Prepared for City of Carmel.

Keery, J., Binly, A., Crook, N., and Smith, J. W. N. (2007). Temporal and Spatial Variability of Groundwater-Surface Water Fluxes: Development and Application of an Analytical Method Using Temperature Time Series. *Journal of Hydrology*, 336:1-16.

Korinek, G. (2013). Potentiometric surface map of the bedrock Aquifers of Tipton County, Indiana. Potentiometric Surface Map 36-B, Indiana Depertment of Natural Resources, Division of Water.

Lapham, W. (1981). Ground-Water Resources of the White River Basin, Madison Counties, Indiana. Water Resources Investigation 81-35, United States Geological Survey.

Layne (2014). Harbour well field yield analysis and preliminary design. Technical report prepared for Citizens Water, Layne-Christensen Company.

Meyer, W. (1978). Hydraulic Characteristsics of the White River Streambed and Glacial-Outwash Deposits at a Site near Indianapolis, Indiana. Technical report.

Meyer, W. (1979). Geohydrologic Setting of and Seepage from a Water-Supply Canal, Indianapolis, Marion County, Indiana. Water Resources Investigation Report 79-115, United States Geological Survey.

Meyer, W., Russow, J., and Gillies, D. (1975). Availability of groundwater in Marion County, Indiana. Open File Report 75-312, United States Geological Survey.

MNDOH (2020). New Burnsvill Plant will use Excess Quarry Water. https:// www.health.state.mn.us/communities/ environment/water/waterline/featurestories/burnsville.html.

NatureConservancy (2020). Ecological Limits of Hydrologic Alteration (ELOHA). https://www.conservationgateway.org/ConservationPractices/Freshwater/Environmental Flows/MethodsandTools/ELOHA/Pages/ecological-limits-hydrolo.aspx.

NRCS (2015). U.S. General Soil Map - STATSGO2. Digital database, Natural Resources Conservation Service.

Richter, B., Davis, M., Apse, C., and Konrad, C. (2011). A presumptive standard for environmental flow protection. *River Research and Applications*.

Risch, M., Bunch, A., Vecchia, A., Martin, J., and Baker, N. (2014). Water Quality in Indiana: Trends in Concentrations of Selected Nutrients, Metals, and Ions in Streams, 2000-10. Scientific Investigation Report 2014-5205, United States Geological Survey.

Rutledge, A. (1998). Computer Programs for Describing the Recession of Ground-Water Discharge and for Estimating Mean Ground-Water Recharge and Discharge from Streamflow Record–Updates. Water-Resources Investigation Report 98-4148, United States Geological Survey.

Rutledge, A. (2007). Program User Guide for PART. Technical report, United States Geological Survey.

Saul, M. and Robinson, B. (2002). Streambed Permeability and Seepage in White River, Marion County, Indiana. Special Project 4, Indiana Department of Natural Resources.

Schmidt, R. (2011). Unconsolidated Aquifer Systems of Marion County, Indiana. Aquifer Systems Map 81-A, Indiana Depertment of Natural Resources, Division of Water.

Schmidt, R. (2014). Potentiometric surface map of the bedrock Aquifers of Madison County, Indiana. Potentiometric Surface Map 37-B, Indiana Depertment of Natural Resources, Division of Water.

Scott, R. (2008). Unconsolidated Aquifer Systems of Clinton County, Indiana. Aquifer Systems Map 52-A, Indiana Depertment of Natural Resources, Division of Water.

Scott, R. (2009). Unconsolidated Aquifer Systems of Tipton County, Indiana. Aquifer Systems Map 45-A, Indiana Depertment of Natural Resources, Division of Water.

Scott, R. (2010a). Unconsolidated Aquifer Systems of Hamilton County, Indiana. Aquifer Systems Map 68-A, Indiana Depertment of Natural Resources, Division of Water.

Scott, R. (2010b). Unconsolidated Aquifer Systems of Madison County, Indiana. Aquifer Systems Map 77-A, Indiana Depertment of Natural Resources, Division of Water.

Shaver, R. (1970). Compendium of Rocks Units in Indiana - A Revision. *Indiana Geological and Water Survey Bulletin*, 43.

Spindler, K. and Denney, M. (2018). Occurences of Arsenic in Indiana ground water. In *Geological Society of America Annual Meeting, Indianapolis.*

Stonestrom, D. and Constantz, J. (2003). Heat as a Tool for Studying the Movement of Groundwater Near Streams. Circular 1260, United States Geological Survey.

Strack, O. (1989). *Groundwater Mechanics.* Prentice Hall, Inc., Englewood Cliffs, NJ.

Strack, O. (2017). Vertically integrated flow in stratified aquifers. *Journal of Hydrology.*

Strack, O. and Ausk, B. (2015). A formulation of groundwater flow in a stratified coastal aquifer using the Dupuit-Forchheimer approximation. *Water Resources Research*, 51:1–20.

Strack, O., Barnes, R., and Verruijt, A. (2005). Vertically integrated flows and the Dupuit-Forchheimer approximation. *Ground Water*, 44(1):72–75.

Suzuki, S. (1960). Percolation Measurements Based on Heat Flow Through Soil with Special Reference to Paddy Fields. *Journal of Geophysical Research*, 65 (9): 2883-2885.

Thornton, P., Thornton, M., Mayer, B., Wei, Y., Devarakonda, R., Vose, R., and Cook, R. (2018). Daily Surface Weather Data on a 1-km Grid for North America, Version 3. Oak Ridge National Lab - Digital Data.

Thornton, P., Thornton, M., Mayer, B., Wilhelmi, N., Wei, Y., Devarakonda, R., and Cook, R. (2014). Daymet – Daily Surface Weather Data on a 1-km Grid for North America, Version 2 Data Set. Oak Ridge National Lab - Digital Data.

Trost, J., Roth, J., Westenbroek, S., and Reeves, H. (2018). Simulation of Potential Recharge for the Glacial Aquifer System East of the Rocky Mountaions, 1980–2011, using the Soil-Water-Balance Model. Scientific Investigations Report 2018–5080, United States Geological Survey.

Trost, J., Roth, J., Westenbroek, S., and Reeves, H. (Accessed 2020). Data Release for USGS SIR 2018-5080. USGS Publications Warehouse.

USEPA (2003). Drinking Water Advisory: Consumer Acceptability Advice and Health Effects Analysis on Sodium. EPA 822-R-03-006, United States Environmental Protection Agency.

USGS (2010). SWB - A Modified Thornwaite–Mather Soil Water Balance Code for Estimating Groundwater Recharge. Techniques and Methods 6–A31, United States Geological Survey.

USGS (2017). 1 Arc-second Digital Elevation Models (DEMs) - USGS National Map 3DEP Downloadable Data Collection. Raster digital data, United States Geological Survey.

USGS (2019). Digital Elevation Models n40w087, n40w086, n41w087, and n41w086, USGS 13 arc-second 1 x 1 degree.

USGS (2020a). The National Map. https://viewer.nationalmap.gov/advanced-viewer/.

USGS (2020b). National Water Information System data available on the World Wide Web (USGS Water Data for the Nation). http://waterdata.usgs.gov/nwis/.

USGS (2020c). USGS National Hydrography Dataset Viewer. Technical report, United States Geological Survey.

WHPA (2003). Phase I Wellhead Protection Plan. Technical report, Wittman Hydro Planning Associates. Prepared for City of Carmel.

WHPA (2005). Well 20 Aquifer Test. Technical report, Wittman Hydro Planning Associates. Prepared for City of Carmel.

WHPA (2010). Central Indiana's Regional Water Supply – a water Synthesis Report with Recommendations for Future Management. Technical report, Indianapolis Chamber of Commerce.

Wiener, M., Jafvert, C., and Nies, L. (2016). The assessment of water use and reuse through reported data: A US case study. *Science of the Total Environment*, 539:70–77.

Wiener, M., Moreno, S., Jafvert, C., and Nies, L. (2020). Times series analysis of water use and indirect reuse within a HUC-4 basin (Wabash) over a nine year period. *Science of the Total Environment*, 738.

Winston, R. (2009). Model Muse – A Graphical User Interface for MODFLOW-2005 and PHAST. Techniques and Methods 6-A29, United States Geological Survey.

Winter, T. C., Harvey, J. W., Franke, O. L., and Alley, W. M. (1998). Ground Water and Surface Water, a Single Resource. Circular 1139, United States Geological Survey.

A Water Budget Analysis

We present a watershed-wide water budget analysis for the purpose of relating the primary hydrologic data sources to the definition of water availability presented in Part 1 of this report. The primary data sources include:

1. USGS daily flow records at the gaging station (q_{usgs}) at the downstream end of the watershed;
2. Individual groundwater and surface water withdrawal records (q_{gww}, q_{sww}) within the watershed;
3. Individual surface water return flows (q_{rf}) within the watershed;
4. Releases from surface-water storage in major reservoirs.

Conservation of mass for a control volume can be written

$$\frac{dV}{dt} = Q_{in} - Q_{out} \tag{19}$$

where

$\frac{dV}{dt} =$ The rate of change in volume of water stored in a control volume;

$Q_{in} =$ the total rate of water flow into the control volume across the surface of the control volume;

$Q_{out} =$ the total rate of water flow out of the control volume across the surface of the control volume.

Each term above is represented by a time series. Each water budget described below is based on equation (19) where the control volume is defined with respect to the waterhsed. Figure A.1 presents a definition sketch of a watershed in the Central Indiana region with a typical cross section through the watershed. We use three control volumes to relate hydrologic processes to the available data for analysis. Each control volume includes a portion of the general features shown in Figure A.1.

The notation used in this appendix does not follow the convention of the main report, where lower case $\boldsymbol{q}$ represents properties of the watershed and upper case $\boldsymbol{Q}$ represents properties of the sub-basin. Here we consider only watershed properties and the upper case $\boldsymbol{Q}$ indicates net inflow or outflow to the control volume.

A.1 Watershed Control Volume

The first control volume consists of the entire watershed, from the outlet to the watershed divide, and extending from above the ground surface to bedrock. Boundaries of the control

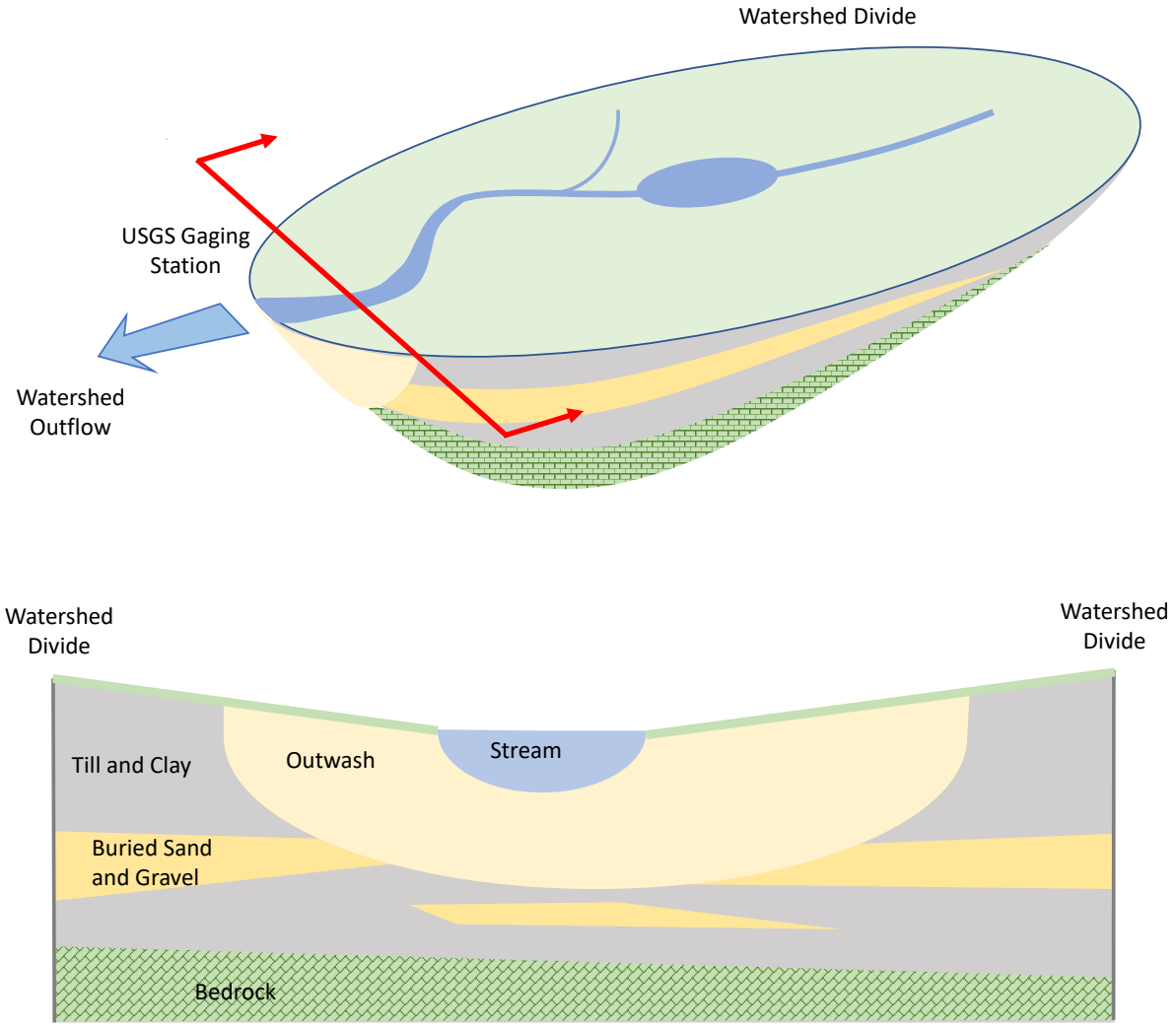


Figure A.1: Watershed schematic and cross-section.

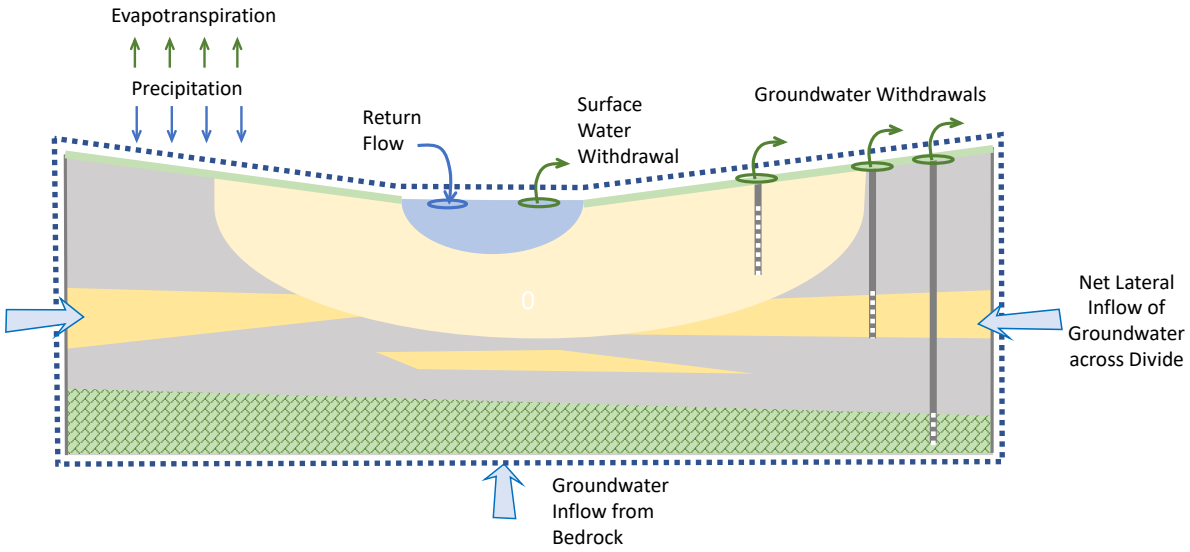


Figure A.2: Control volume boundary for watershed-wide water budget.

volume are illustrated in section in Figure A.2 as the heavy dotted line. Flows crossing the control volume surfaces are presented graphically in the figure. The water budget for the control volume can be expressed as

$$\frac{dV}{dt} = (Q_{gw} + Q_{ppt} + Q_{rf}) - (Q_{et} + Q_{gww} + Q_{sww} + Q_{sw}) \tag{20}$$

where the first grouping in parenthesis on the right hand side is the total inflow (Q_{in}), and the second grouping is the total outflow (Q_{out}) from the control volume, and

$\frac{dV}{dt}$ = the rate of change in volume of groundwater and surface water stored in the watershed;

Q_{gw} = the net rate of groundwater water flow into the control volume across the lateral surfaces and bottom surface of the control volume;

Q_{ppt} = direct precipitation onto the surface of the watershed;

Q_{rf} = rate of return flows;

Q_{et} = evapotranspiration from the surface of the watershed;

Q_{sww} = rate of surface water withdrawals in the watershed, equal to individual withdrawals summed over the watershed ($\sum q_{sww}$);

Q_{gww} = rate of groundwater withdrawals in the watershed, equal to individual withdrawals summed over the watershed ($\sum q_{gww}$);

Q_{sw} = the surface water flow rate measured at the downstream end of the watershed = q_{usgs}.

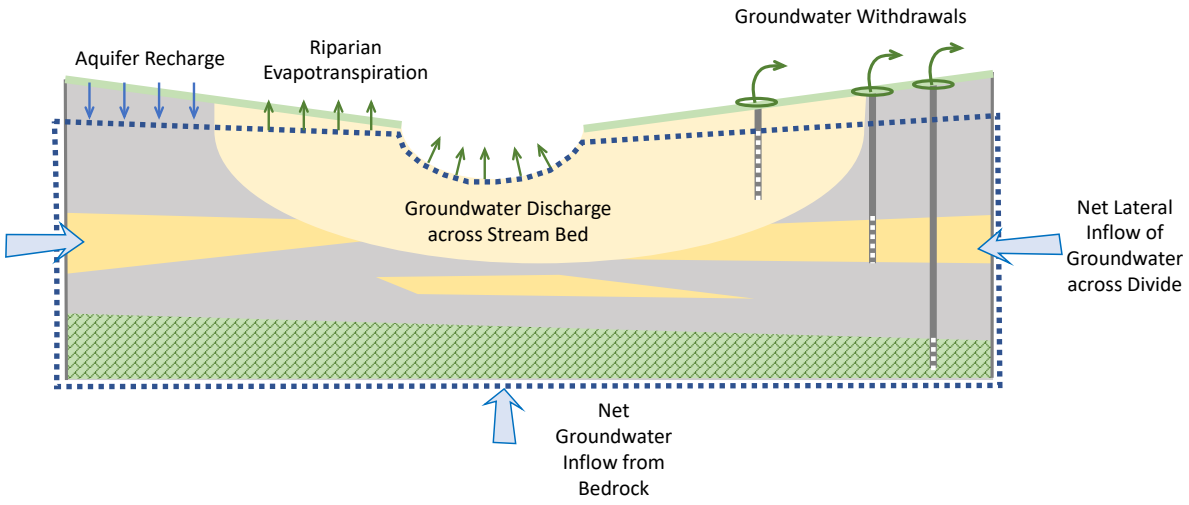


Figure A.3: Control volume boundary for groundwater water budget with flows across the boundaries.

A.2 Groundwater Control Volume

The second control volume, illustrated in Figure A.3, is again bounded laterally by watershed boundaries, and below by bedrock; the control volume is bounded on top above the saturated groundwater level and by the boundary between all groundwater and surface waters. The resulting statement of conservation of mass is:

$$\frac{dV_{gw}}{dt} = (Q_{gw} + Q_{rech}) - (Q_{sb} + Q_{ret} + Q_{gww}) \tag{21}$$

where

$\frac{dV_{gw}}{dt} =$ the rate of change in the volume of groundwater water stored in the aquifer;

$Q_{sb} =$ the net rate of groundwater discharge across the stream bed;

$Q_{rech} =$ rate of recharge to the aquifer;

$Q_{ret} =$ rate of riparian evapotranspiration near surface waters where the groundwater level approaches the ground level;

The net groundwater discharge to surface waters in the watershed is then given by

$$Q_{sb} = Q_{gw} + Q_{rech} - Q_{ret} - Q_{gww} - \frac{dV_{gw}}{dt} \tag{22}$$

We further define groundwater withdrawals as

$$Q_{gww} = Q_{sd} + \frac{dV_{gww}}{dt} \tag{23}$$

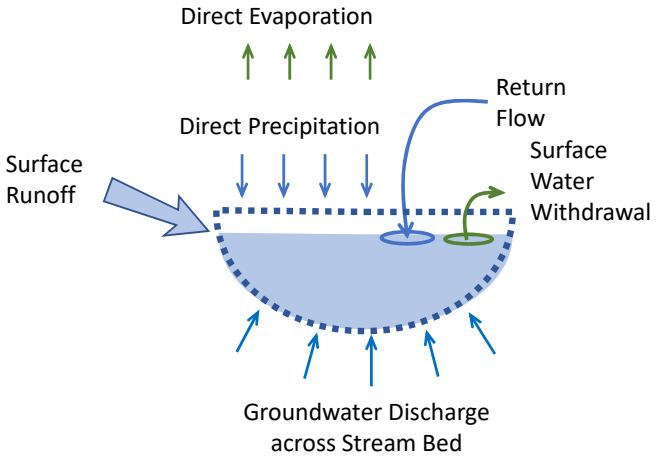


Figure A.4: Control volume for surface-water budget with flows across the boundaries.

where Q_{sd} represents stream depletion due to groundwater withdrawals and the second term reflects a change in aquifer storage caused by the groundwater withdrawals. In the following analysis, we make the approximation that Q_{gww}=Q_{sd}, or that stream depletion is instantaneous.

A.3 Surface Water Control Volume

Finally, we introduce a surface water control volume, illustrated in Figure A.4, extending from the stream bed to above the water surface throughout the watershed. Conservation of mass is expressed as

$$\frac{dV_{sw}}{dt} = (Q_{sb} + Q_{ppt} + Q_{rf} + Q_{sro}) - (Q_{evap} - Q_{sww} - Q_{sw}) \tag{24}$$

where

$\frac{dV_{sw}}{dt}$ = The rate of change in volume of surface water in storage in reservoirs;

Q_{ppt} = direct precipitation onto surface waters in the watershed;

Q_{evap} = direct evaporation from the surface waters in the watershed;

Q_{sro} = rate of surface runoff from the watershed to surface waters;

Q_{sw} = the surface water flow rate measured at the downstream end of the watershed = q_{usgs}.

Rearranging, we obtain

$$q_{usgs} = \left[Q_{sb} + Q_{ppt} + Q_{rf} + Q_{sro} - Q_{evap} - Q_{sww} - \frac{dV_{sw}}{dt}\right] \tag{25}$$

For simplicity we introduce the symbol Q_{stor} to represent all flows released from reservoirs in the watershed as

$$Q_{stor} = -\frac{dV_{sw}}{dt} \tag{26}$$

The value is positive for flows released from reservoirs, and negative for flow captured by reservoirs when refilling.

A.4 Baseflow and Stormflow

Substitution for Q_{sb} from equation (22) yields

$$q_{usgs} = \left[Q_{gw} + Q_{rech} - Q_{ret} - Q_{gww} - \frac{dV_{gw}}{dt}\right] + [Q_{sro} + Q_{ppt} - Q_{evap} - Q_{sww} + Q_{stor}] \quad (27)$$

Rearranging terms,

$$q_{usgs} - Q_{rf} + Q_{sww} + Q_{gww} - Q_{stor} = \left[Q_{gw} + Q_{rech} - Q_{ret} - \frac{dV_{gw}}{dt}\right] + [Q_{ppt} + Q_{sro} + Q_{rf} - Q_{evap}] \quad (28)$$

where the left hand side of the equation represents natural streamflow, or the flow that would have occurred in the stream if the anthropogenic effects of water withdrawal, returns, and diversions are removed

$$q_{nsf} = q_{usgs} - Q_{rf} + Q_{sww} + Q_{gww} - Q_{stor} \quad (29)$$

or, in notation consistent with Part I (see equation(28)), where the summations occur over the watershed

$$q_{nsf} = q_{usgs} - \sum(q_{rf} - q_{ww}) - \sum q_{stor} \quad (30)$$

where the surface water and groundwater withdrawals are combined in the term Q_{ww}. The first term in brackets on the right hand side of the equation 28 represents the natural baseflow, or the portion of the natural stream flow due to groundwater processes. The second term in brackets on the right hand side represents the portion of the natural streamflow due to stormflow and surface water processes.

A.5 Natural Baseflow

The basis for evaluation of water availability is the natural baseflow, which, from equation (28) is expressed as

$$q_{nbf} = Q_{gw} + Q_{rech} - Q_{ret} - \frac{dV_{gw}}{dt} \quad (31)$$

We approximate the lateral boundaries of the groundwater-shed to be equivalent to the surface watershed boundaries; this is a good approximation for the Central Indiana region, as evaluated by groundwater flow modeling. The result of this approximation is no lateral inflow of groundwater across basin divides. Further, we approximate the net groundwater inflow from

the bedrock as negligible. The final result is

$$Q_{gw} = 0 \tag{32}$$

We also approximate the riparian evapotranspiration (Q_{ret}) to be negligible in comparison to the term representing aquifer recharge (Q_{rech}), leaving the remaining terms:

$$q_{nbf} = Q_{rech} - \frac{dV_{gw}}{dt} \tag{33}$$

Although we use baseflow separation to extract the natural baseflow from the natural streamflow, it is important to understand how the natural baseflow relates to groundwater processes in the waterhed. Watersheds in the midwest are controlled by seasonal hydrologic processes; when averaging over a year, the term dV_{gw}/dt often vanishes. On an annual average basis, aquifer recharge is equivalent to the natural baseflow, although the two are distributed differently within a year:

$$\overline{q_{nbf}} = \overline{Q_{rech}} \tag{34}$$

where the overbar indicates an annual average.

A.6 Annual Evapotranspiration

An expression for estimating the annual evapotranspiration from a watershed may be obtained by returning to the watershed control volume of equation 20 with substitution of equation 32,

$$\frac{dV}{dt} = (Q_{ppt} - Q_{et}) - (q_{usgs} - Q_{rf} + Q_{ww}) \tag{35}$$

where

$$\frac{dV}{dt} = \frac{d(V_{sw} + V_{gw})}{dt} = \frac{dV_{gw}}{dt} - Q_{stor} \tag{36}$$

Substitution of equation 36 into 35 along with 30

$$\frac{dV_{gw}}{dt} = Q_{ppt} - Q_{et} - q_{nsf} \tag{37}$$

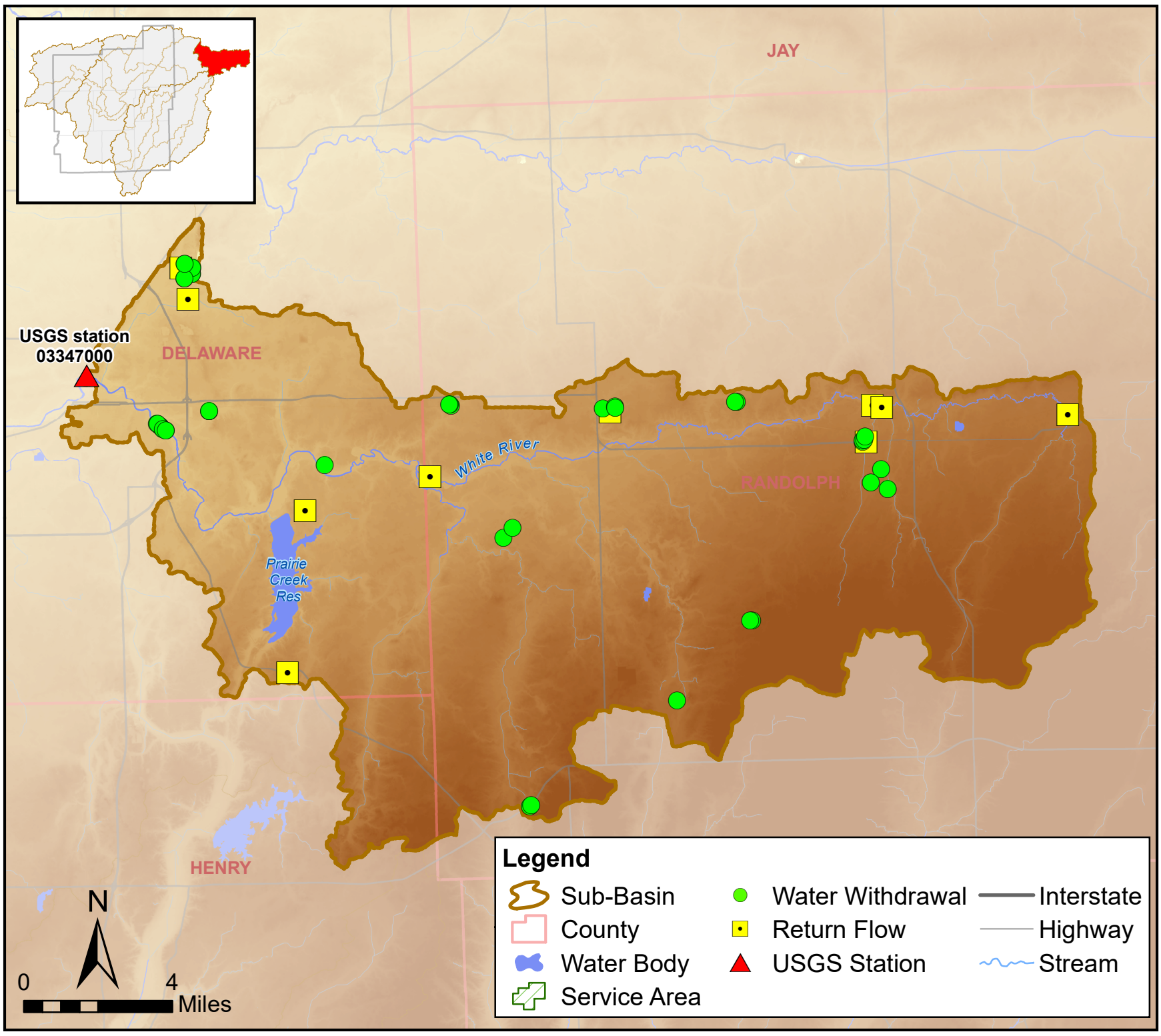
Averaging over a year, and rearranging yields

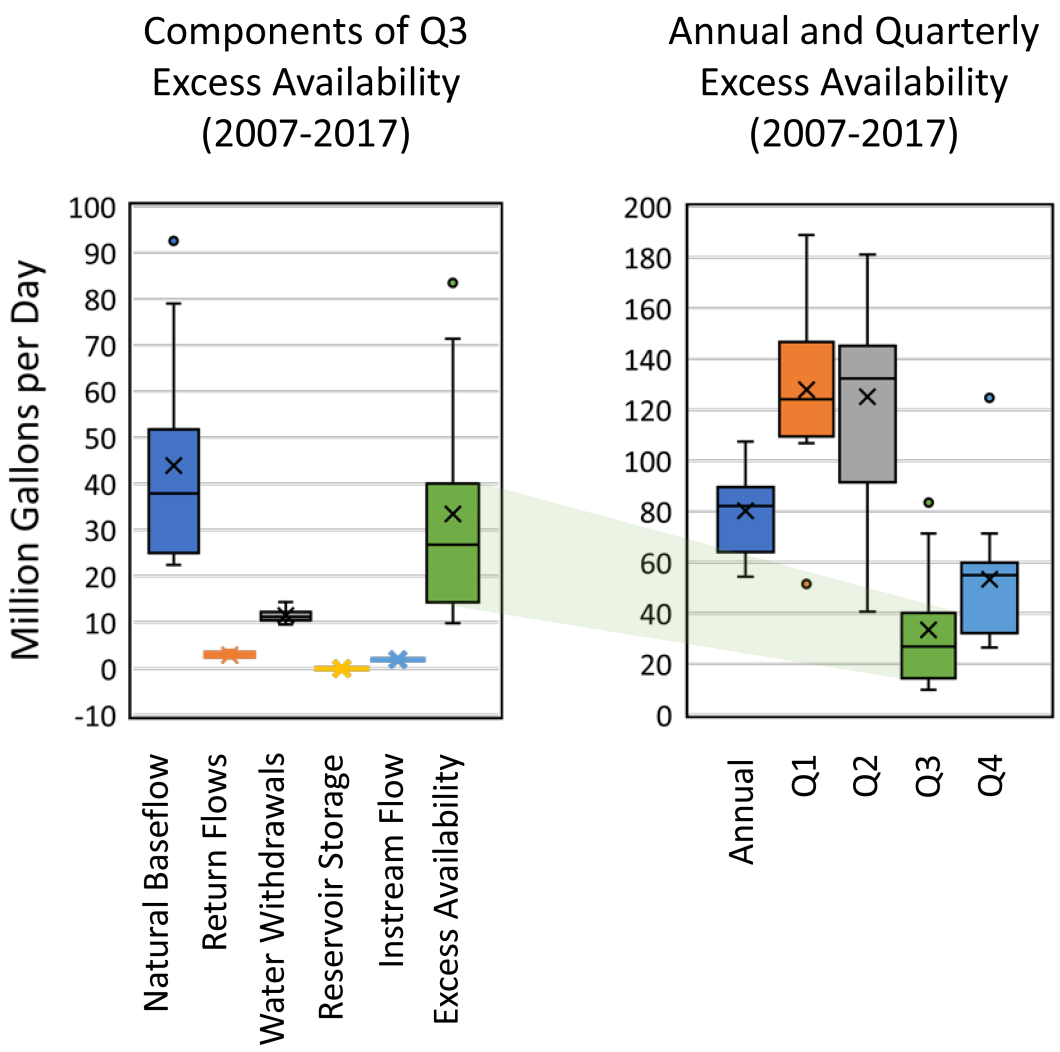
$$\overline{Q_{et}} = \overline{Q_{ppt}} - \overline{q_{nsf}} \tag{38}$$

which provides an estimate of the total evapotranspiration in a given year or multi-year period based on precipitation records and the reconstructed natural streamflow.

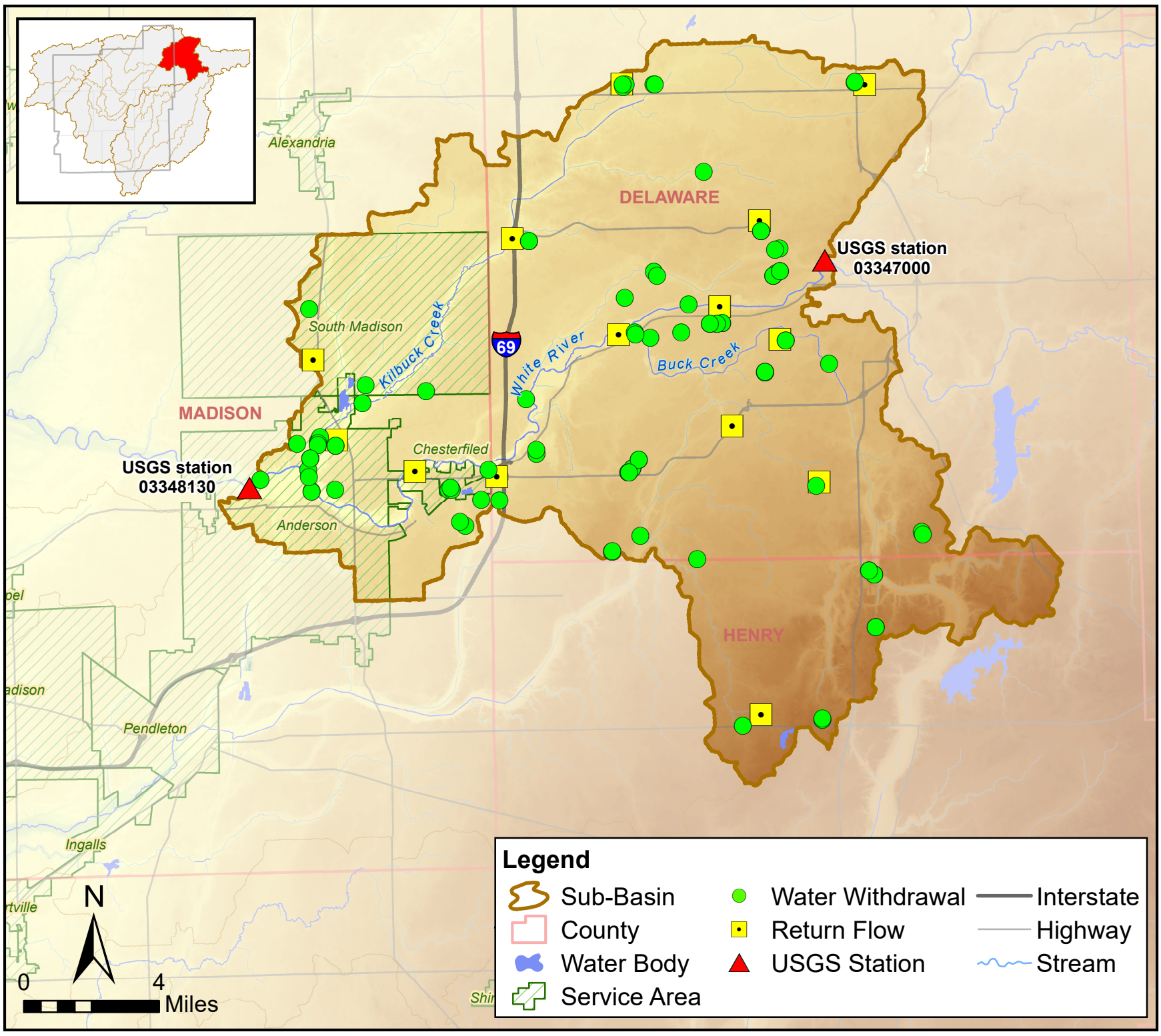
B Excess Water Availability Graphs

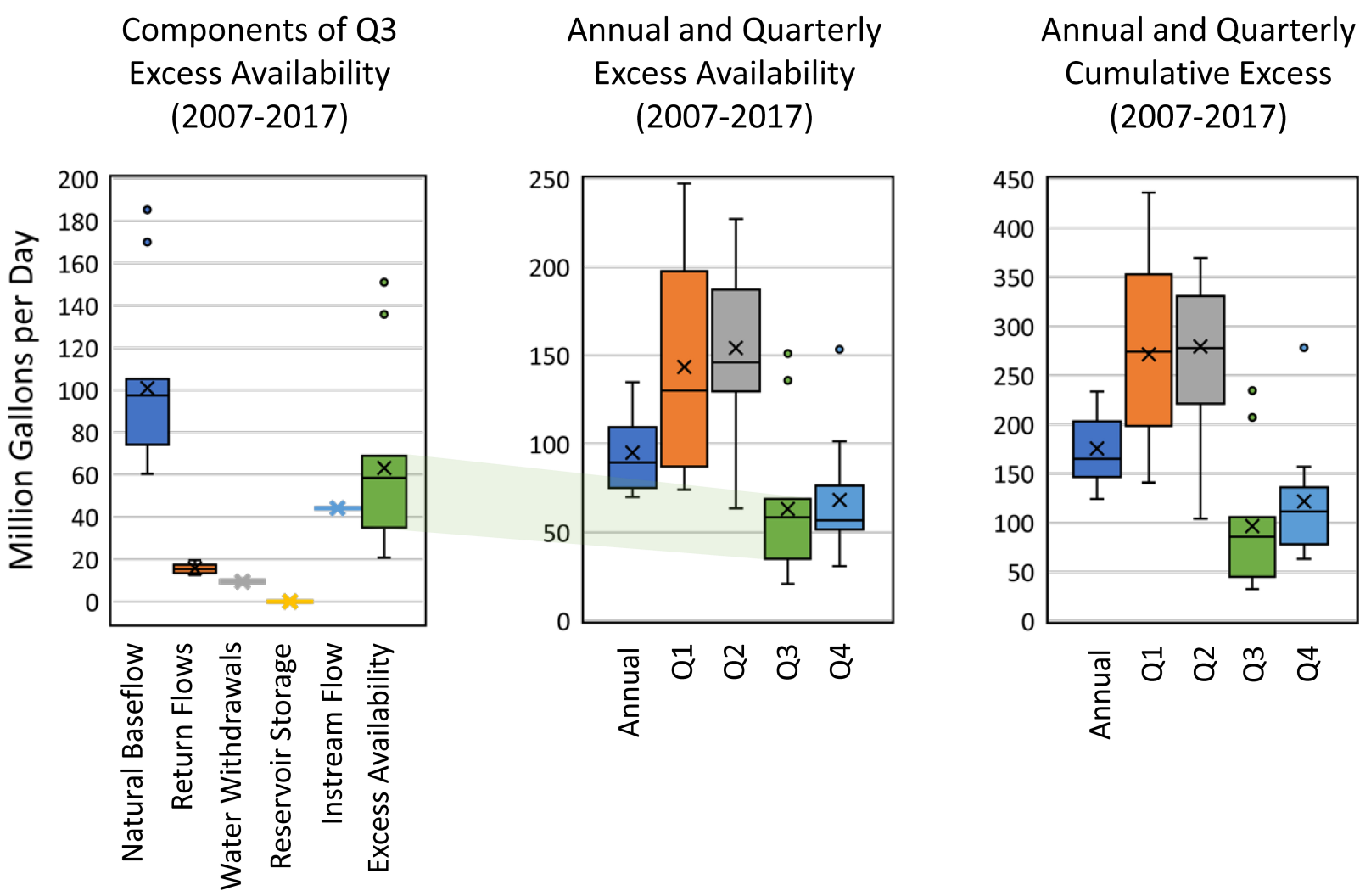
B.1 White River and Tributaries Drainage System



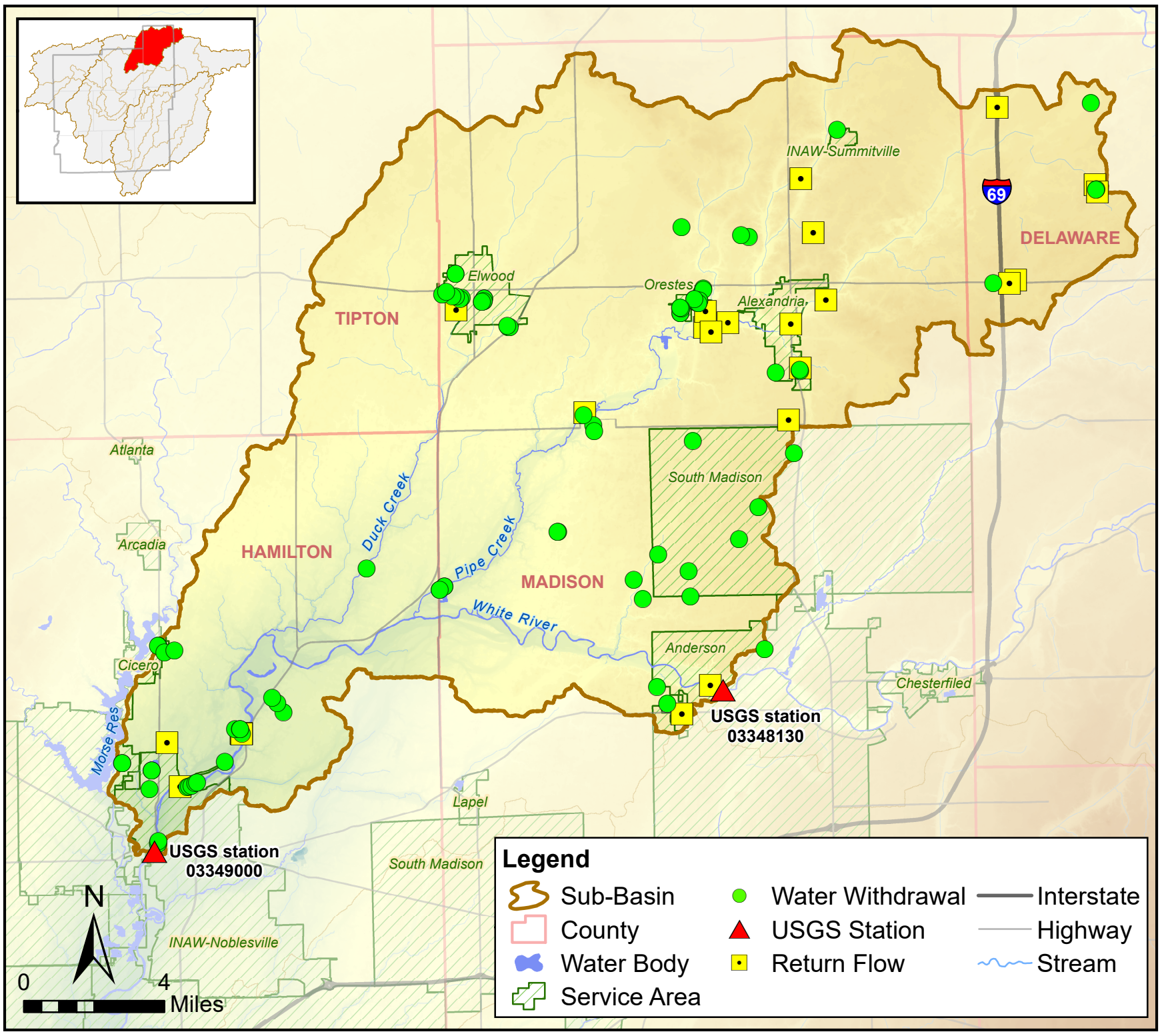


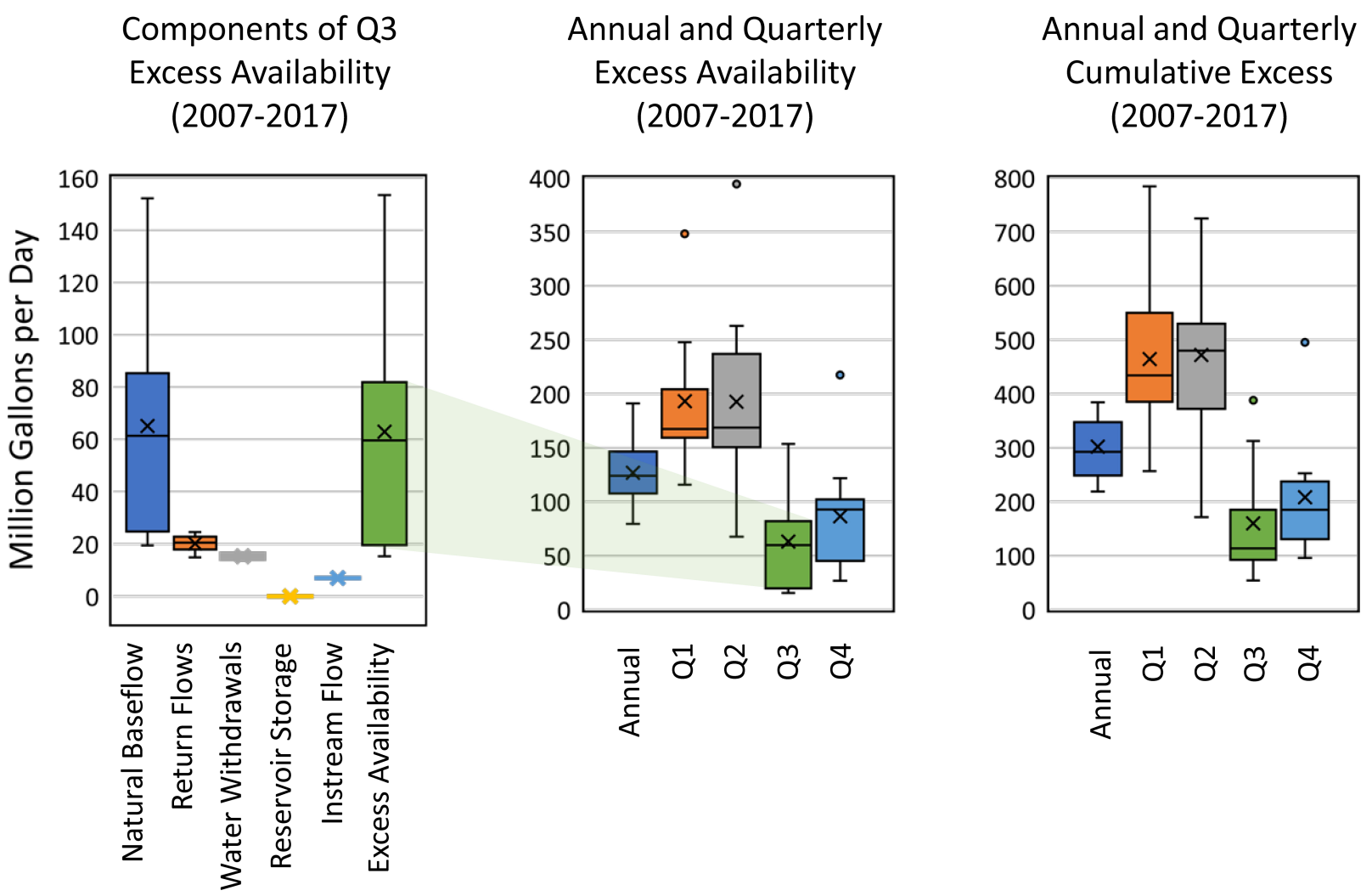
Sub-basin 1 of the White River and Tributaries drainage system



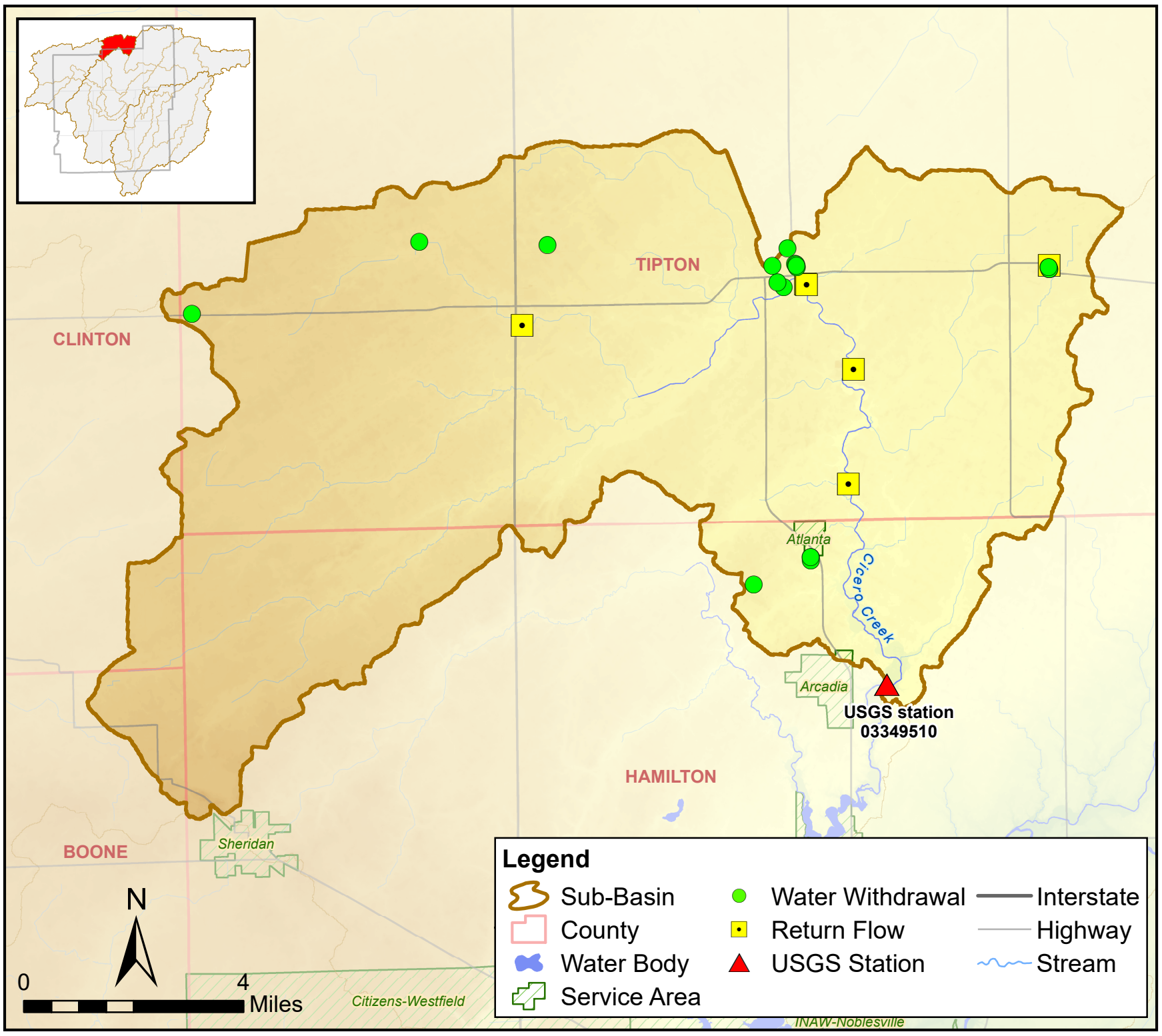


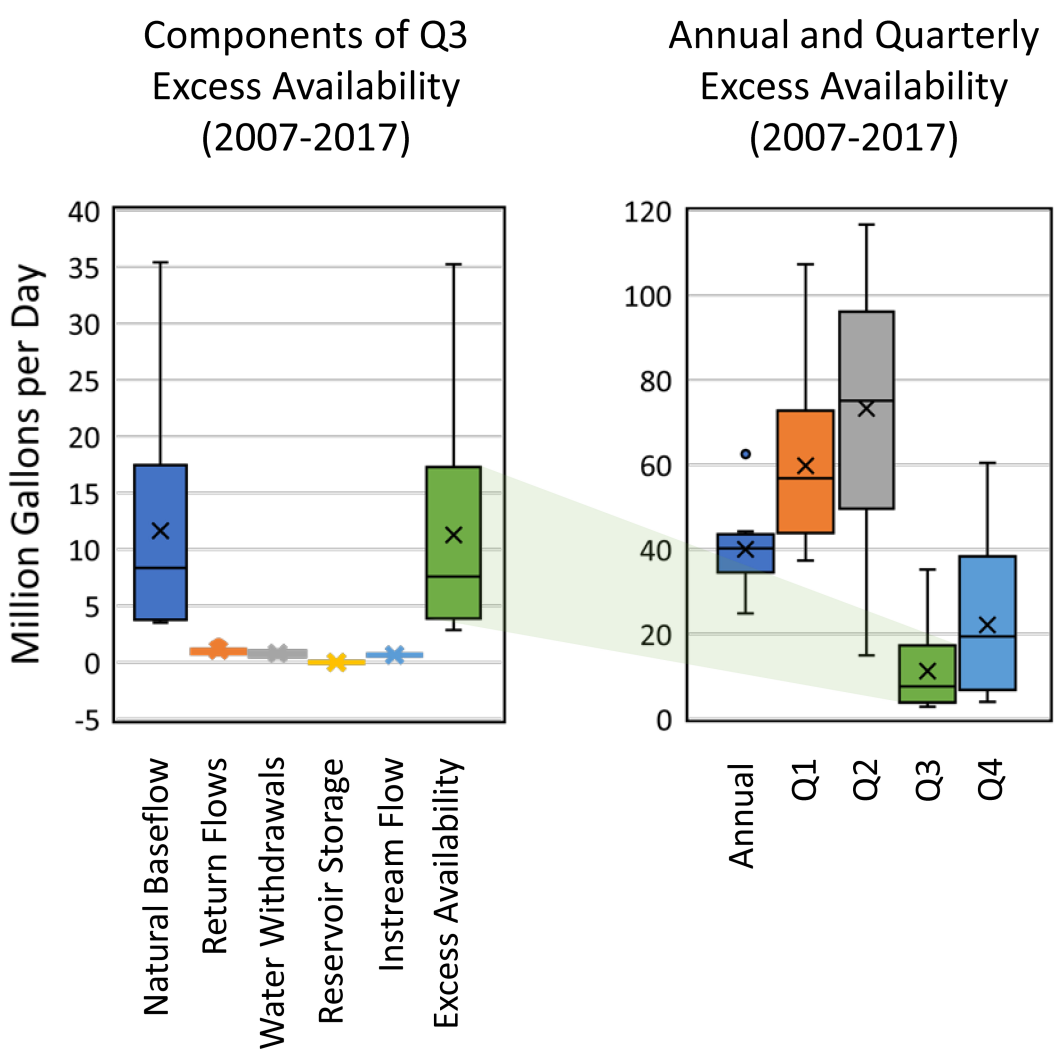
Sub-basin 2 of the White River and Tributaries drainage system



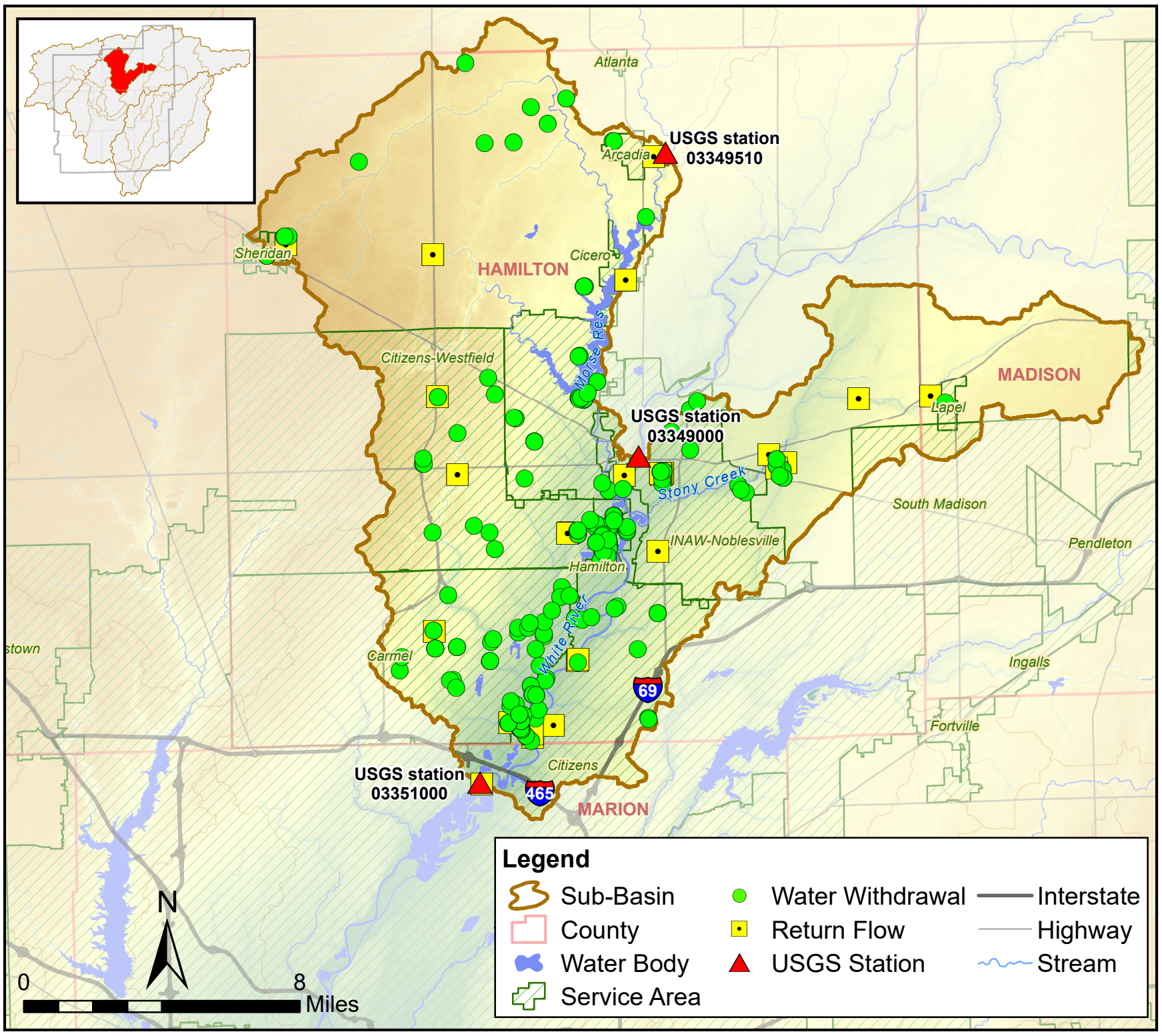


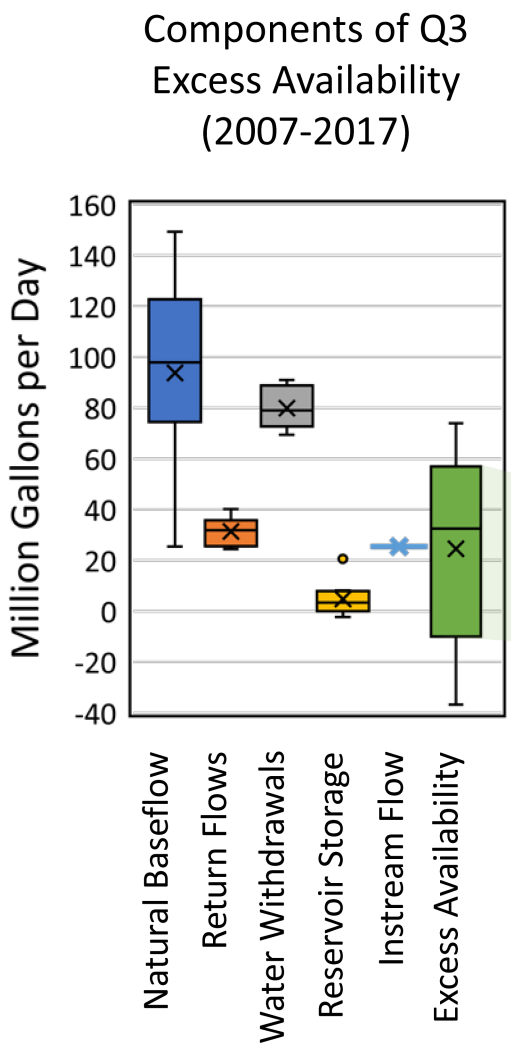
Sub-basin 3 White River and Tributaries drainage system

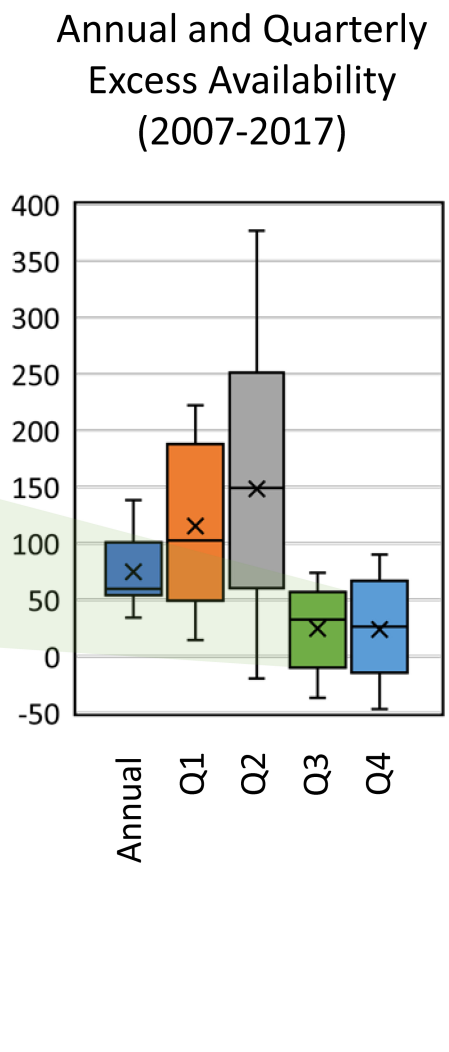


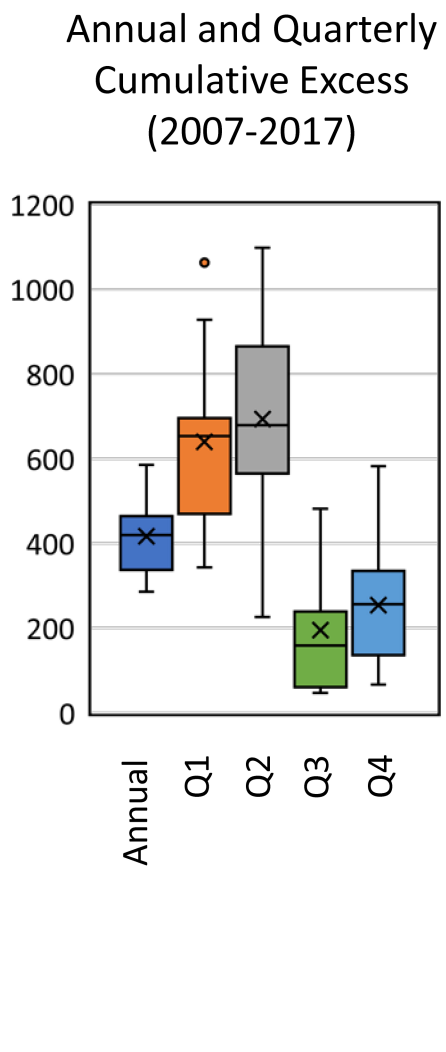


Sub-basin 4 of the White River and Tributaries drainage system

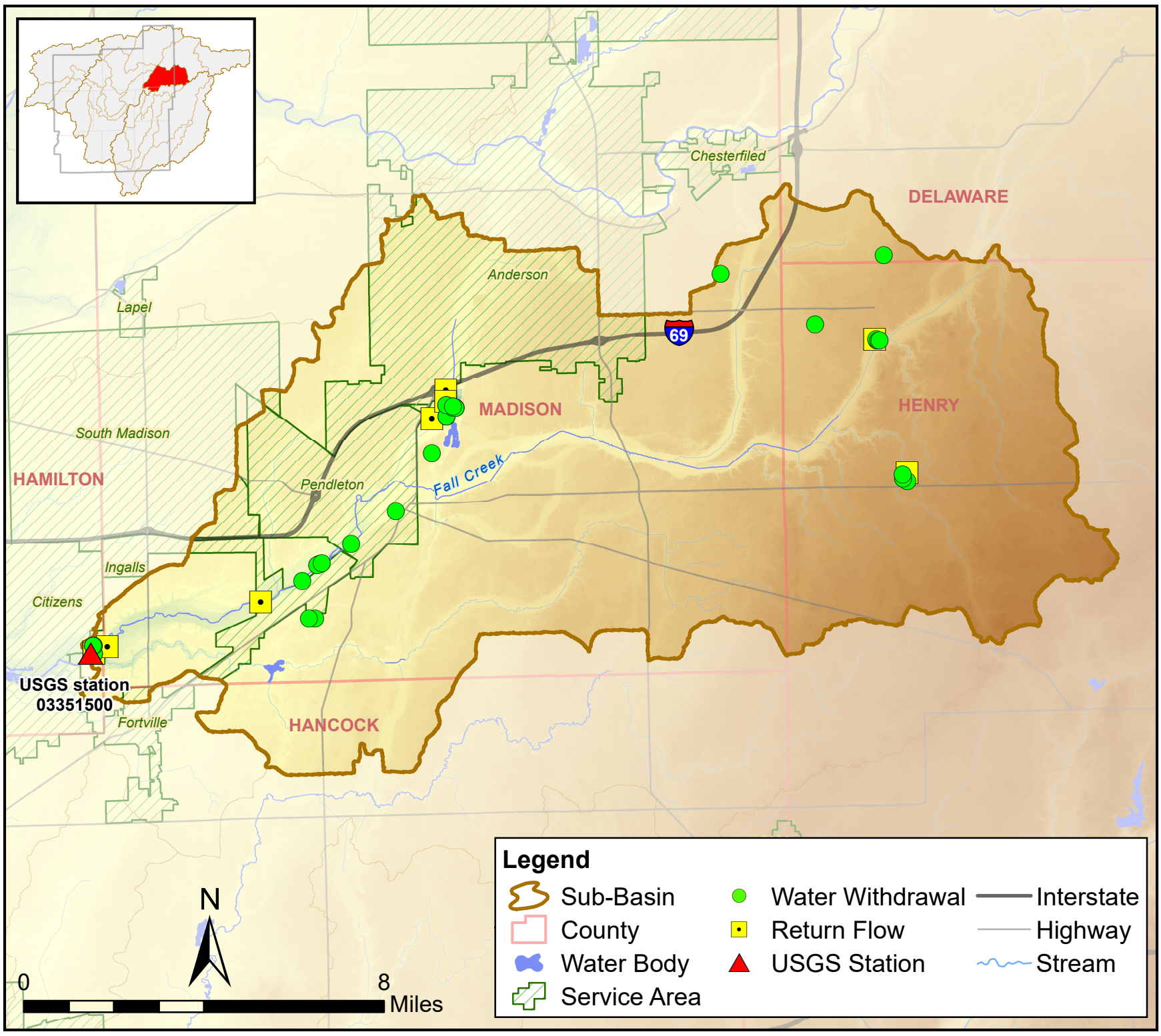


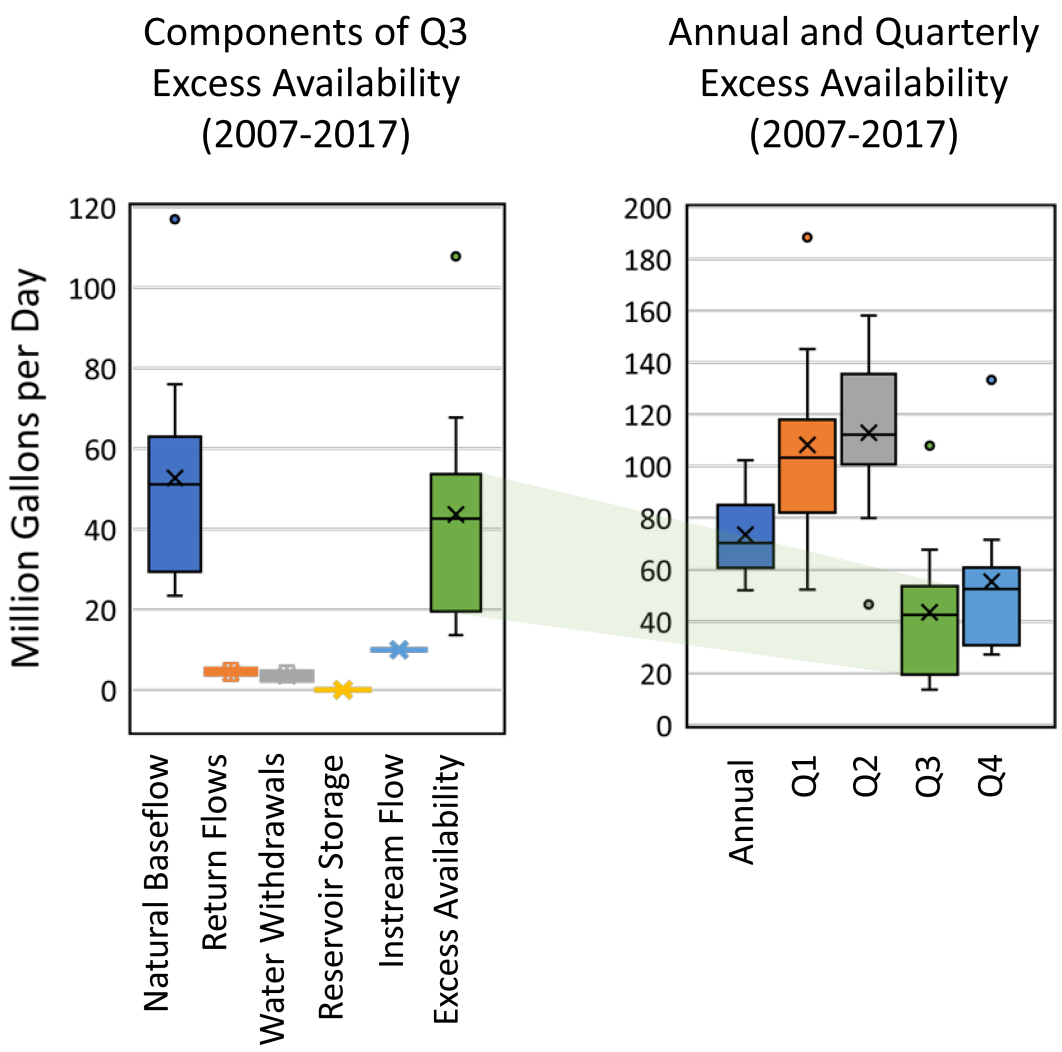




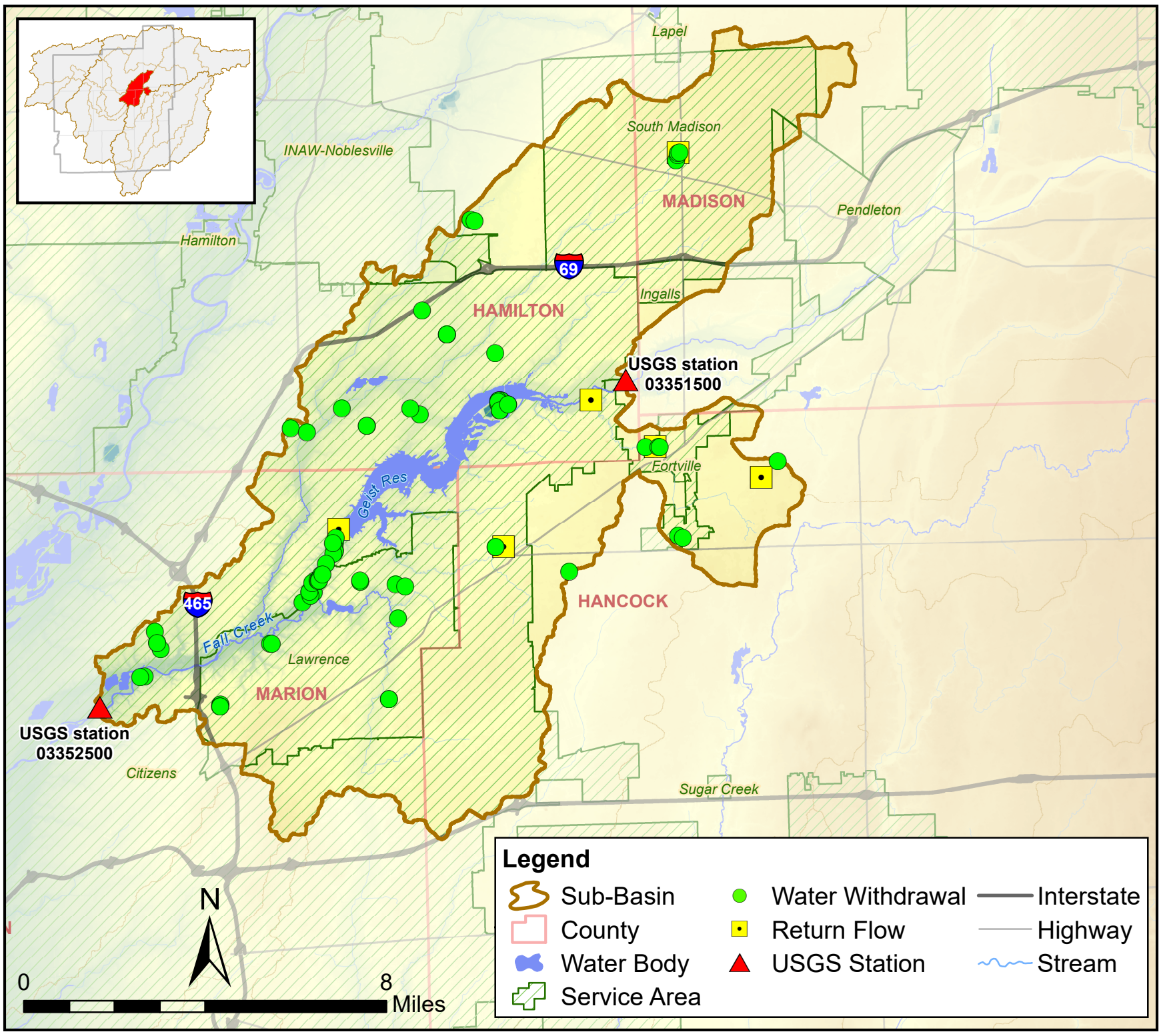


Sub-basin 5 of the White River and Tributaries drainage system

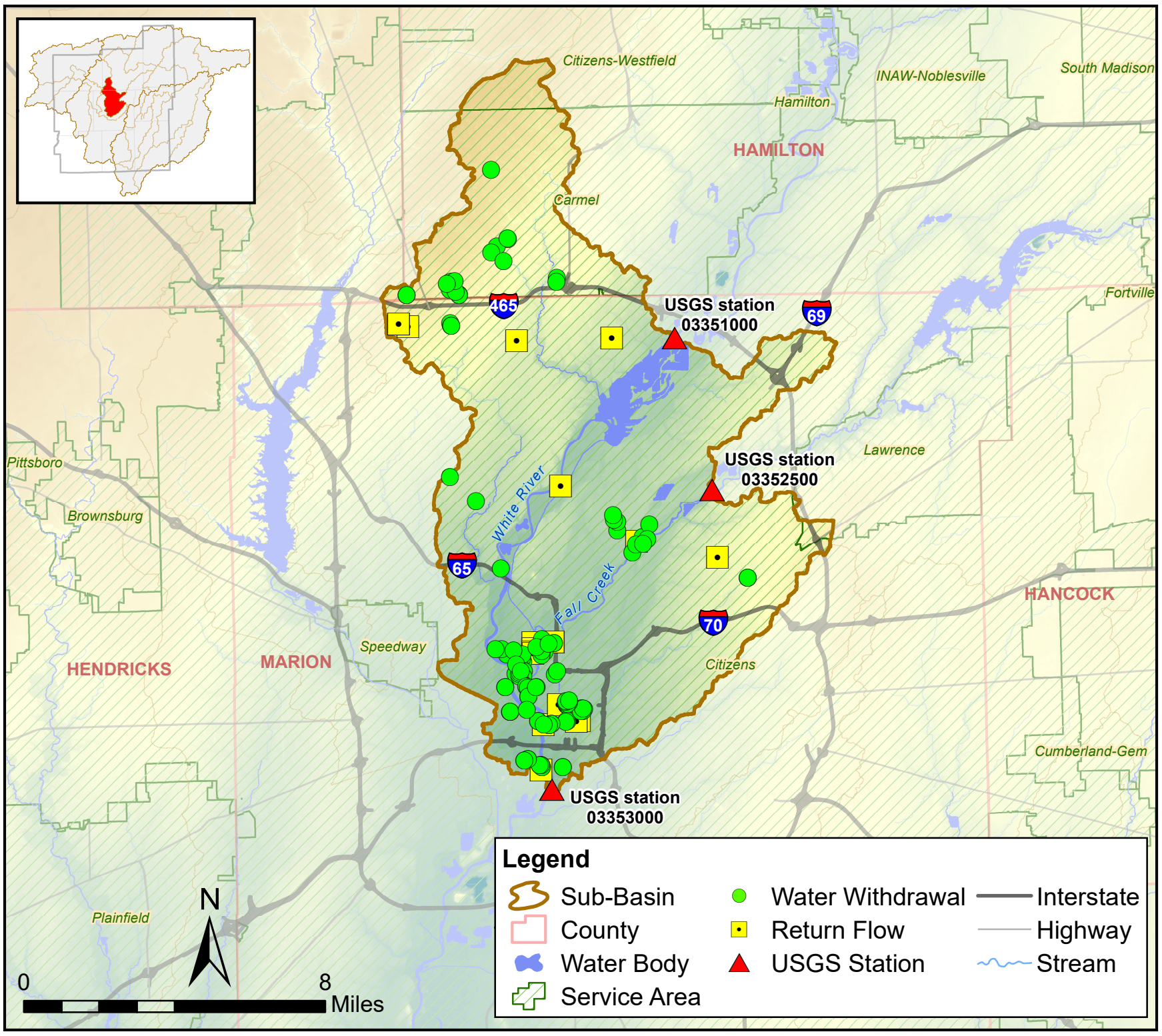




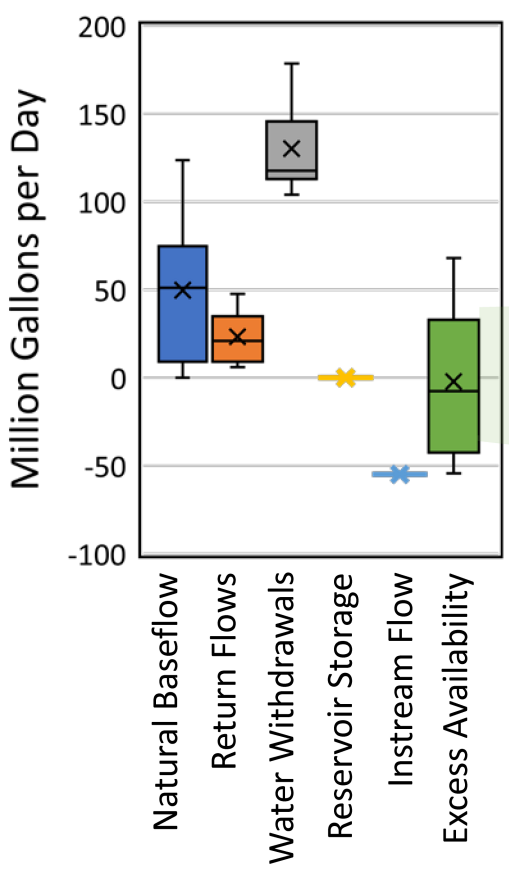
Sub-basin 6 of the White River and Tributaries drainage system



Sub-basin 7 of the White River and Tributaries drainage system



Components of Q3 Excess Availability (2007-2017)



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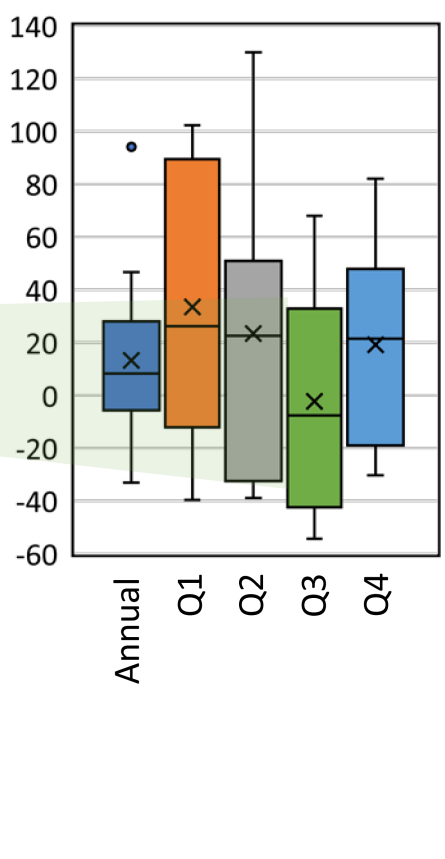

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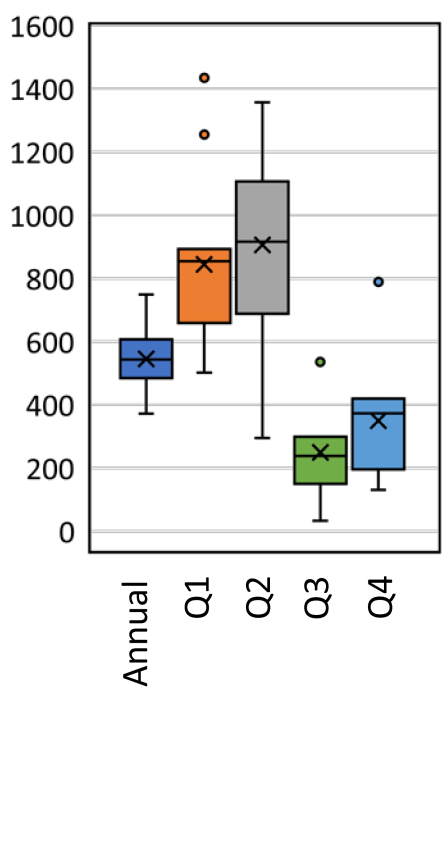
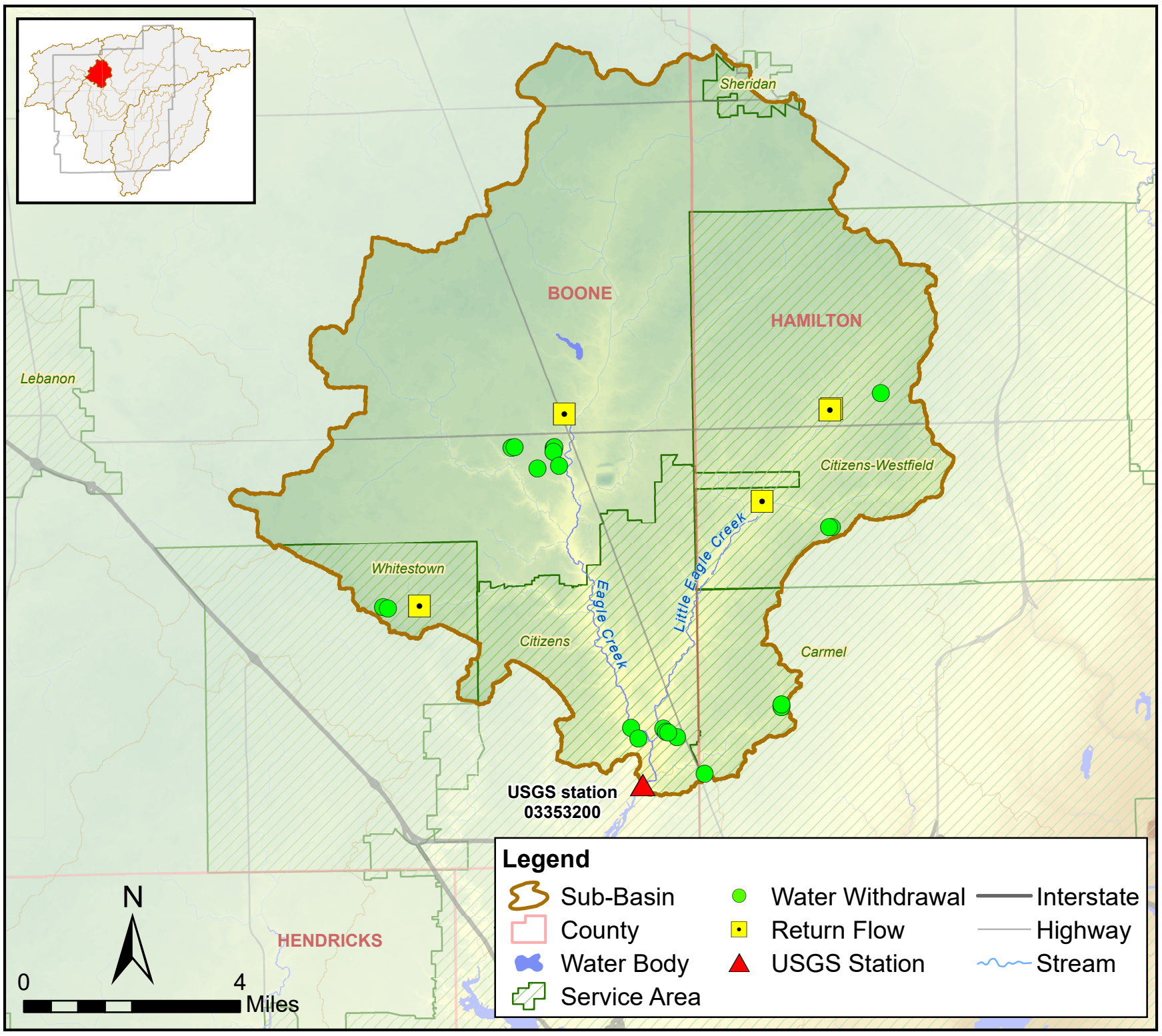
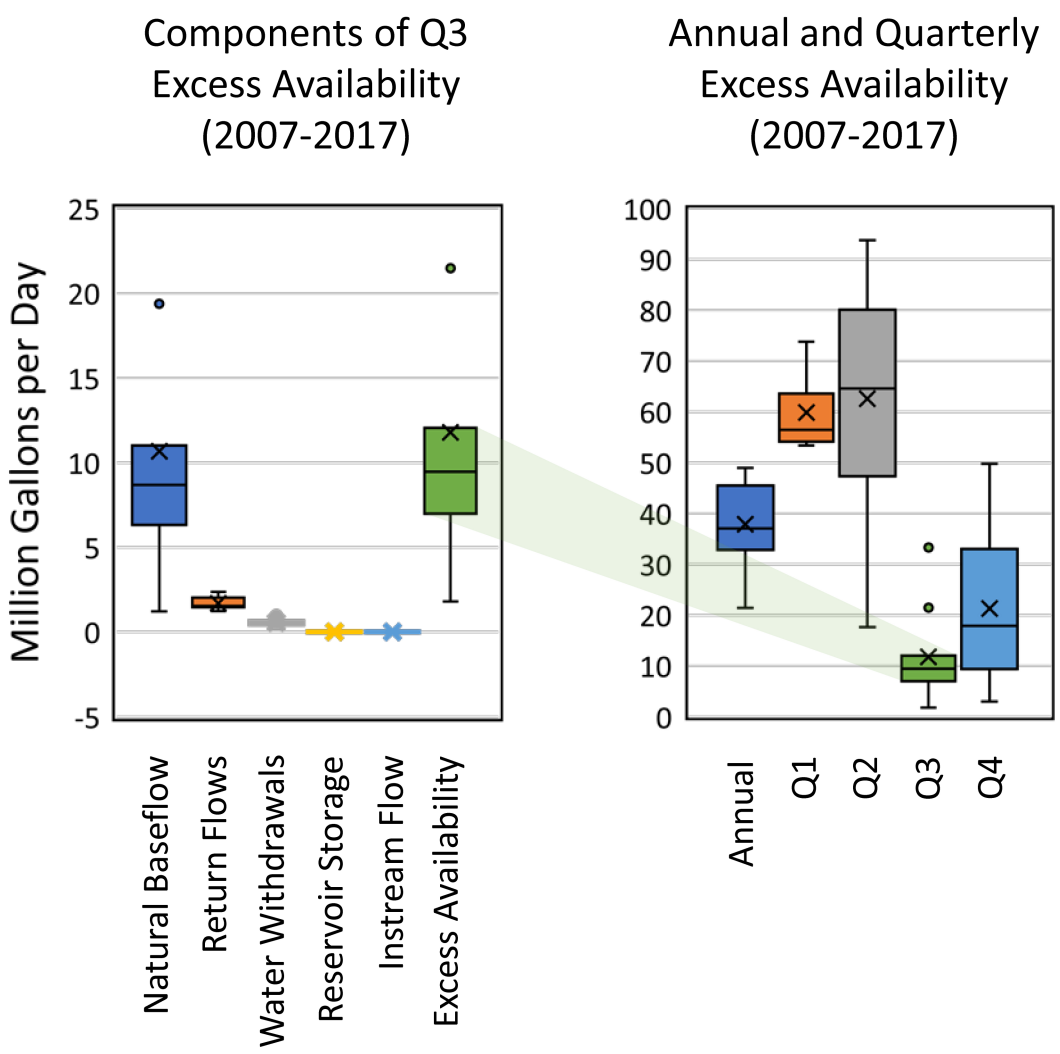


Sub-basin 8 of the White River and Tributaries drainage system





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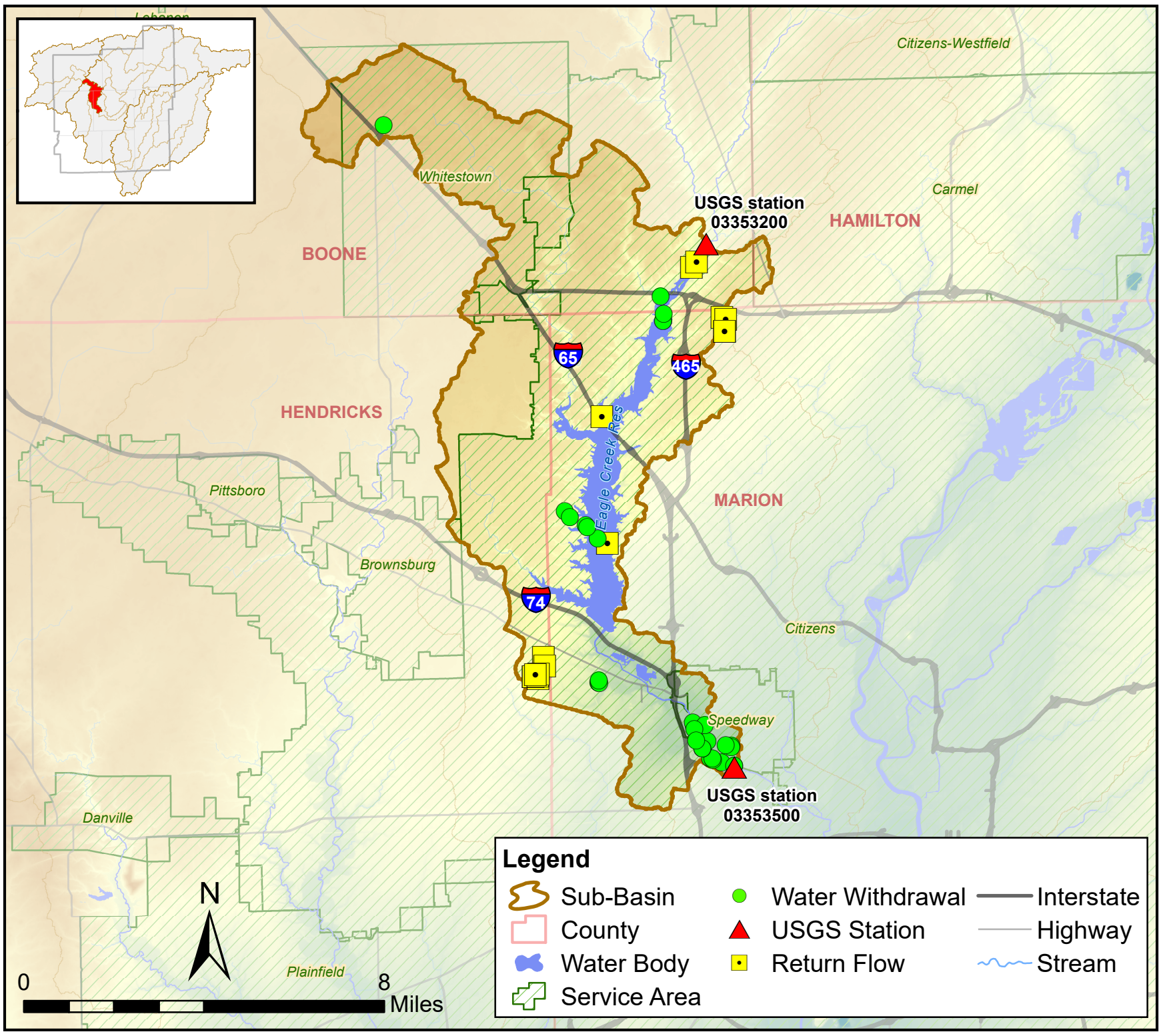

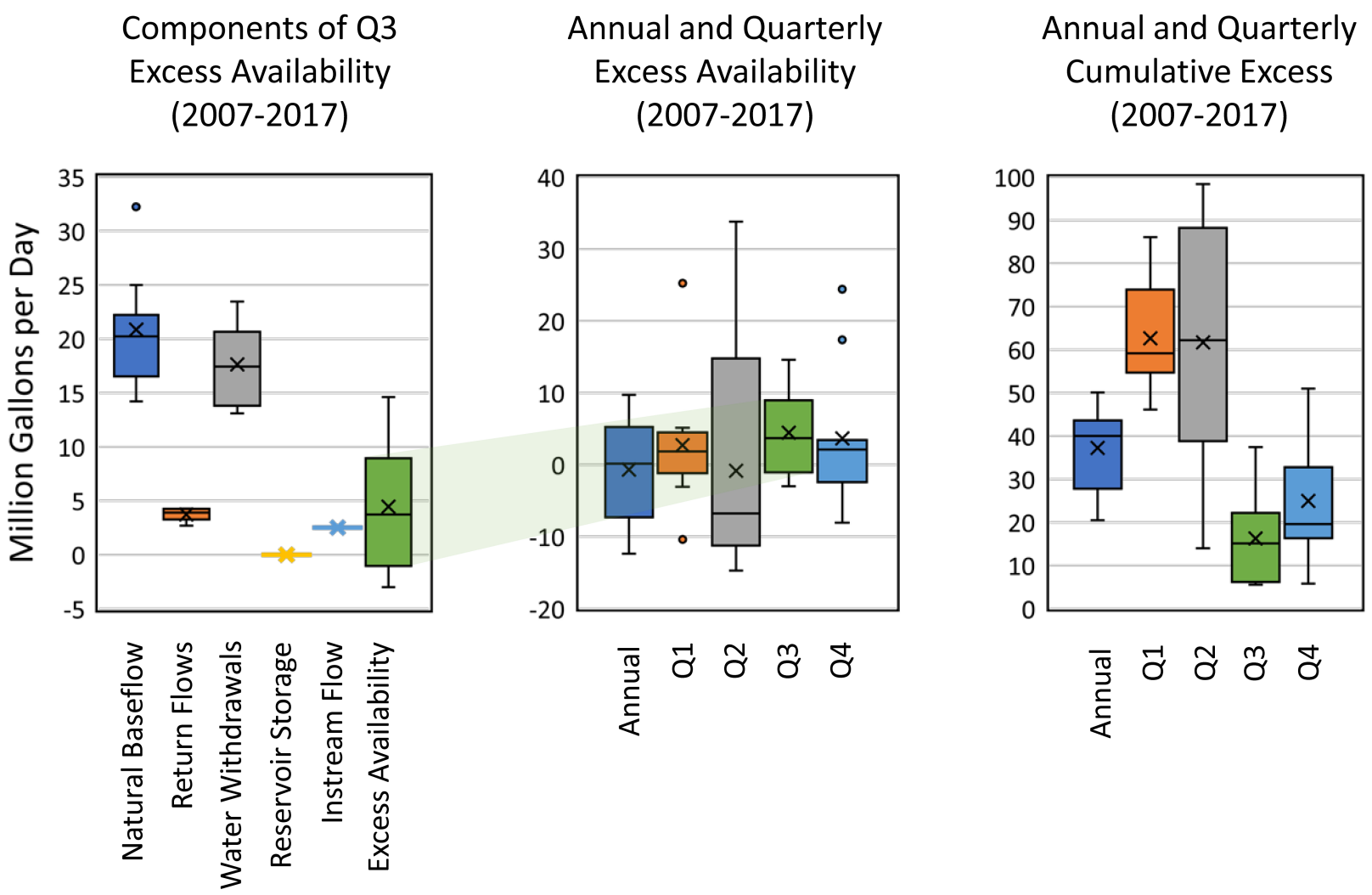

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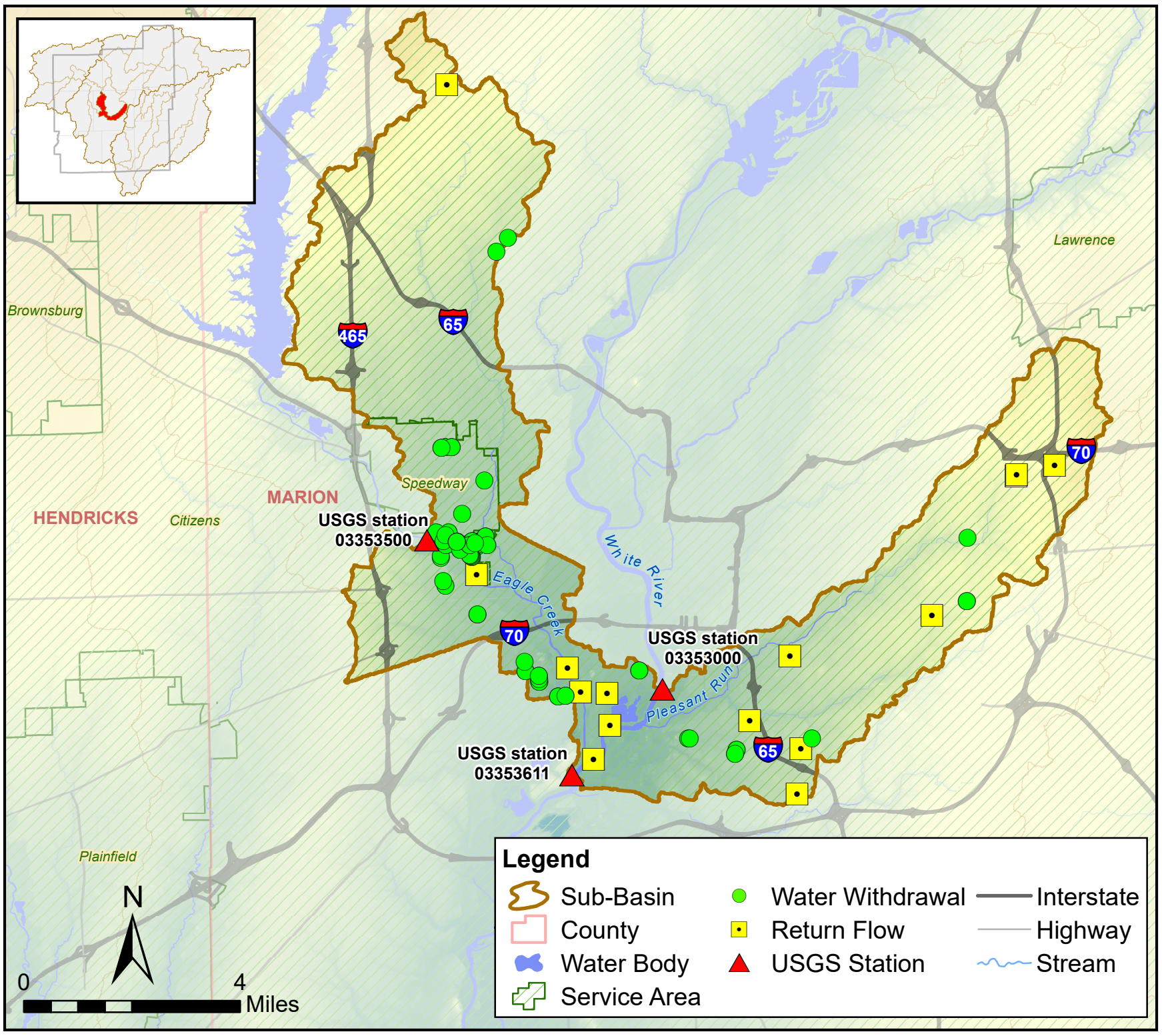

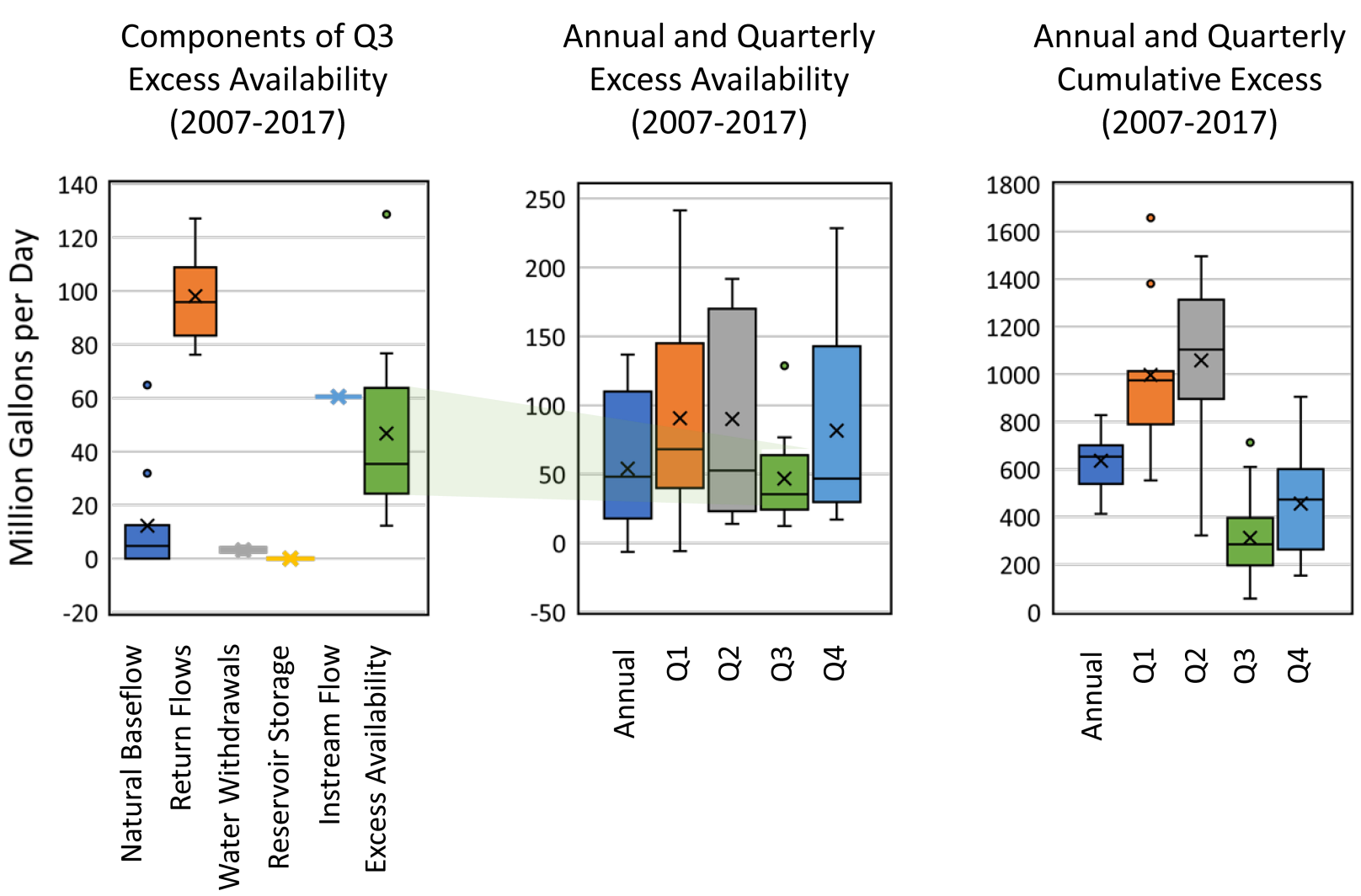

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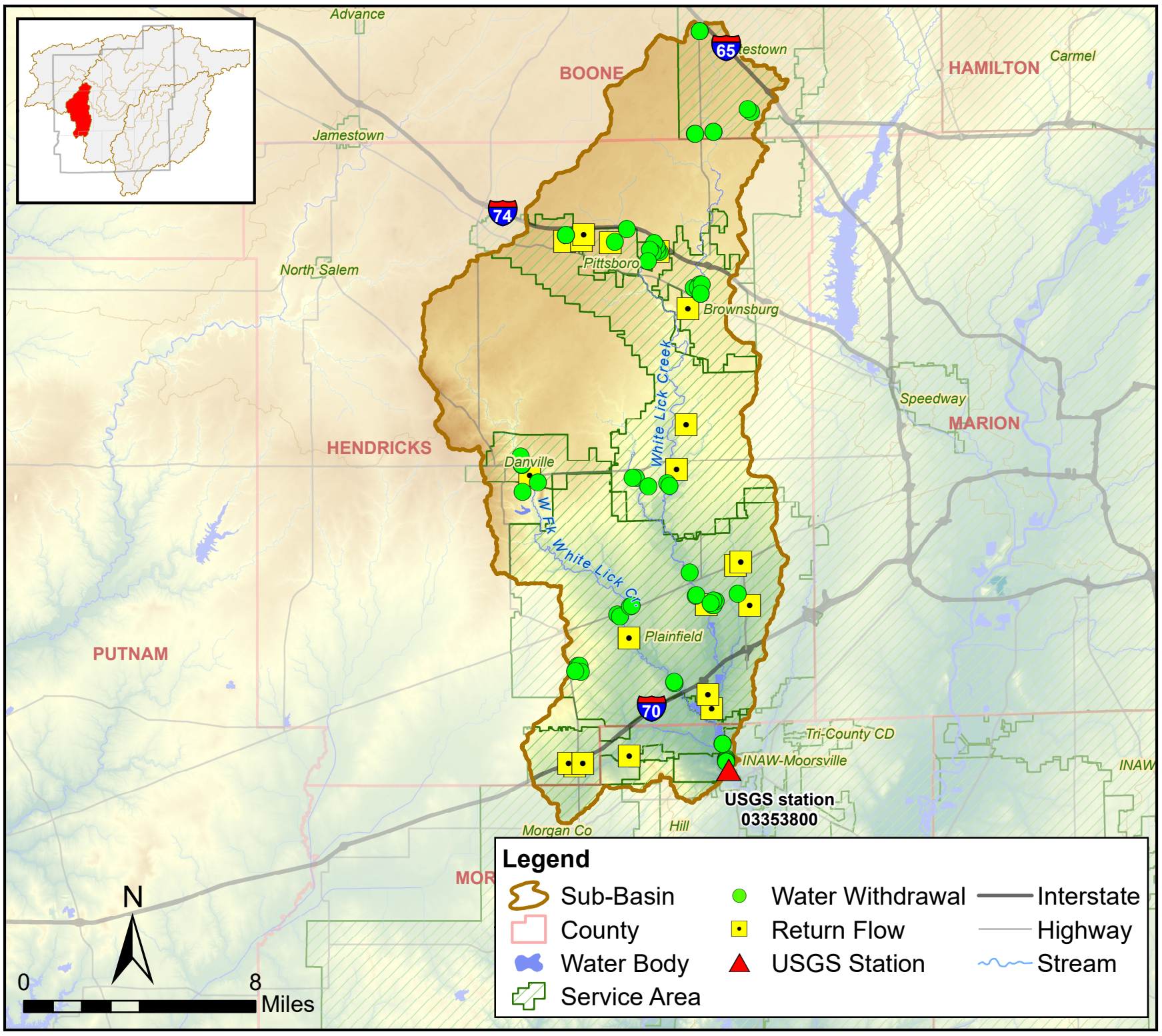
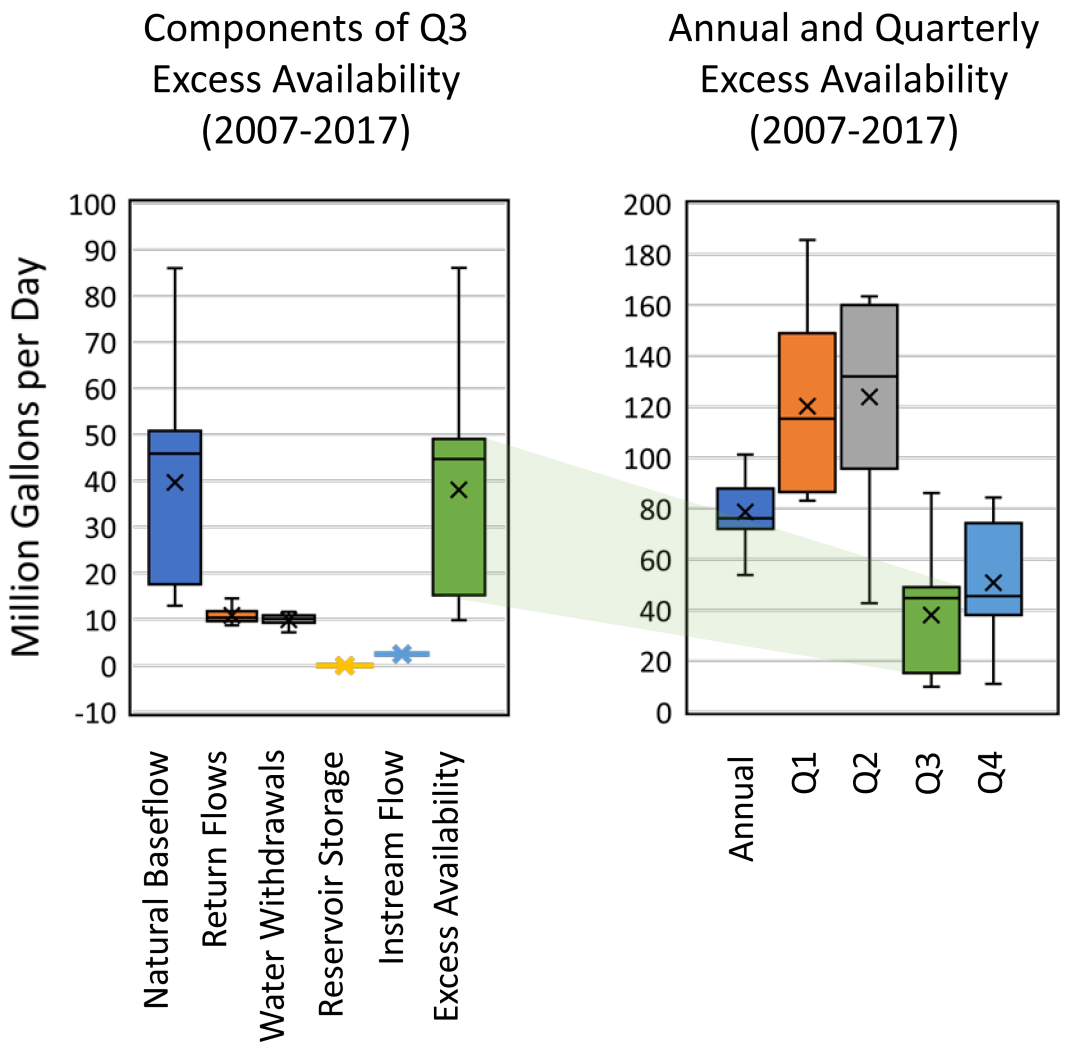
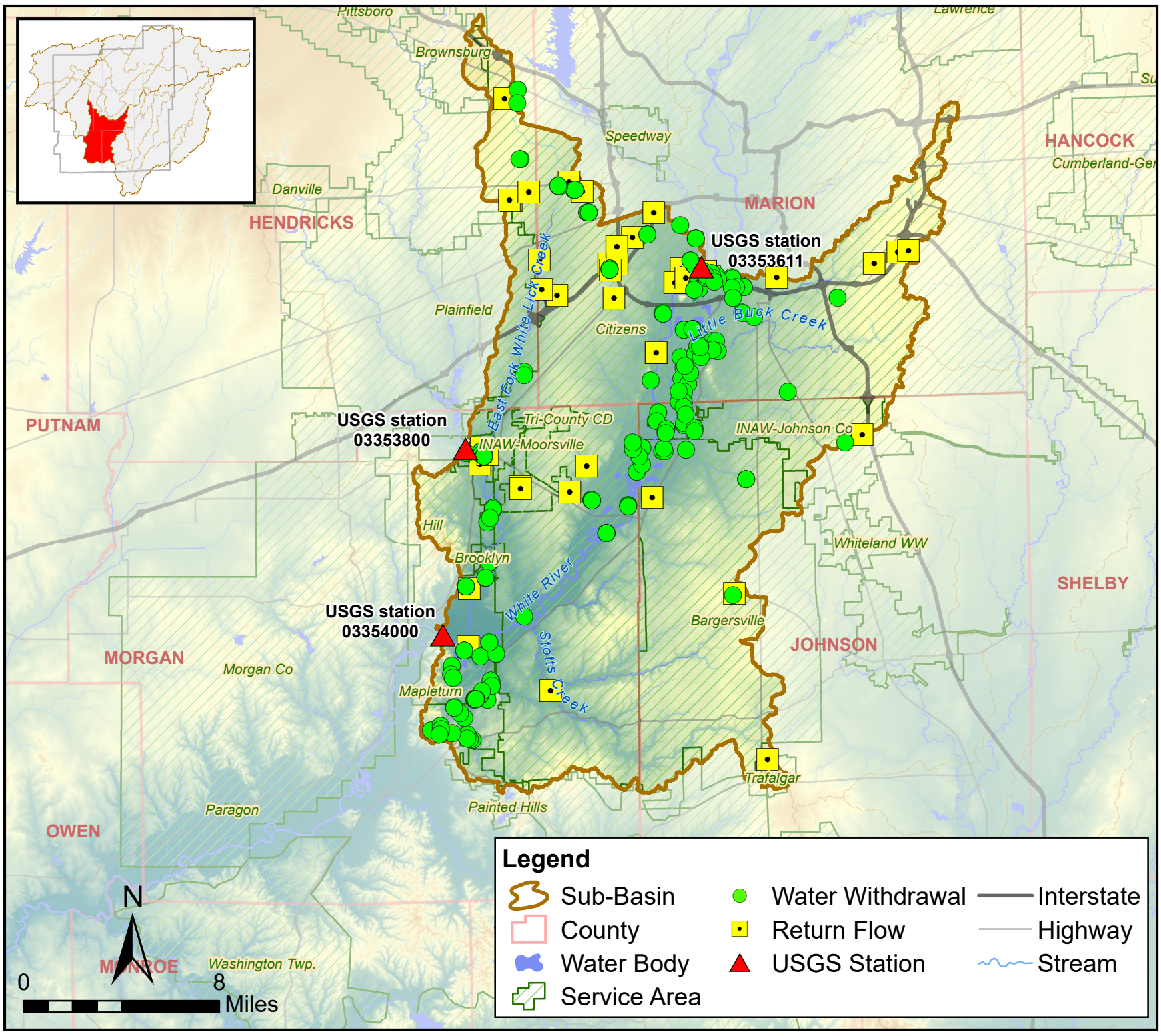
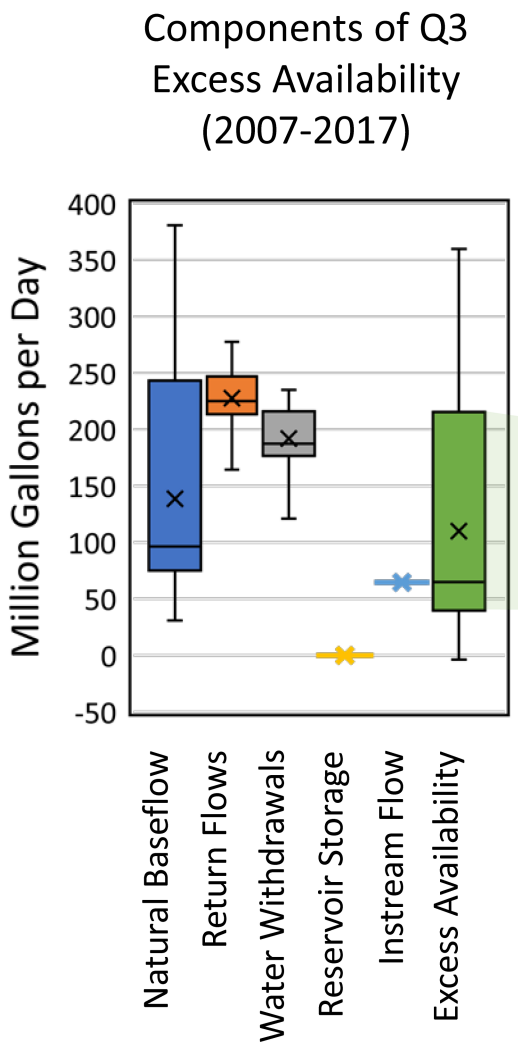
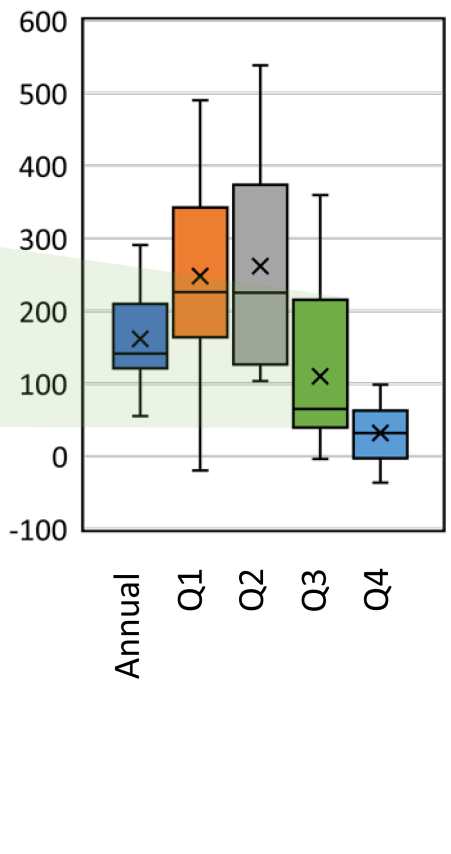


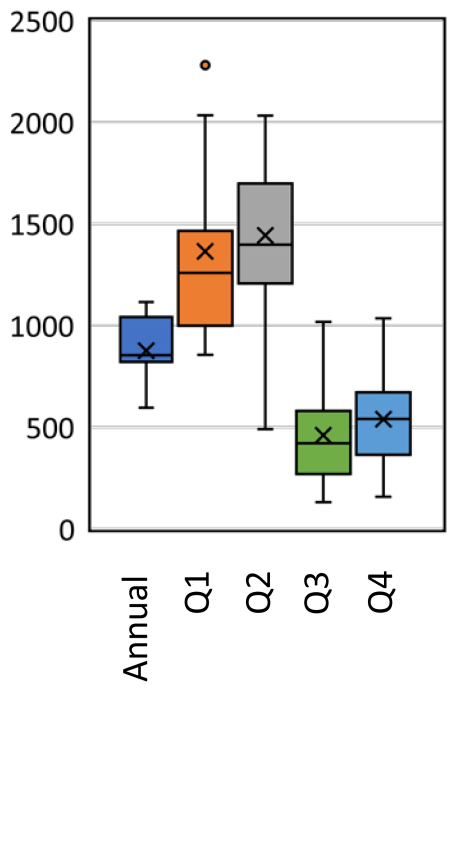


Sub-basin 12 of the White River and Tributaries drainage system



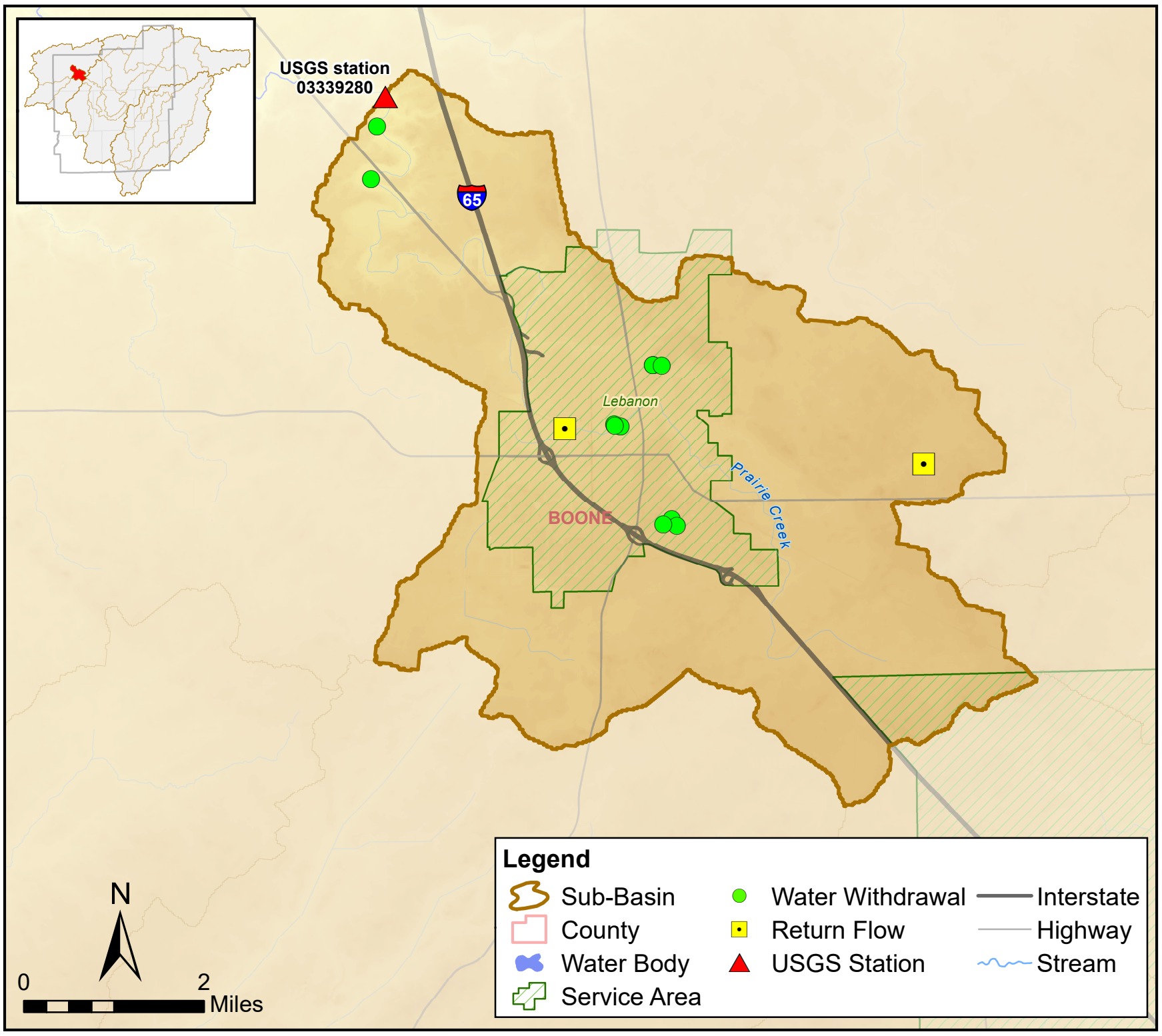


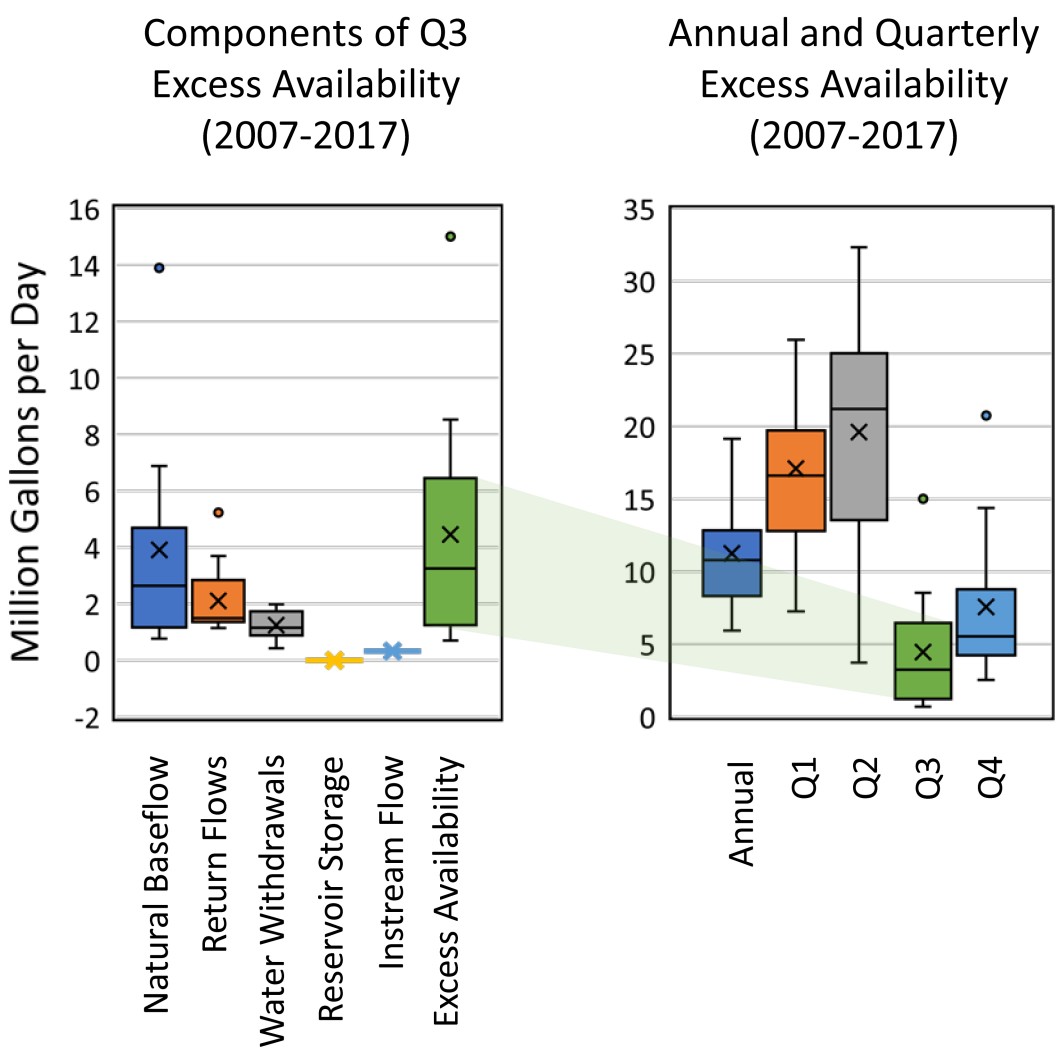




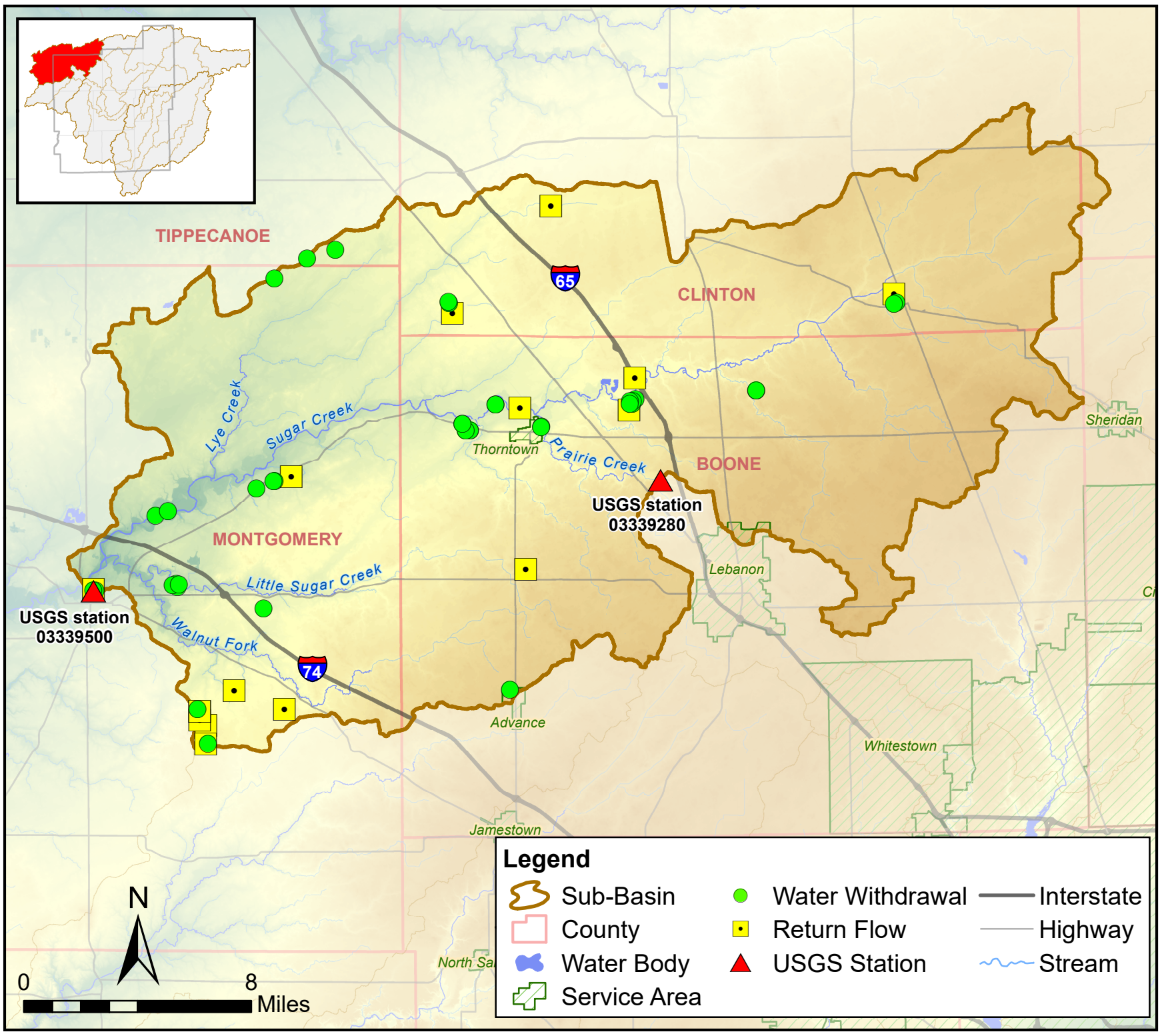
Sub-basin 13 of the White River and Tributaries drainage system

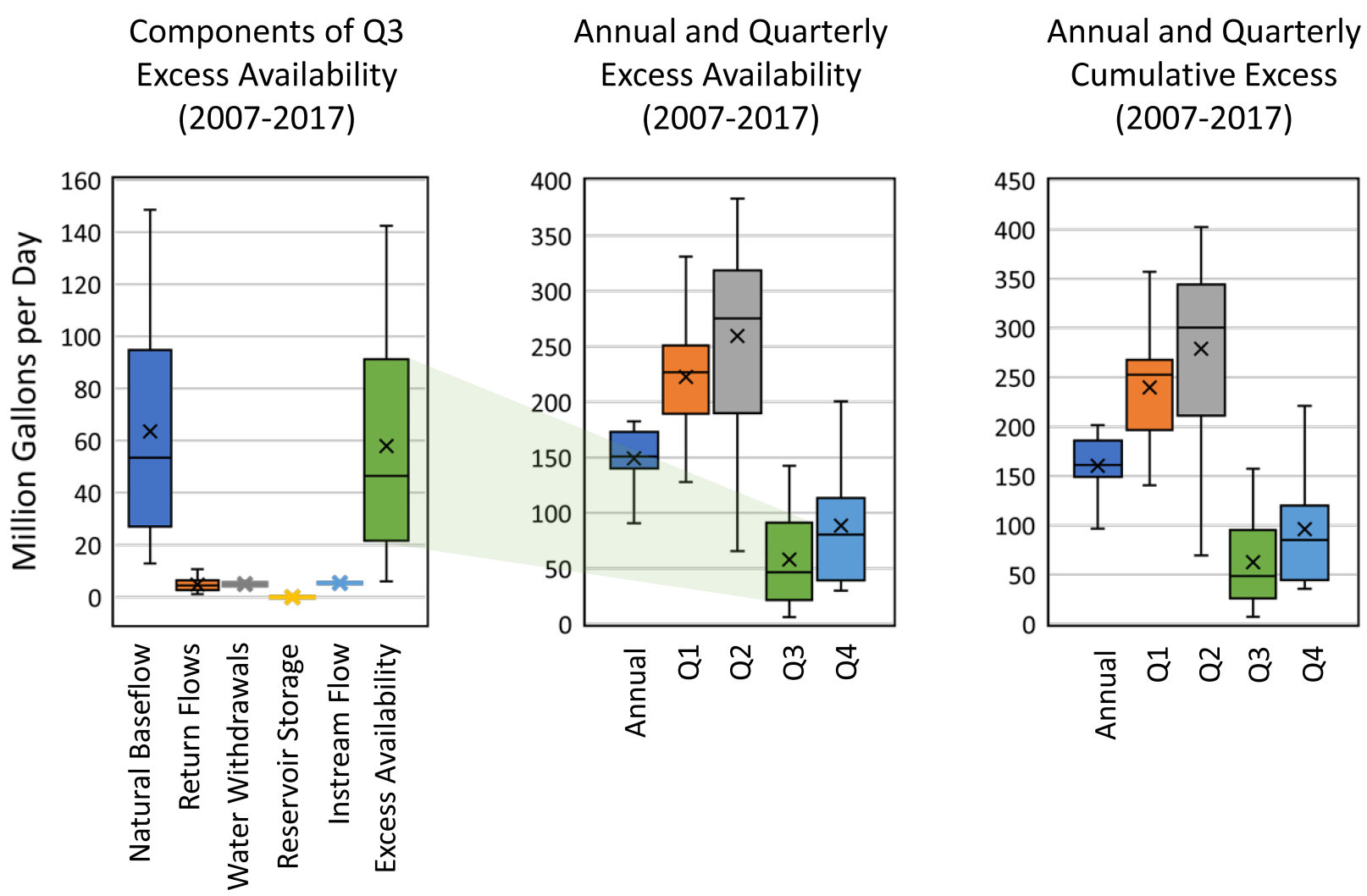
B.2 Tributaries of the Wabash River Drainage System





Sub-basin 1 of the Tributaries of the Wabash River drainage system





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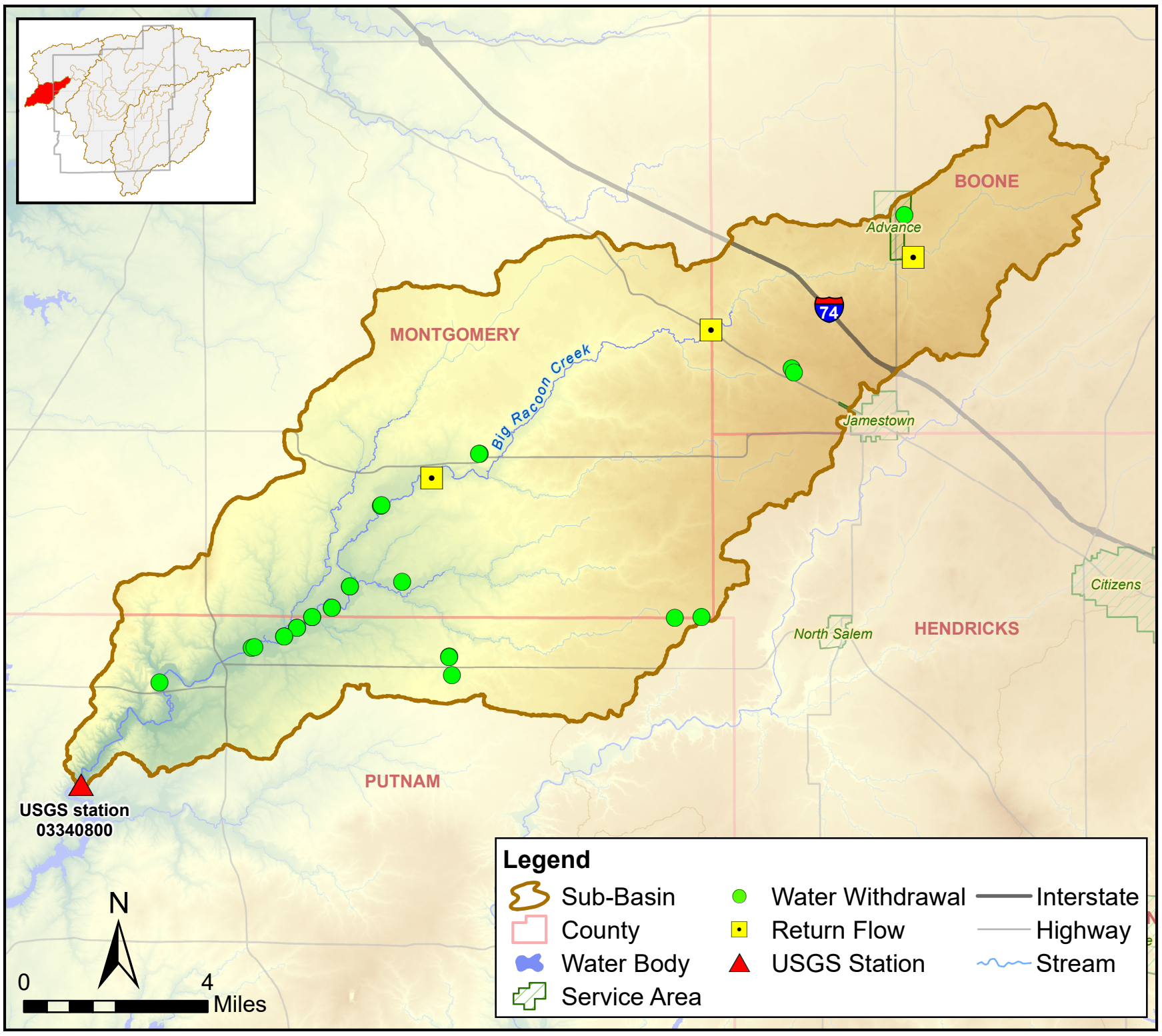
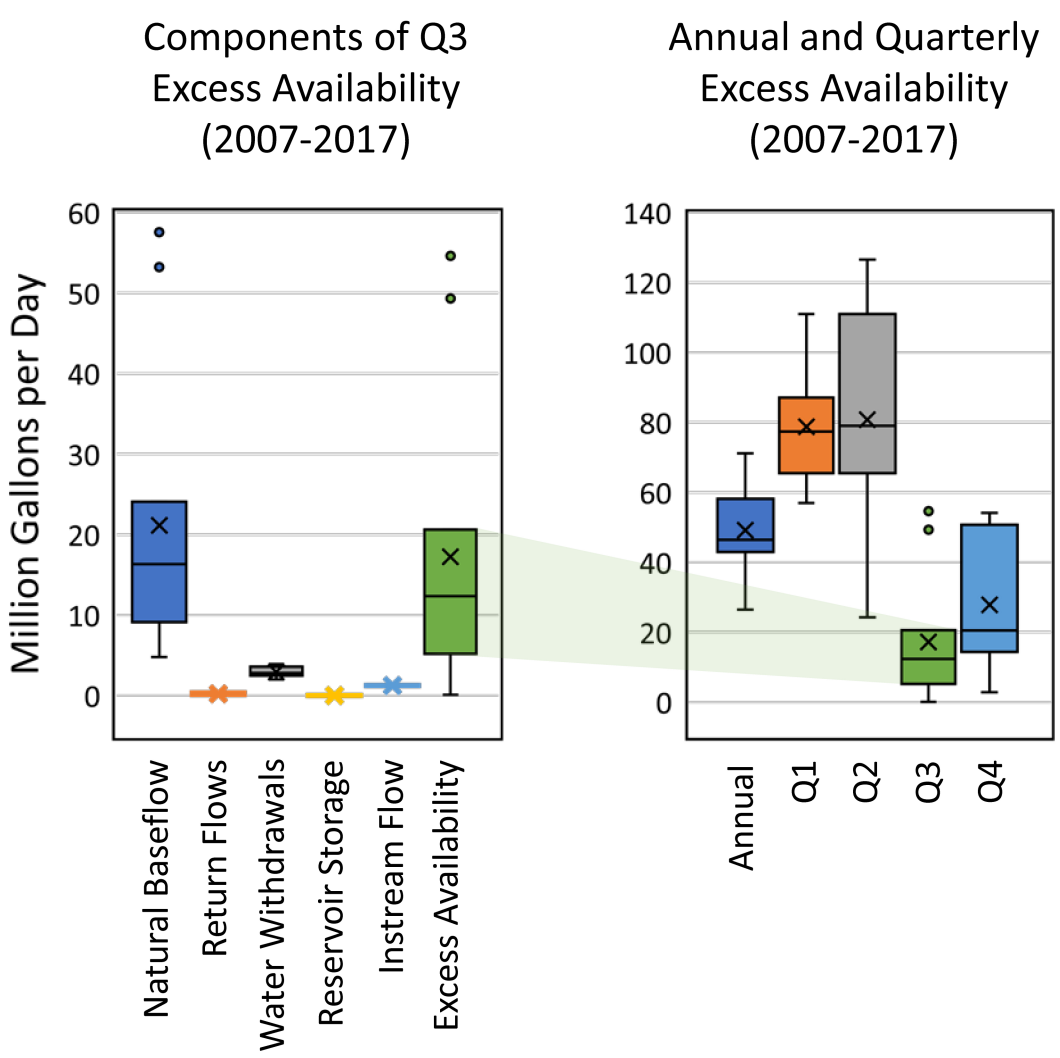
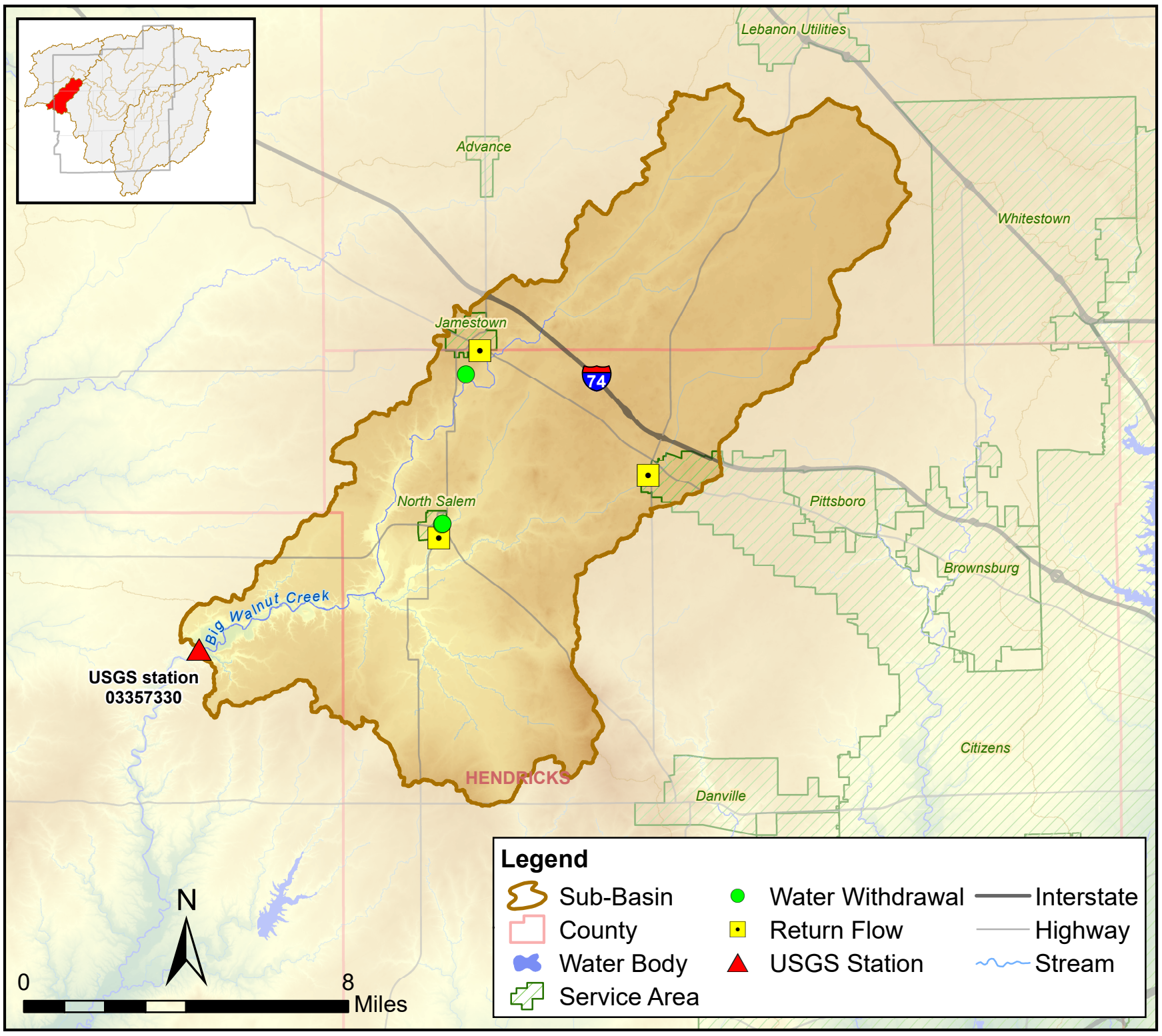
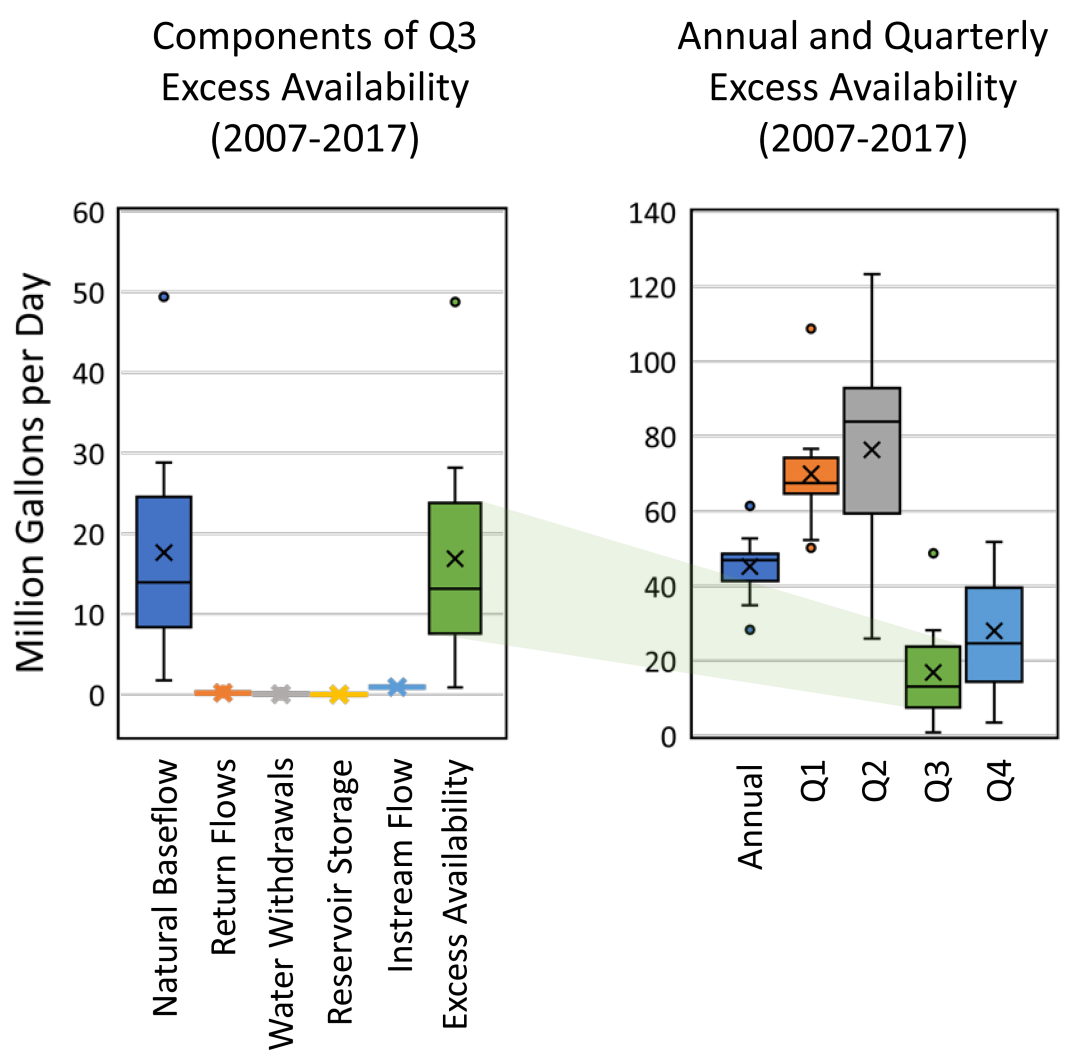




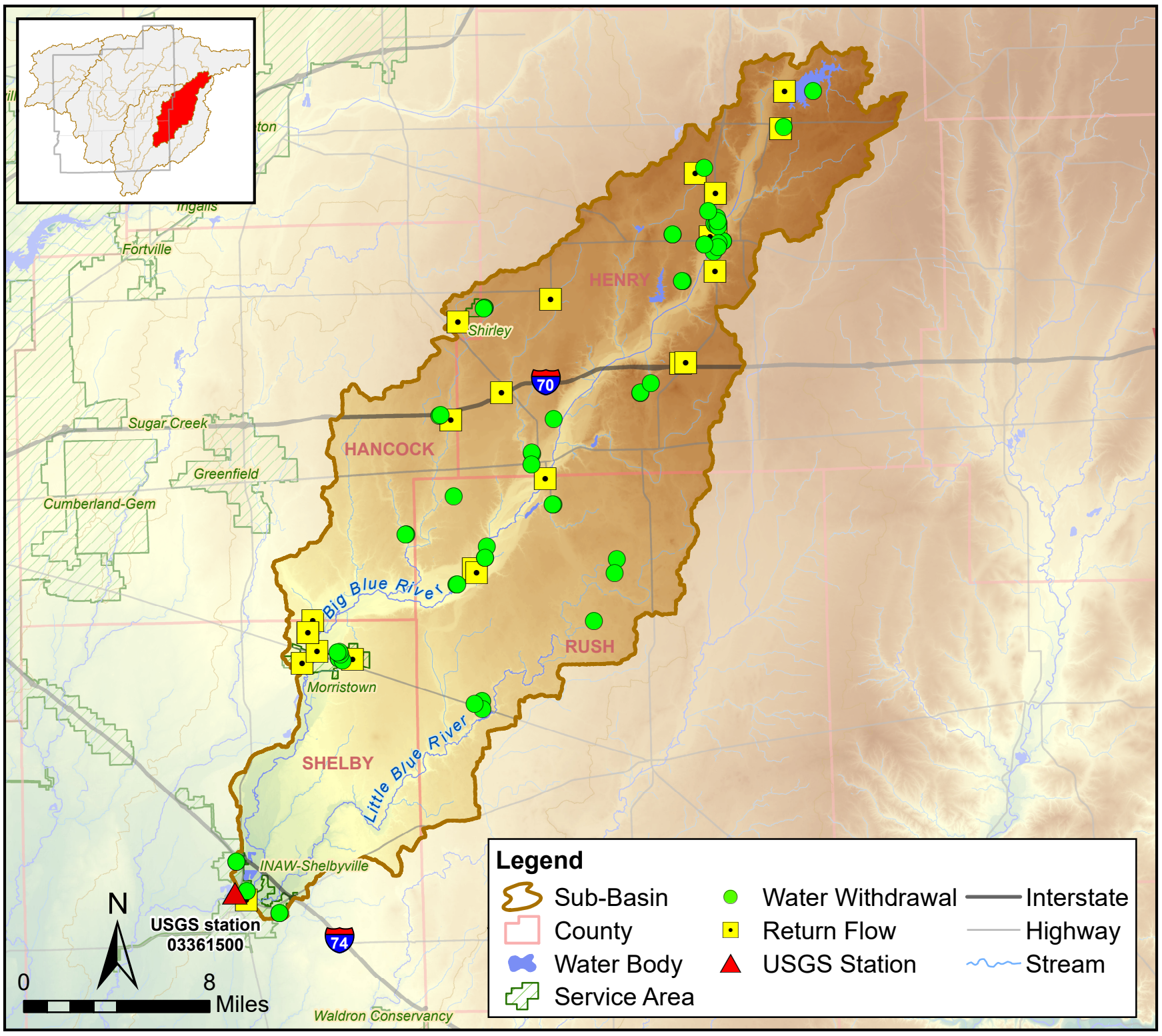
Sub-basin 3 of the Tributaries of the Wabash River drainage system

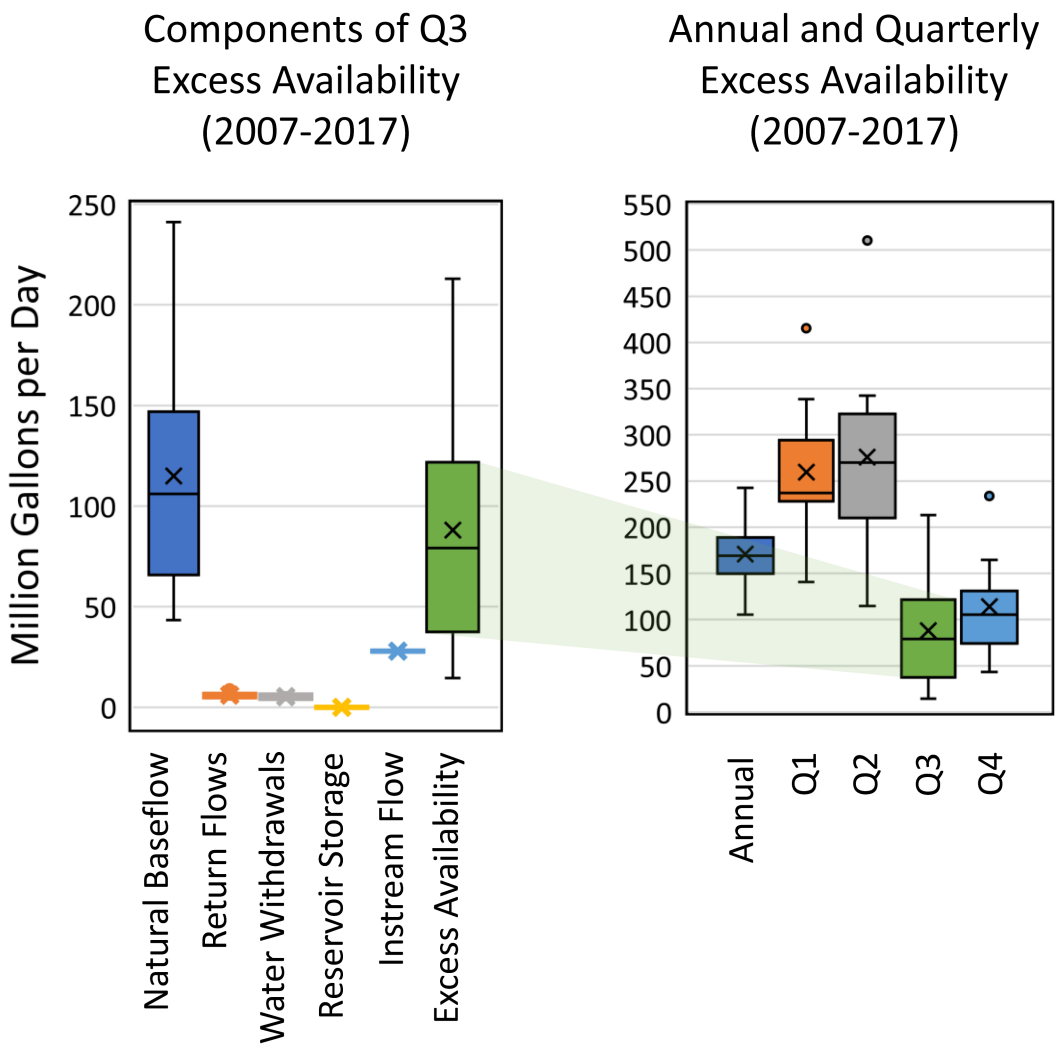




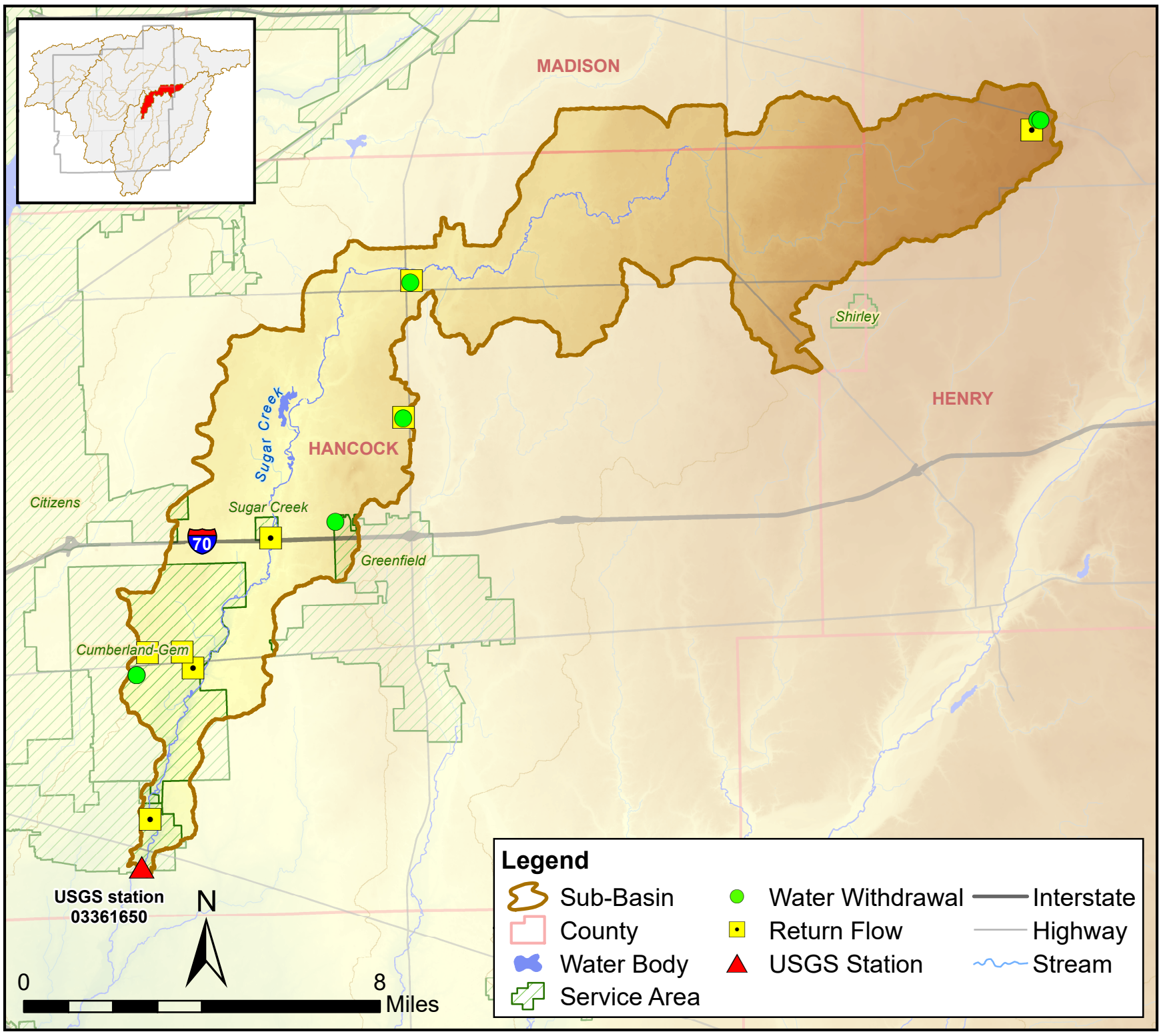
Sub-basin 4 of the Tributaries of the Wabash River drainage system

B.3 Tributaries of East Fork White River Drainage System

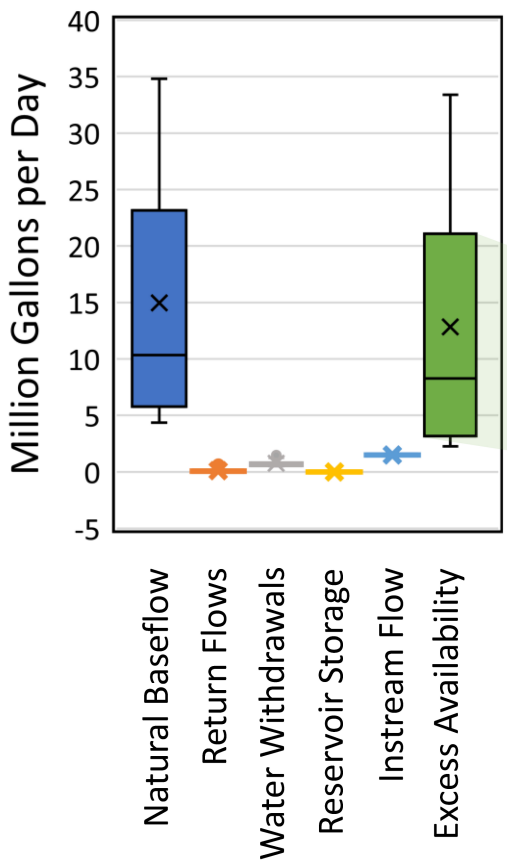




Sub-basin 1 of the Tributaries of the East Fork White River drainage system



Components of Q3 Excess Availability (2007-2017)



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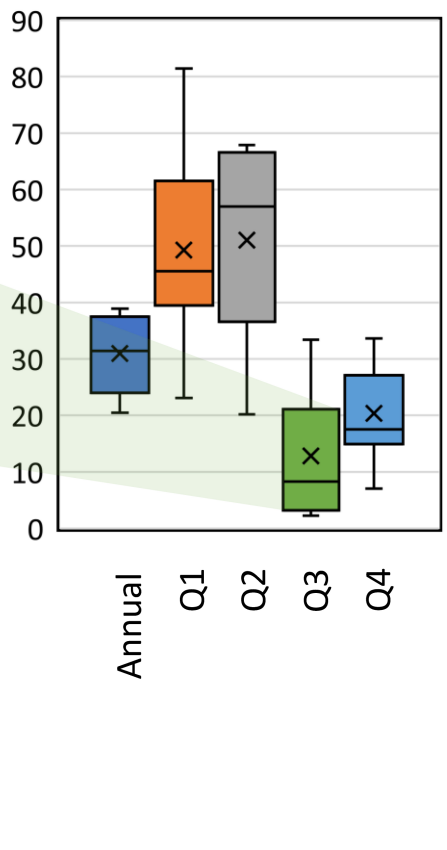
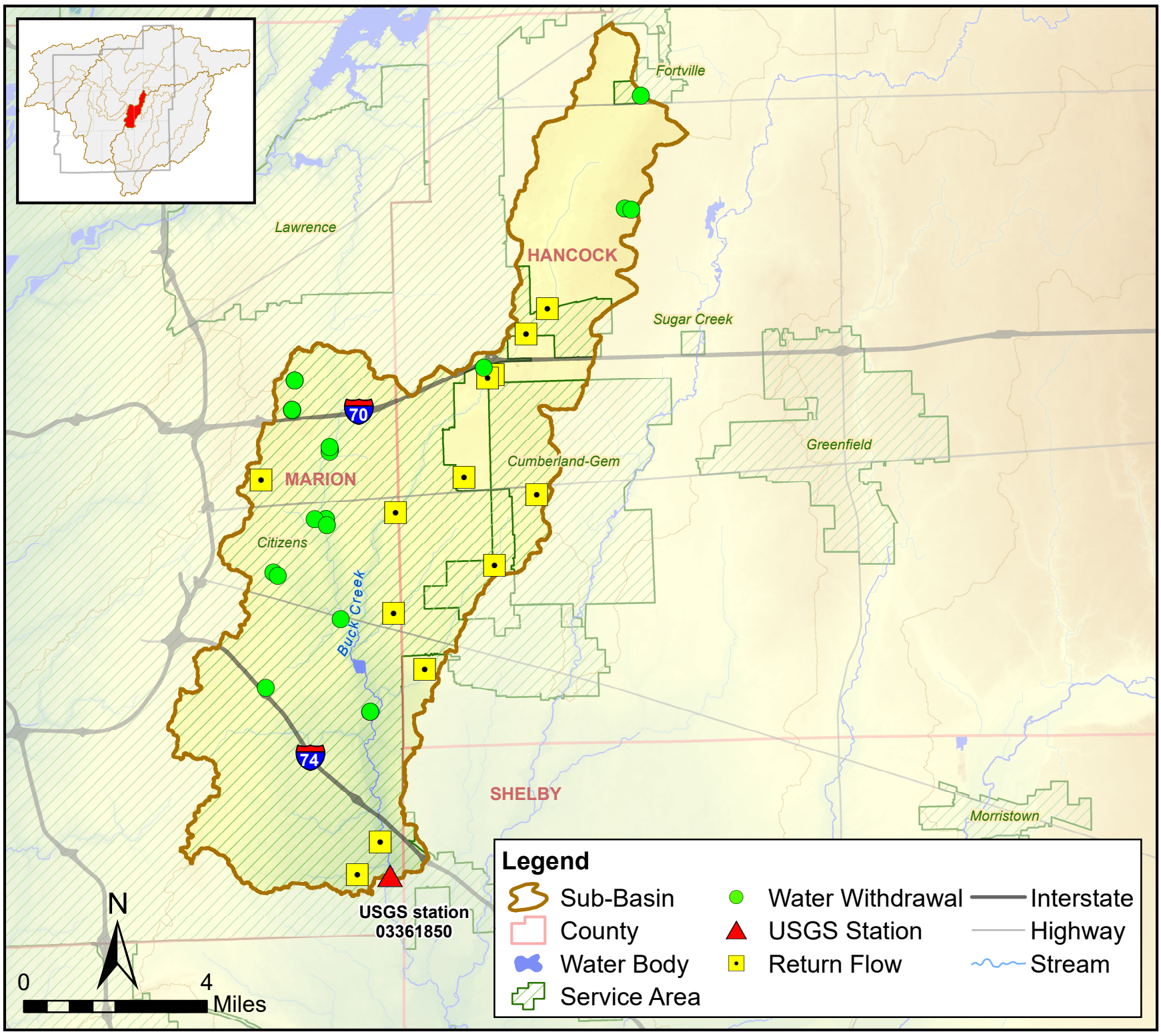
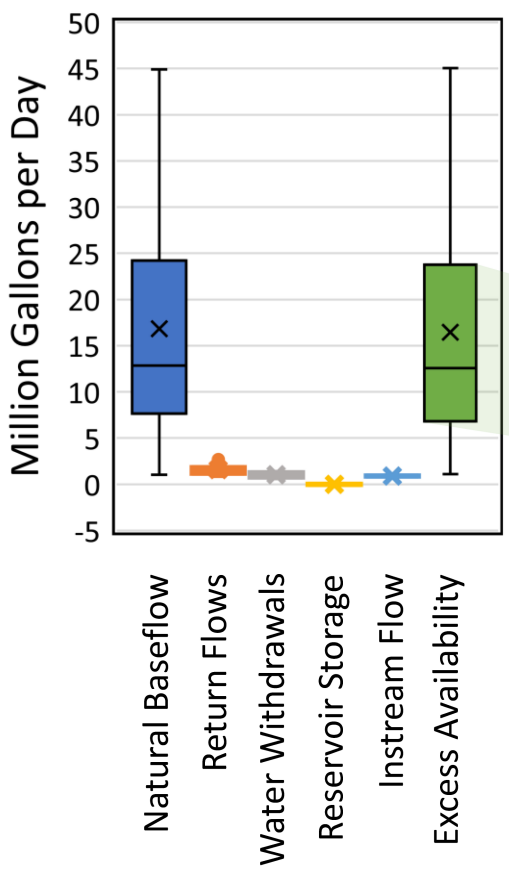


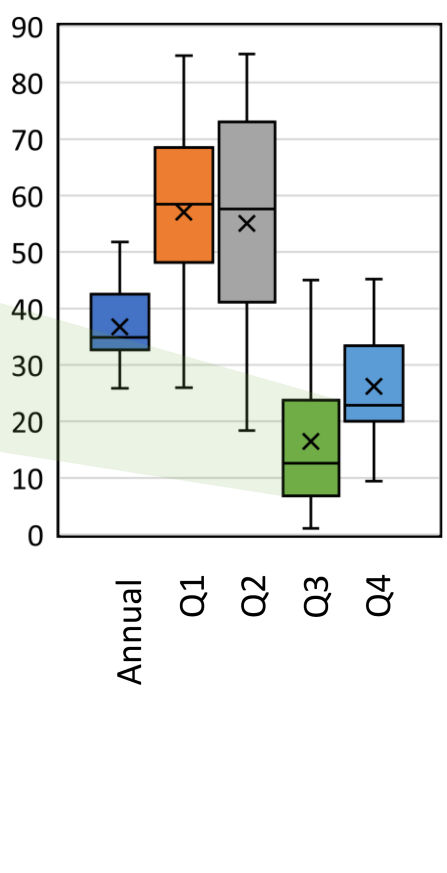
Sub-basin 2 of the Tributaries of the East Fork White River drainage system



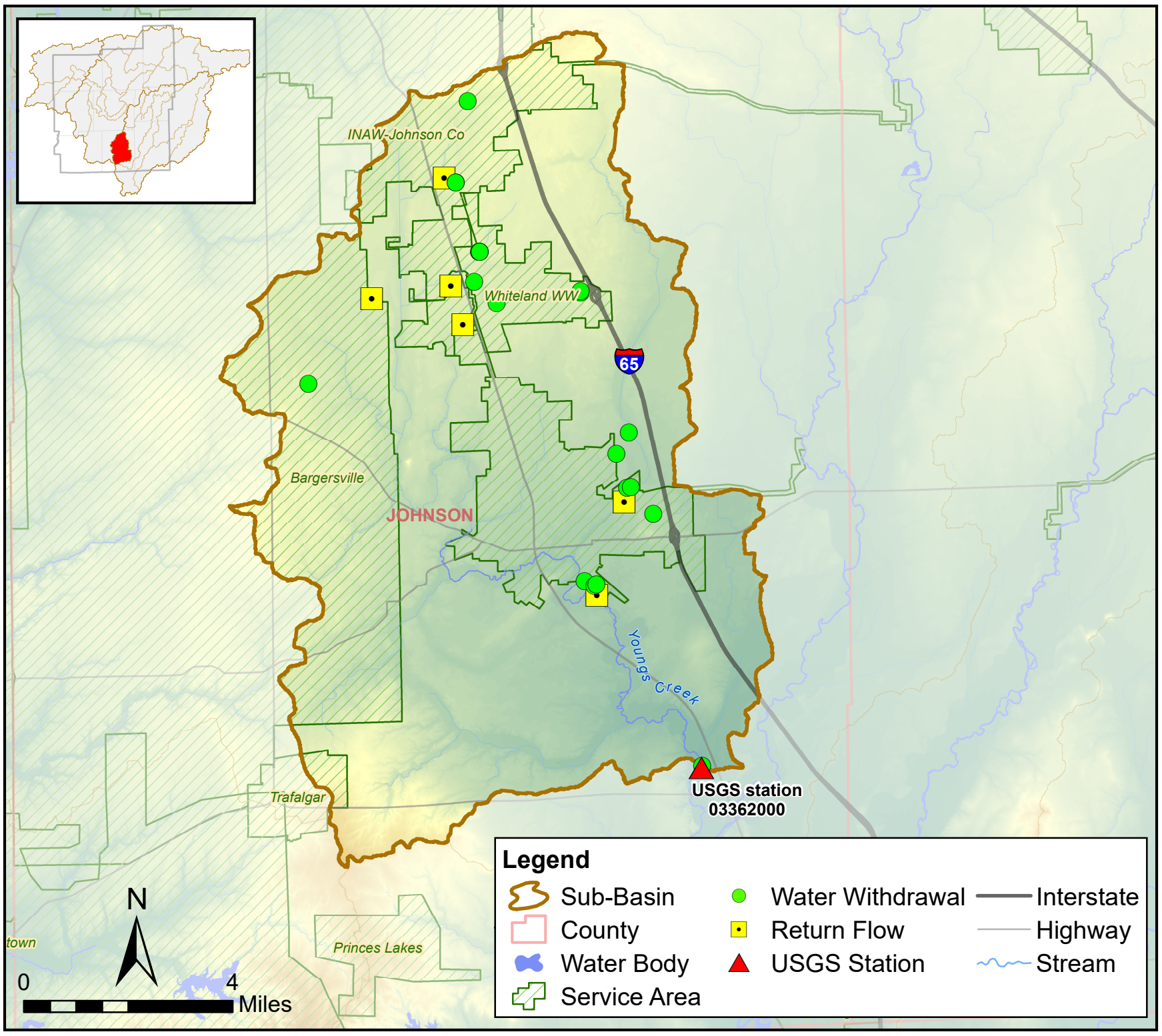
Components of Q3 Excess Availability (2007-2017)

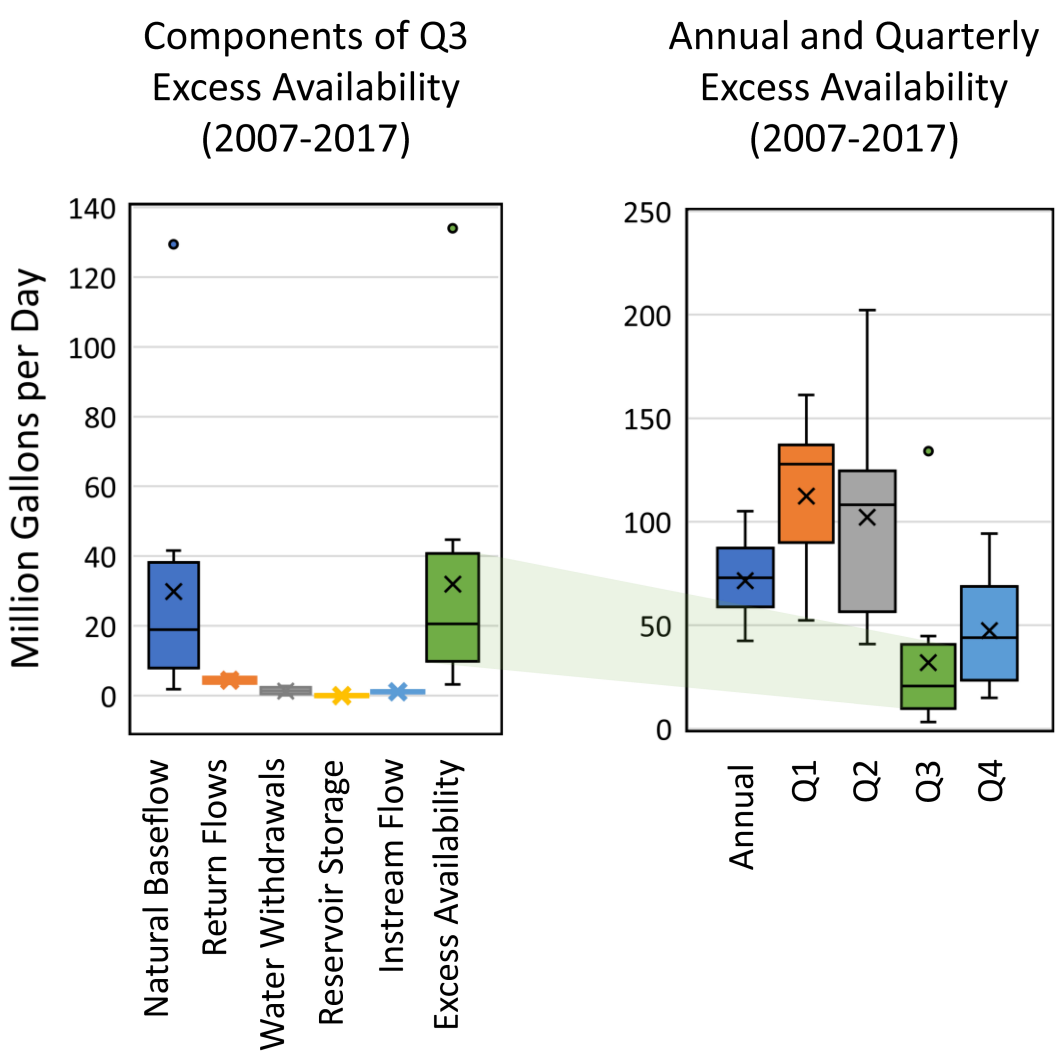


Annual and Quarterly Excess Availability (2007-2017)

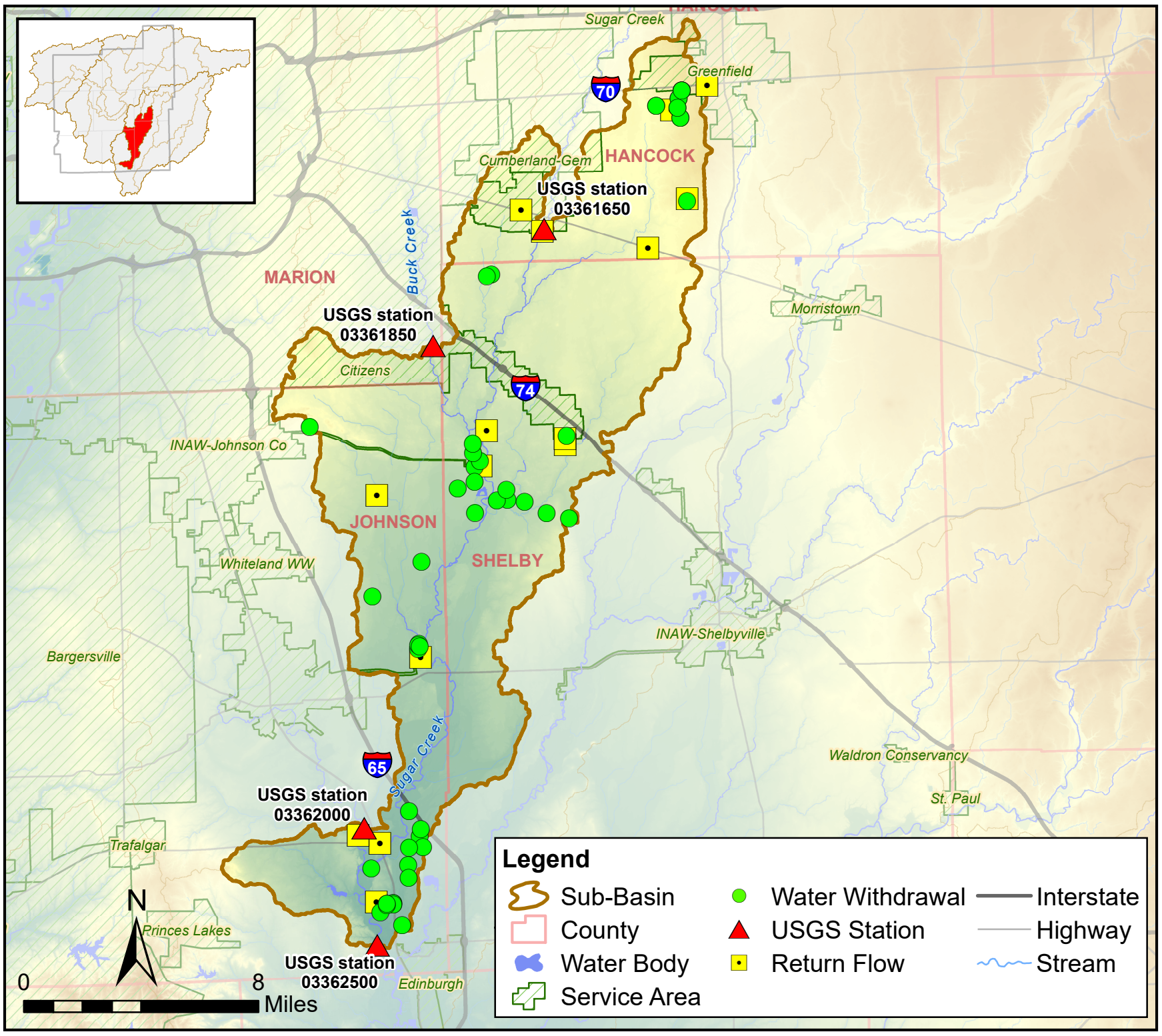


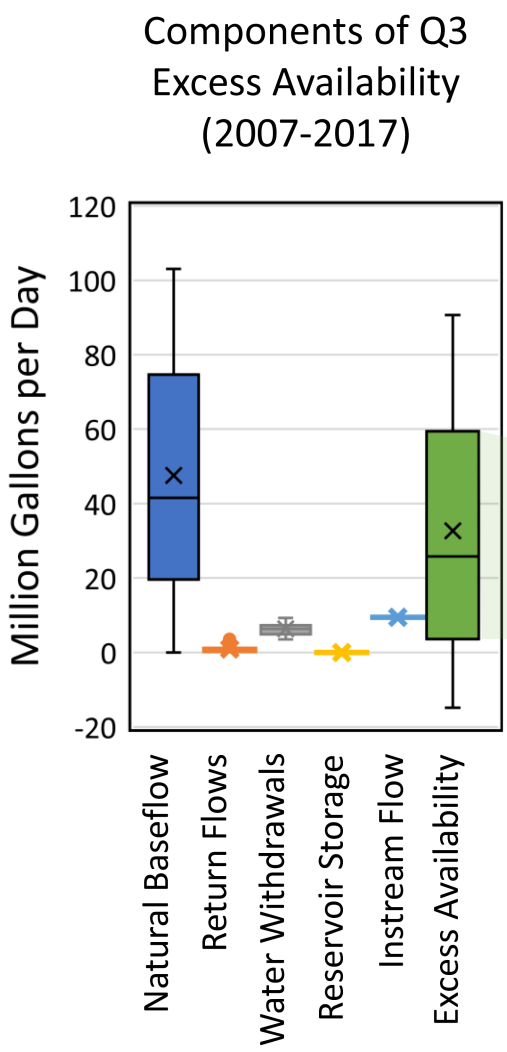
Sub-basin 3 of the Tributaries of the East Fork White River drainage system

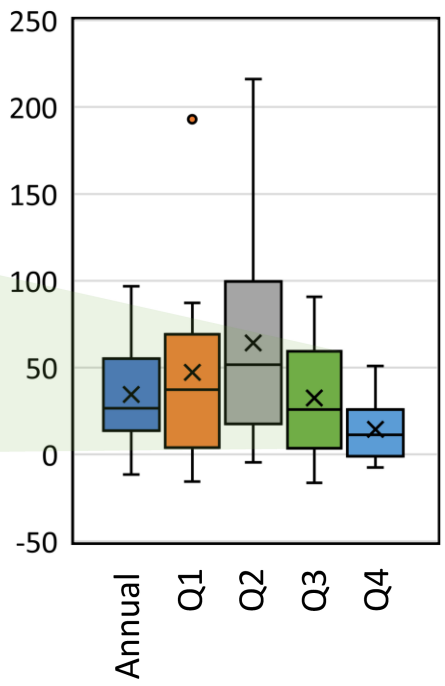


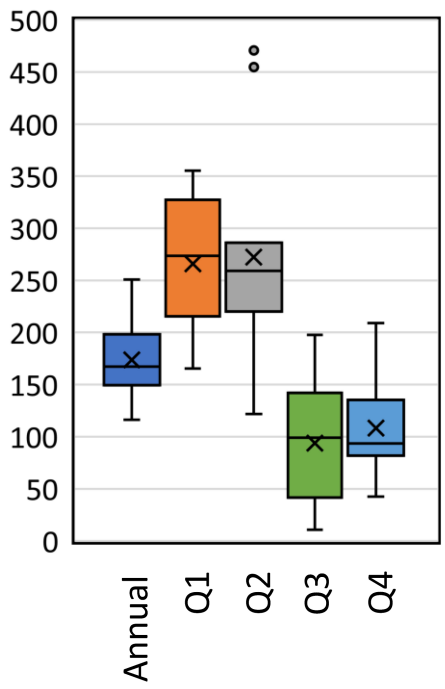


Sub-basin 4 of the Tributaries of the East Fork White River drainage system

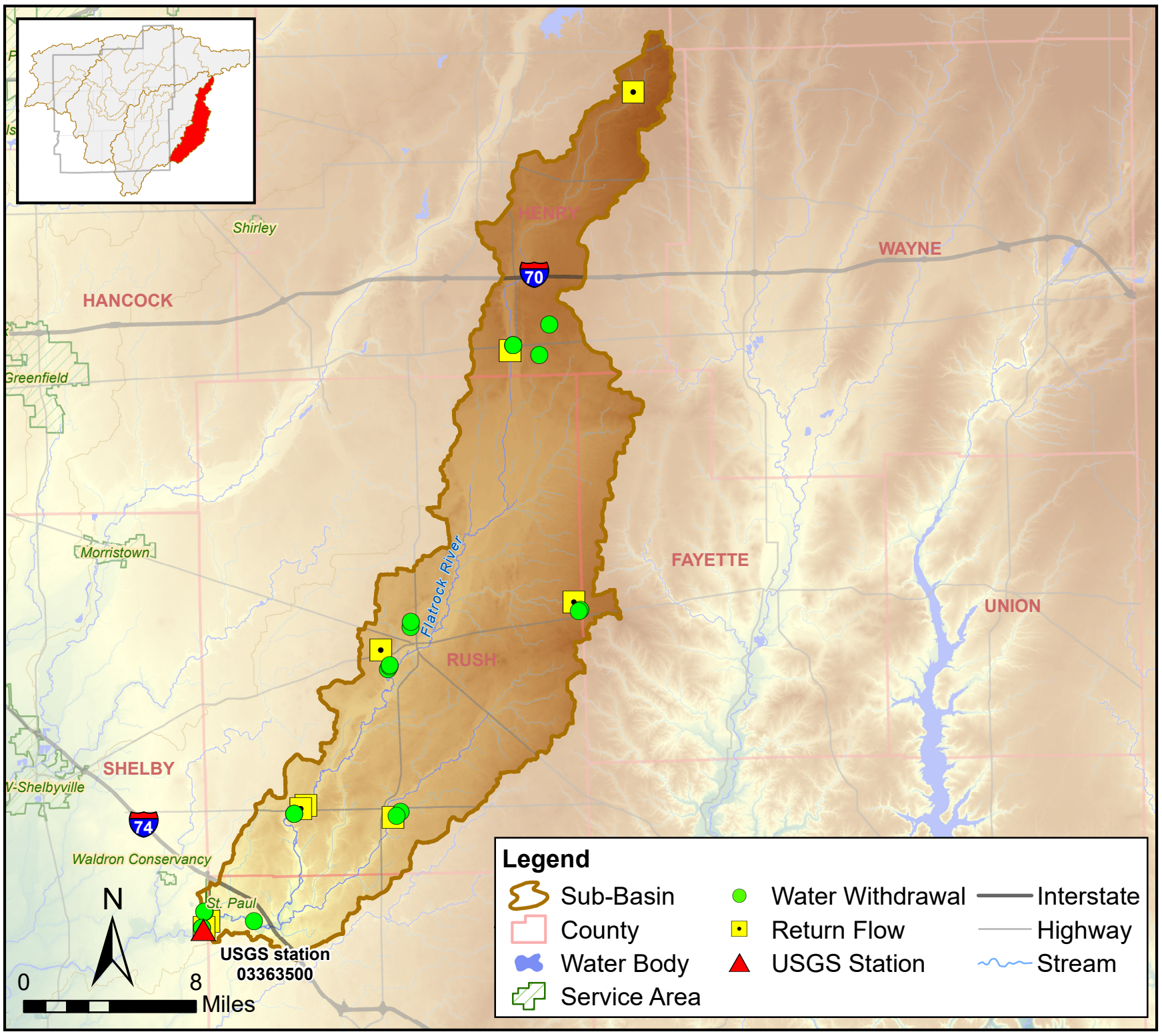


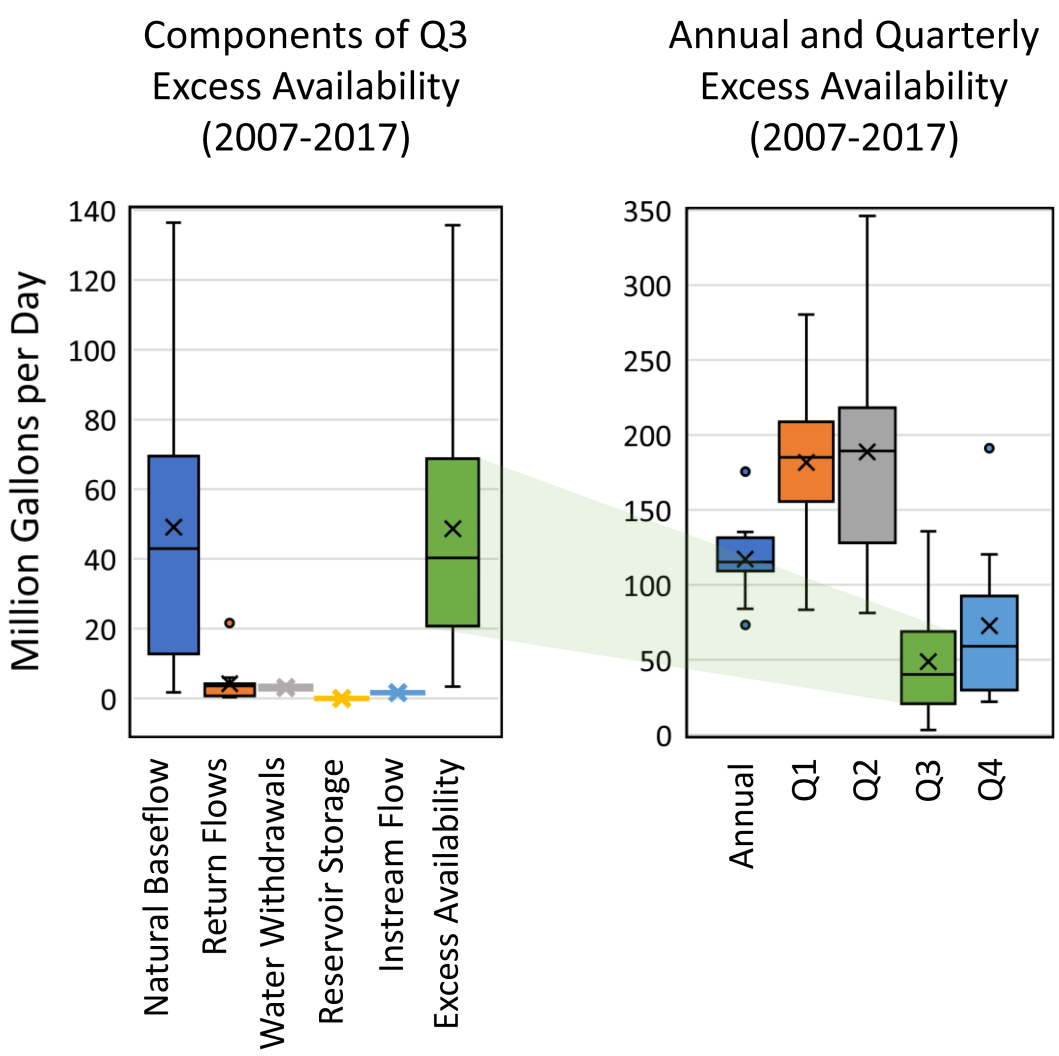






Sub-basin 5 of the Tributaries of the East Fork White River drainage system





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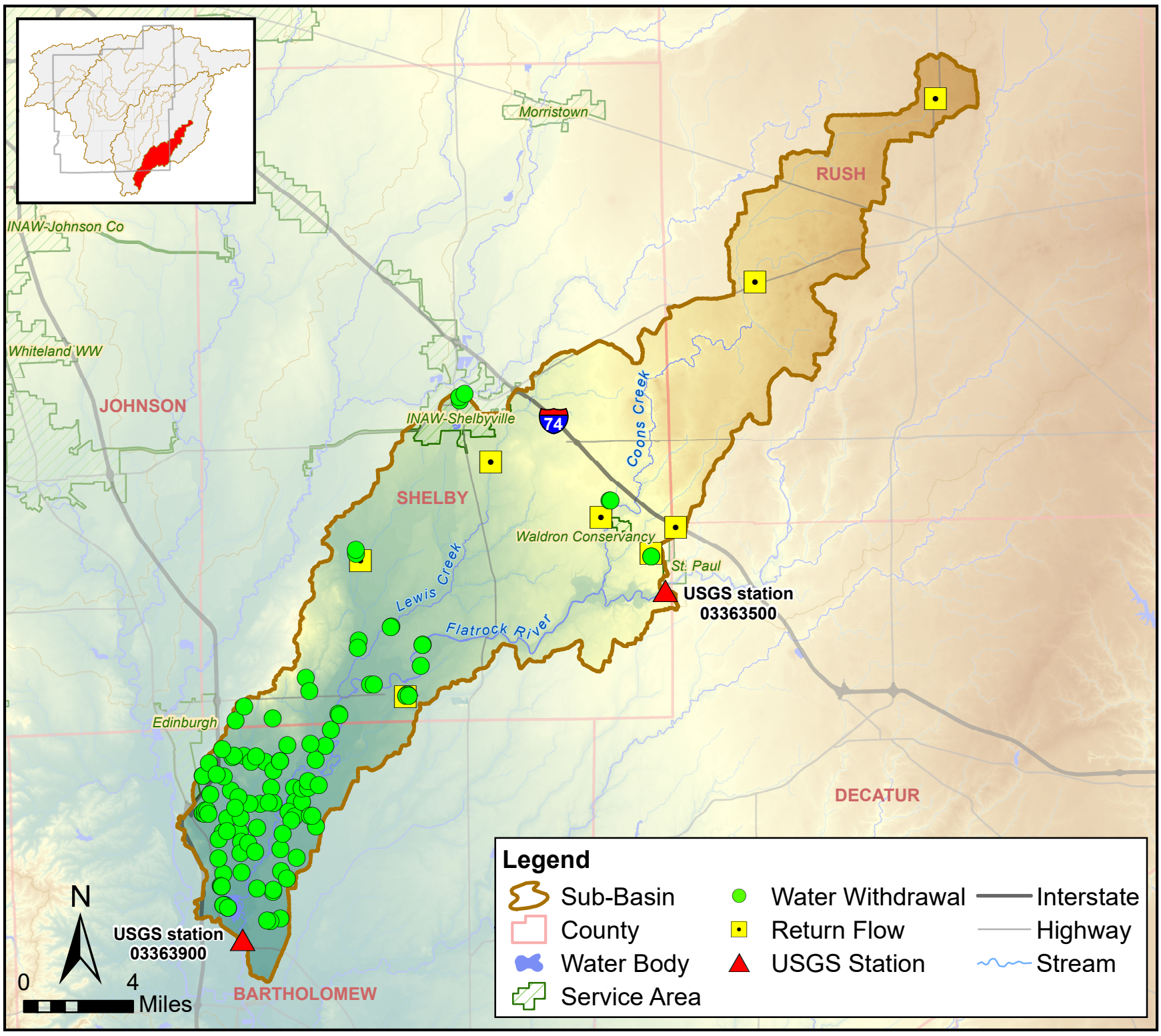
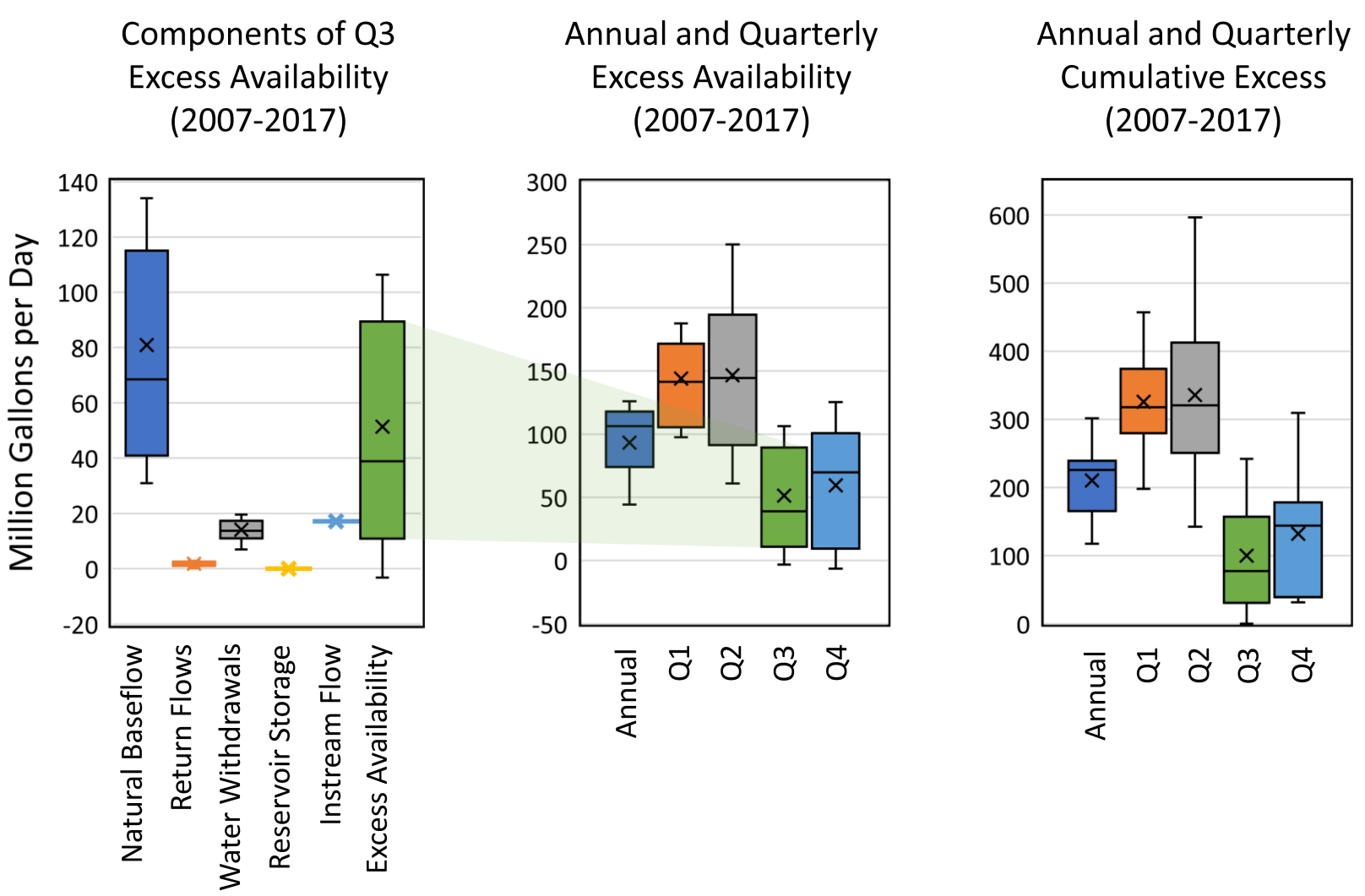
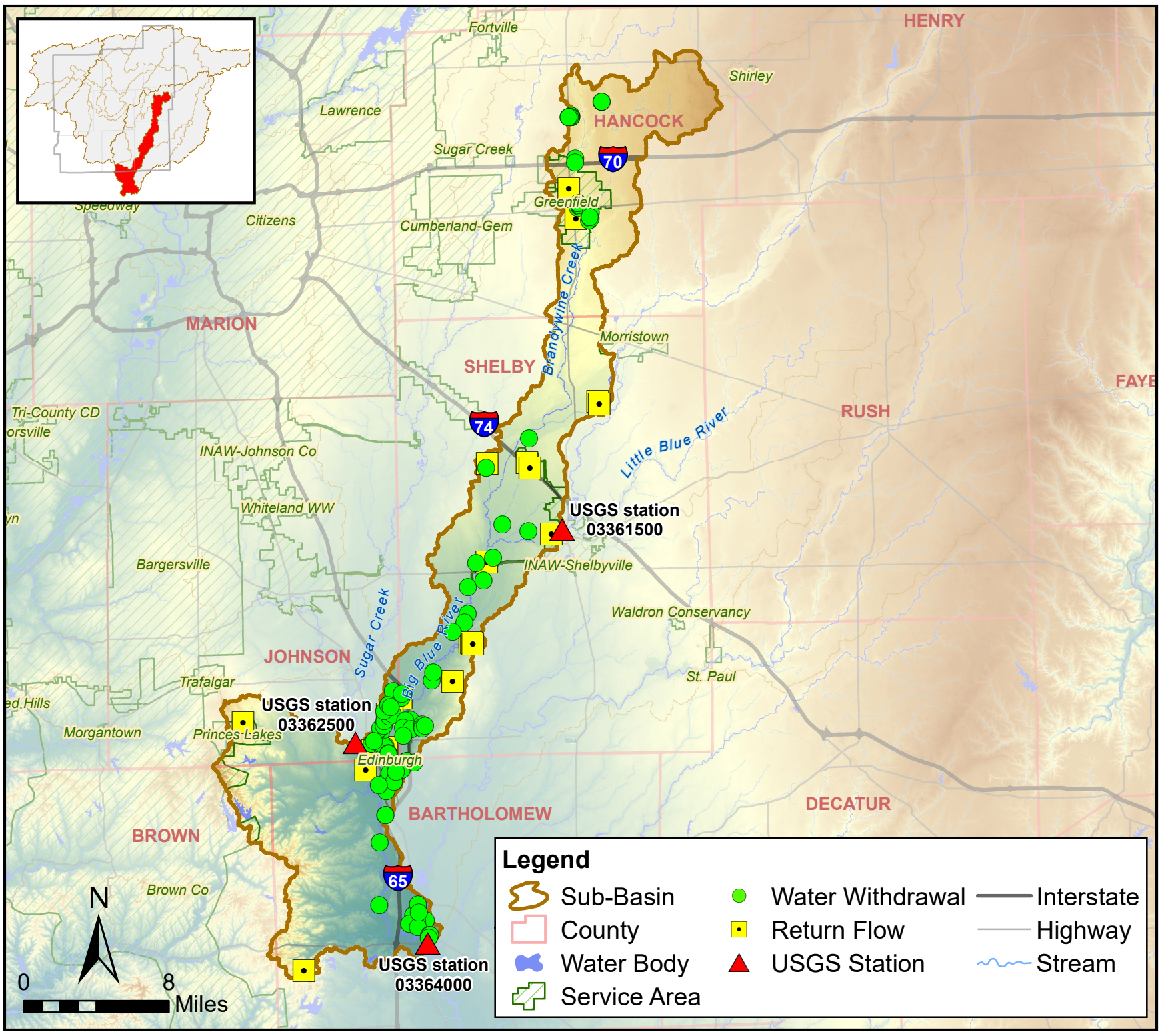
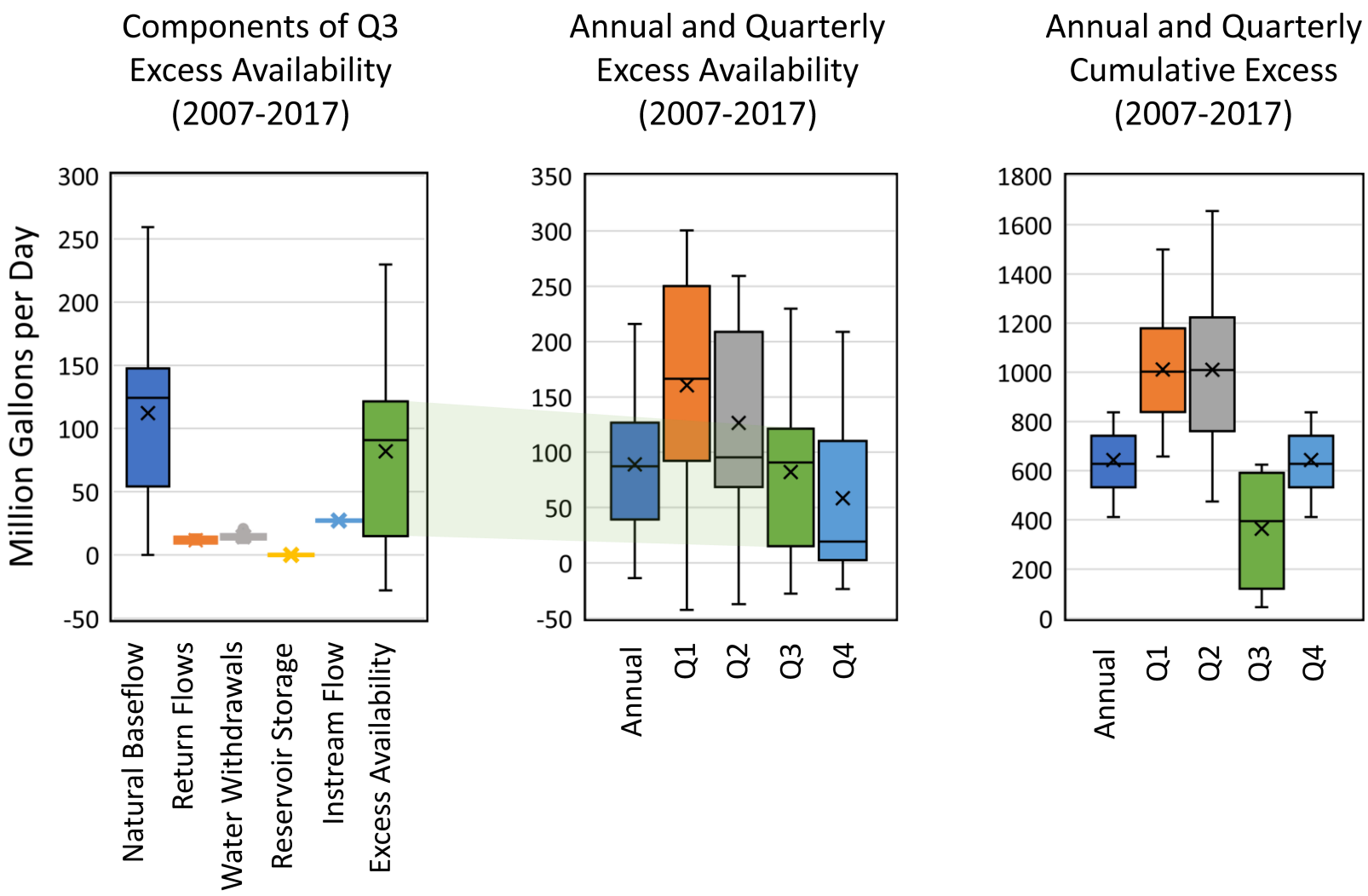




Sub-basin 7 of the Tributaries of the East Fork White River drainage system





Sub-basin 8 of the Tributaries of the East Fork White River drainage system

C SWB Recharge Model

We used the USGS Soil-Water-Balance computer code (SWB) to estimate the spatial and temporal variability of groundwater recharge in the Central Indiana region. The SWB code is applicable for this project; it was developed to provide a quick method for estimating recharge over regional scales. The code is a physically based, spatially and temporally variable recharge model (USGS, 2010). Model inputs include high-resolution meteorological, land cover, and soil hydrology data sets that are nationally consistent and publicly available.

C.1 SWB

The SWB code uses a modified Thornthwaite-Mather approach to calculate recharge; it estimates potential direct recharge, defined as precipitation water in excess of interception, runoff, evapotranspiration (ET), and soil-water storage capacity (Figure C.1). The method assumes that excess water infiltrates vertically below the root zone and reaches the water table. The code does not explicitly consider indirect recharge or localized recharge mechanisms. This means that interactions between groundwater and surface water features are not simulated and that the model does not perform well in areas where the water table is near the land surface.

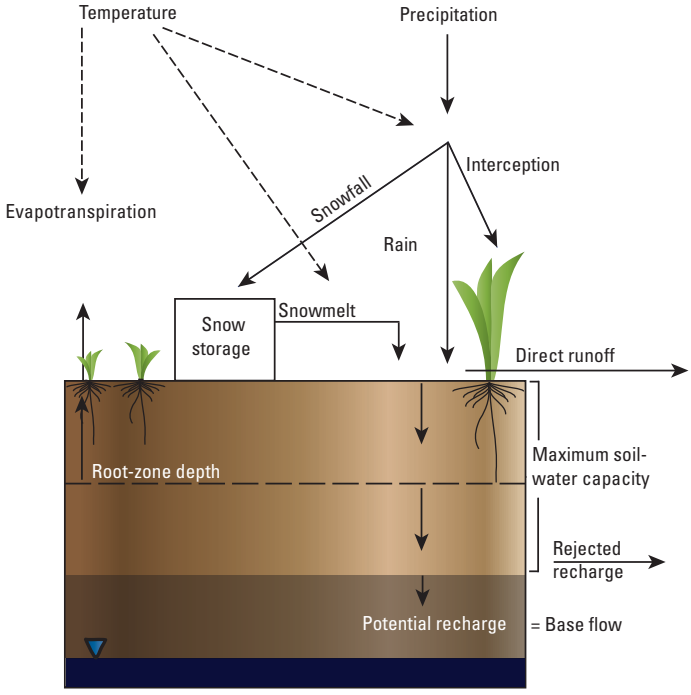


Figure C.1: Conceptual framework of the Soil-Water-Balance Model (Trost et al., 2018).

C.2 USGS Glacial SWB Model

To estimate recharge in the Central Indiana region, we made use of an existing USGS SWB model of the glacial aquifer system east of the Rocky Mountains (glacial SWB model) (Trost et al., 2018). The glacial SWB model simulates annual potential groundwater recharge. The glacial SWB model was constructed with a 1 kilometer grid, extending from central Montana east to Maine (Figure C.2).

The gridded datasets used as input to the glacial SWB are described below:

1. **Meteorological data** Potential recharge estimates were based on meteorological data from the Daymet data set (Thornton et al., 2014). Daymet is a data product derived from software designed to interpolate and extrapolate from daily meteorological observations to produce gridded estimates of daily weather parameters. Weather parameters used in the glacial SWB model include daily continuous surfaces of meteorological data, including precipitation and daily minimum/maximum air temperature at a 1-km resolution.

2. **Land-cover** Input land-cover data for the glacial SWB model were derived from the National Land Cover Database (NLCD) dataset for the reference years of 2001, 2006, and 2011 (Trost et al., 2018). The 2001 NLCD data set (Homer et al., 2007) was used for 1980 to 2003, the 2006 NLCD (Fry et al., 2011) was used for 2004 to 2008 , and the 2011 NLCD (Homer et al., 2015) was used for 2009 to 2011-2019. Use of the NLCD data sets provide a consistent classification scheme, based on 16 categories, that characterize the spatial and temporal variability in land use over the model domain through time. Input data sets were re-sampled from the native 30-m resolution of the NLCD to the 1-km model resolution.

3. **Soil characteristics** Input grids related to soil characteristics, including the hydrologic soil group (HSG) and available water capacity (AWC) were derived from the Digital General Soil Map of the United States (STATSGO2) (NRCS, 2015). The U.S. General Soil Map is comprised of general soil association units and is maintained and distributed as a spatial and tabular data set. The tabular data contains estimates of physical and chemical soil properties, soil interpretations, and static and dynamic metadata.

The glacial SWB model was calibrated to base flow estimates derived from daily streamflow records for 39 representative basins throughout the domain of the glacial aquifer system. Observed recharge rates from a second set of 38 validation basins were used as an independent validation of the ability of the SWB model to simulate potential recharge across the model domain (Trost et al., 2018). Calibration targets for each basin included the mean annual base flow, annual total base flow, and annual total base-flow deciles (Trost et al., 2018).

Use of multiple years of climate data helps to minimize the effect of year-to-year climate variability on estimated recharge values. The glacial SWB model was run with daily time steps

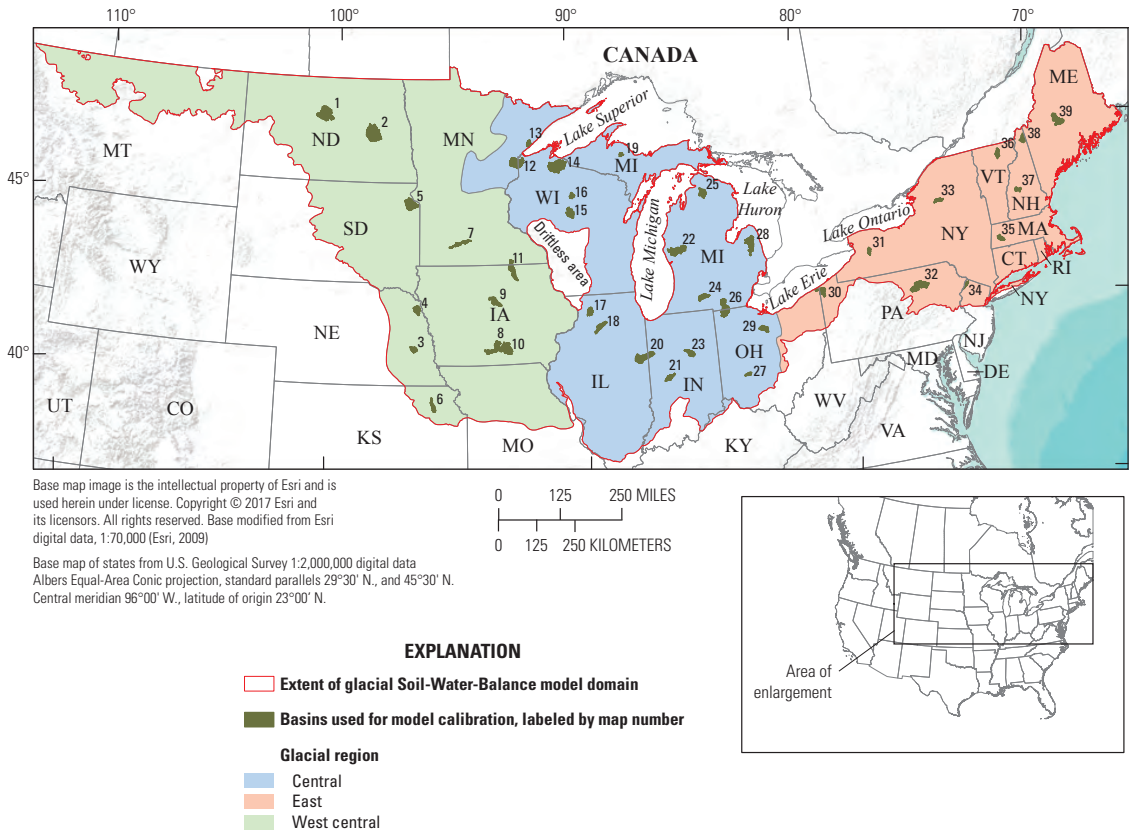


Figure C.2: Extent of the USGS SWB model of the glacial aquifer system (Trost et al., 2018).

to estimate daily potential recharge, for calendar years 1980-2011. Simulated daily potential recharge results were summed to produce annual potential recharge rates.

C.3 Model Extension

The USGS has archived the calibrated model and associated input files and made these available for public use (Trost et al., 2020). To speed simulation times, the USGS divided the regional model into sub-models. INTERA extended the simulation of the glacial SWB model period to include the years 2012-2018. The 2011 NLCD data set was used as input land cover data for the years 2012-2018. The model was extended by incorporating current climate data sets as input (Thornton et al., 2018) and running a simulation from 1980 to 2018 for the sub-model corresponding to the Central Indiana region (subgrid14).

C.4 Results

The updated SWB model provides insight into the spatial and temporal distribution of potential annual recharge in the Central Indiana region. The mean annual potential recharge predicted for the simulation period of 1980-2018 is the most reliable recharge estimate from application of

the model. The hydrograph separation techniques to calibrate the glacial SWB model assume that base flow from hydrograph separation is equal to groundwater recharge and does not account for changes in storage. Assuming that base flow from hydrograph separation is equal to groundwater recharge requires a period of analysis that is long enough, at least one year or more in this case, so that the effect of changes in storage on the water balance can be considered negligible (Trost et al., 2018).

Results are presented for the 25 sub-basins used for this study and an additional four sub-basins at the western edge of the Study area. The four additional sub-basins are delineated by their HUC10 identification number and name. The average potential recharge rate for the simulation period by model cell is shown in Figure C.3 and by sub-basin in Figure C.4. Sub-basin variation is due to differences in land cover and soil hydrology. Average potential recharge by sub-basin ranged from a low 3.8 inches/year (Sub-basin 1, 03347000 -- White River at Muncie, IN) to a high of 10.2 inches/year (Sub-basin 11, 03353611 -- White River at Stout Generating Station).

Annual potential recharge in each sub-basin is variable through time. While the individual annual potential recharge estimates may not be as reliable as the mean annual rates over the simulation period, the annual values demonstrate the temporal variability in potential recharge under changing climatic and land-use conditions (Trost et al., 2018). The distribution of simulated annual potential recharge rates by sub-basin is summarized in Tables C.1 through C.4 and shown with box plots in Figure C.5. The variability in simulated recharge is driven by year-to-year climate variations. Predicted annual recharge varies in response to precipitation and antecedent conditions. SWB model results are most sensitive to input climatic data, followed by surface runoff (curve number) and root-zone depth parameters (USGS, 2010). The relationship between annual precipitation and simulated recharge for an example sub-basin (Sub-basin 3, 0334900-White River at Noblesville) is shown in Figure C.6.

C.5 Comparison with Baseflow Separation Analysis

In PartI and Appendix A, the natural baseflow was defined and evaluated for each sub-basin for the period 2007-2107. Annual recharge may be estimated from the natural baseflow, as described in Appendix A. Here, we compare results of annual recharge estimated with the SWB model with recharge estimated from baseflow separation. In general, the SWB estimates are lower than the baseflow results. Two typical comparisons are presented in Figure C.7. The annual variations in recharge are similar, but offset by 2 to 4 inches, with SWB results consistently under-estimating the recharge predicted by baseflow separation.

As discussed above, SWB results are sensitive to the evaluation of evapotranspiration, estimated from daily temperature data, and partitioning of the precipitation into runoff, based on the Curve Number (CN). We investigated the quality of the evapotranspiration estimate made by SWB by comparison with the annual evapotranspiration based on the following relationship developed in Appendix A:

Table C.1: Annual recharge predicted by SWB, 1980-2018. Sub-basins in the White River drainage system.

Sub-Basin ID	USGS Station at outlet of Sub-Basin	Range (inch/yr)	Mean (inch/yr)	Median (inch/yr)
1	03347000 White River at Muncie, IN	1.7–7.0	3.8	3.7
2	03348130 White River at Raible Ave. at Anderson, IN	2.2–8.8	5.0	4.8
3	03349000 White River at Noblesville, IN	1.4–7.4	4.6	4.7
4	03349510 Cicero Creek at Arcadia, IN	1.5–10.5	6.5	6.7
5	03351000 White River near Nora, IN	2.0–10.8	6.4	6.7
6	03351500 Fall Creek near Fortville, IN	2.1–9.6	5.7	5.6
7	03352500 Fall Creek at Millersville, IN	2.5–11.2	6.3	6.8
8	03353000 White River at Indianapolis, IN	3.5–16.3	9.5	10.0
9	03353200 Eagle Creek at Zionsville, IN	4.0–17.5	4.6	4.9
10	03353500 Eagle Creek at Indianapolis, IN	3.5–15.8	7.2	7.4
11	03353611 White River at Stout Gen. Stn., Indianapolis, IN	4.0–17.5	10.2	10.6
12	03353800 White Lick Creek at Mooresville, IN	2.9–12.4	7.3	7.8
13	03354000 White River near Centerton, IN	3.5–16.3	8.8	8.7

Notes: inch/yr = inches per year.

Table C.2: Annual recharge predicted by SWB, 1980-2018. Sub-basins in the Wabash River drainage system.

Sub-Basin ID	USGS Station at outlet of Sub-Basin	Range (inch/yr)	Mean (inch/yr)	Median (inch/yr)
1	03339280 Prairie Creek near Lebanon, IN	1.2–8.3	5.1	5.3
2	03339500 Sugar Creek at Crawfordsville, IN	0.9–8.6	5.1	5.1
3	03340800 Big Raccoon Creek near Fincastle, IN	2.1–10.2	6.1	6.3
4	03357330 Big Walnut Creek near Roachdale, IN	2.4–11.5	6.5	6.5

Notes: inch/yr = inches per year.

Table C.3: Annual recharge predicted by SWB, 1980-2018. Sub-basins in the East Fork White River drainage system.

Sub-Basin ID	USGS Station at outlet of Sub-Basin	Range (inch/yr)	Mean (inch/yr)	Median (inch/yr)
1	03361500 Big Blue River at Shelbyville, IN	2.1–9.6	5.2	4.9
2	03361650 Sugar Creek at New Palestine, IN	2.2–9.3	5.6	5.5
3	03361850 Buck Creek at Acton, IN	2.7–11.8	6.6	6.7
4	03362000 Youngs Creek near Edinburgh, IN	2.7–14.1	7.3	7.4
5	03362500 Sugar Creek near Edinburgh, IN	2.0–10.8	5.6	5.6
6	03363500 Flatrock River at St. Paul, IN	2.5–10.7	5.9	5.7
7	03363900 Flatrock River at Columbus, IN	1.6–11.5	5.9	5.9
8	03364000 East Fork White River at Columbus, IN	2.7-15.0	7.8	8.4

Notes: inch/yr = inches per year.

Table C.4: Annual recharge predicted by SWB, 1980-2018. Additional HUC-10 basins.

HUC-10 ID	Name	Range (inch/yr)	Mean (inch/yr)	Median (inch/yr)
0512020115	Lambs Creek–White River	3.5–16.2	8.8	9.0
0512020117	Butler Creek–White River	3.1–17.2	9.1	9.4
0512020116	Indiana Creek	3.6–16.9	8.5	8.4
0512020305	Mill Creek	3.6–12.5	7.8	7.8

Notes: inch/yr = inches per year.

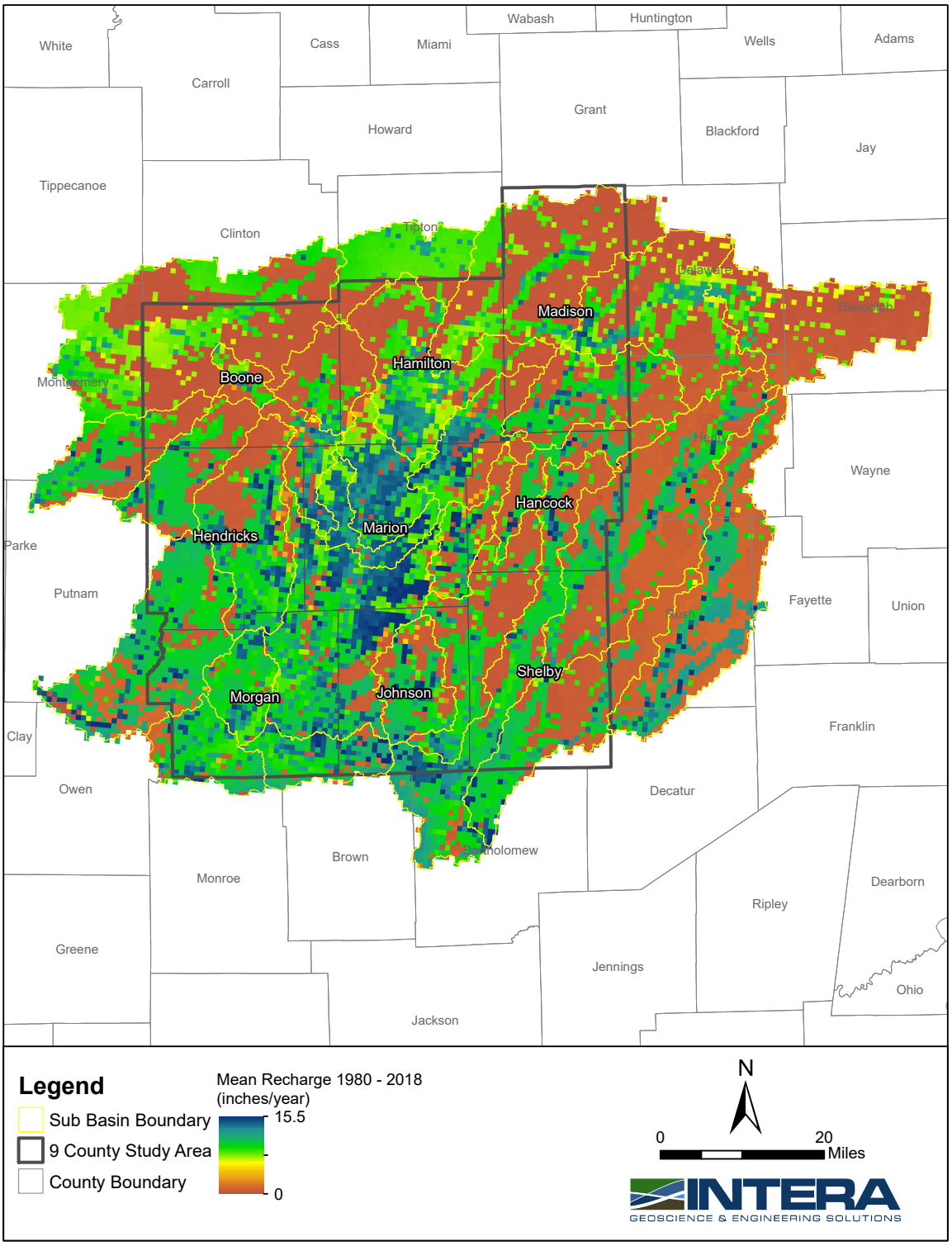


Figure C.3: Average recharge predicted by SWB, 1980-2018, by model cell.

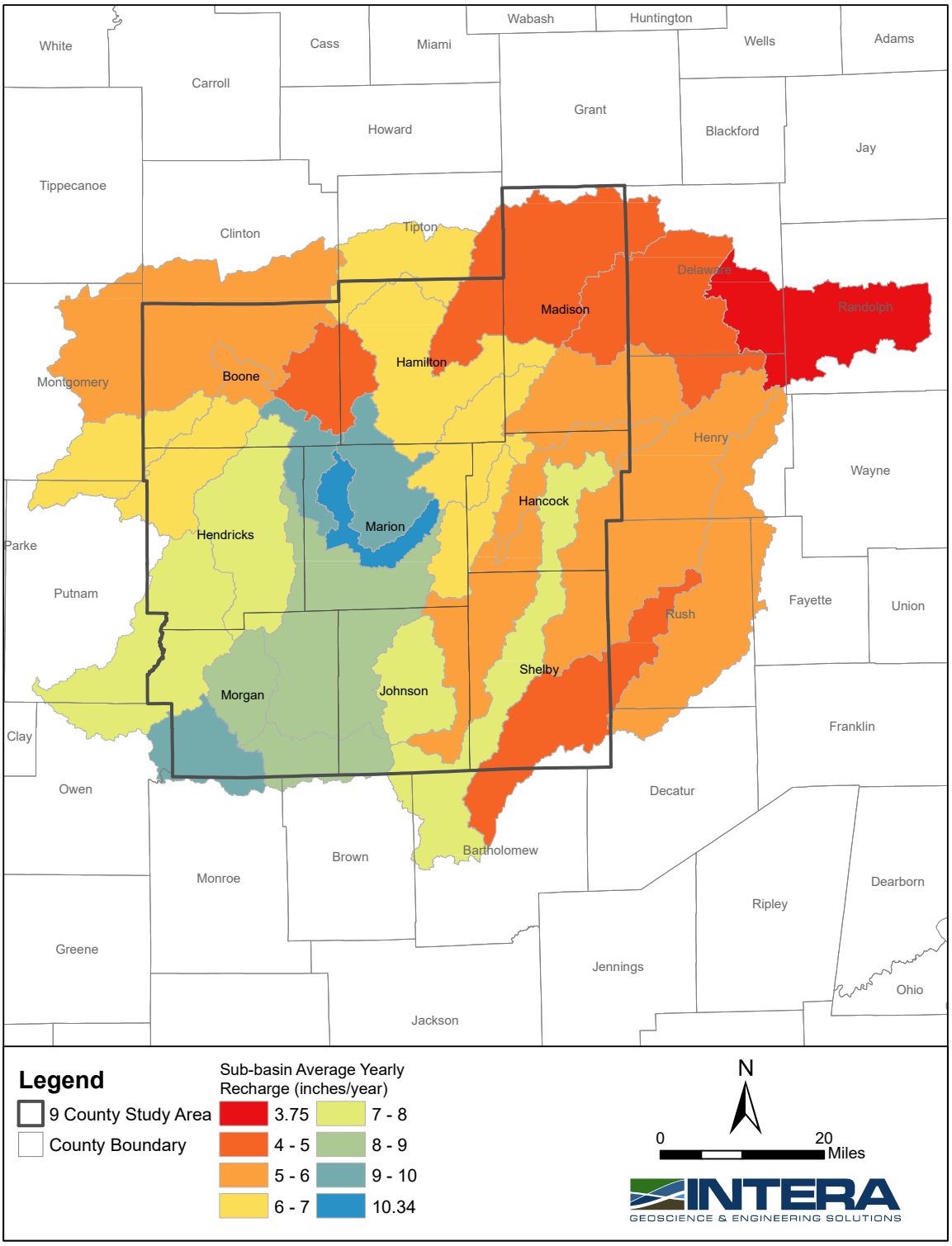


Figure C.4: Average annual recharge predicted by SWB, 1980-2018, by sub-basin.

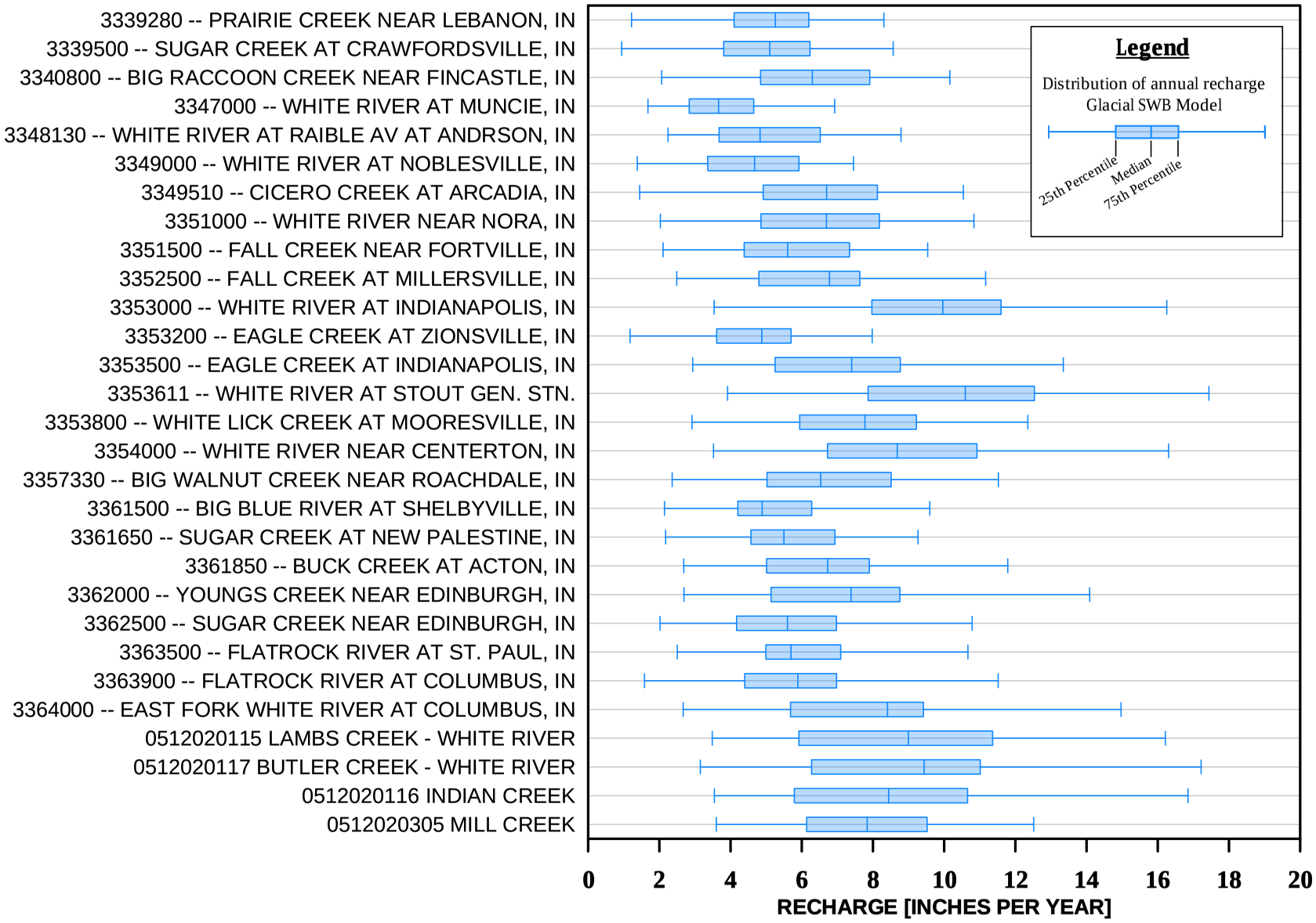


Figure C.5: Distribution of annual recharge predicted by SWB, 1980-2018, by sub-basin.

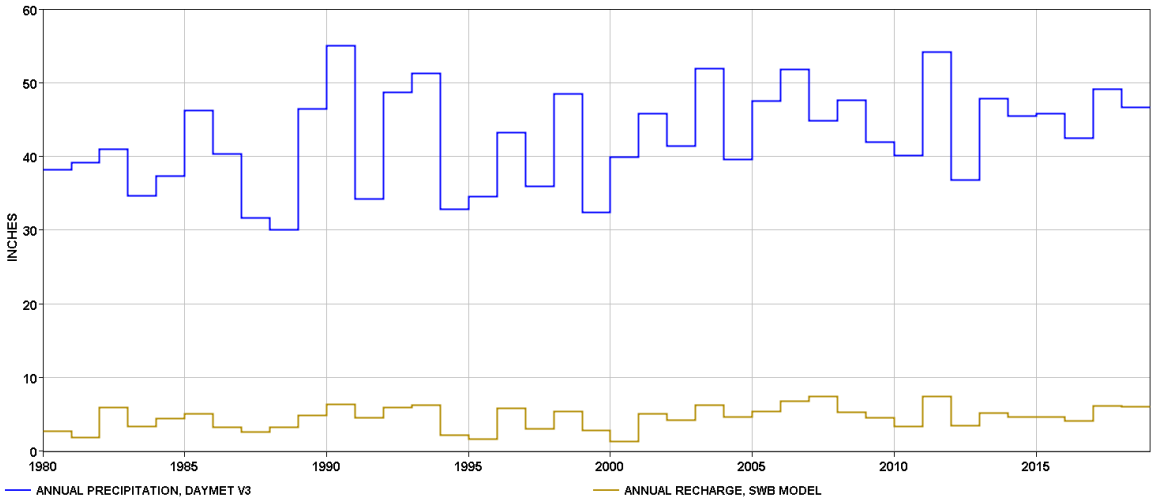


Figure C.6: Annual precipitation and predicted recharge for sub-basin 03349000 - White River at Noblesville, 1980-2018.

$$\overline{Q_{et}} = \overline{Q_{ppt}} - \overline{q_{nsf}} \tag{39}$$

Results of this comparison are presented in Figure C.8 for two sub-basins in the White River drainage system: annual evapotranspiration is consistently overestimated by the SWB model by 0 to 7 inches per year. Figure C.9 illustrates the relationship between annual precipitation over a sub-basin with annual natural runoff, obtained from the natural streamflow,$\overline{q_{nsf}}$.

Complete comparisons between SWB results and results from natural streamflow analysis for both average annual recharge and average annual evapotranspiration for all sub-basins are included in Tables C.5 through C.6.

C.6 Comparison with Indiana Water Balance Network

The Indiana Water Balance Network (IWBN) consists of thirteen sites across the state, where continuous monitoring of the local climate and soil moisture conditions is performed. The data is used to monitor trends in the hydrologic cycle. Potential evapotranspiration (PET)–the maximum possible evapotranspiration at a site if the water source is unlimited–is computed at each site, base on climate variable including solar and atmospheric radiation, wind speed, and relative humidity.

SWB also estimates PET when computing the water budget; the estimate is based on a less rigorous evaluation than the estimate made at the IWBN sites. A comparison of PET values at three IWBN sites has been made with results from the SWB model. IWBN stations include Muncie North, Rushville South, and Glenwood North, and results are shown in Figures C.10 through C.12. In each comparison of monthly PET (top of each figure), the SWB model



Figure C.7: Comparison of annual recharge results from the SWB model and natural baseflow analysis for Sub-basin 1 (*top*), and Sub-basin 6 (*bottom*) in the White River drainage system.



Figure C.8: Comparison of annual evapotranspiration results from the SWB model and natural baseflow analysis for Sub-basin 1 (*top*), and Sub-basin 6 (*bottom*) in the White River drainage system.

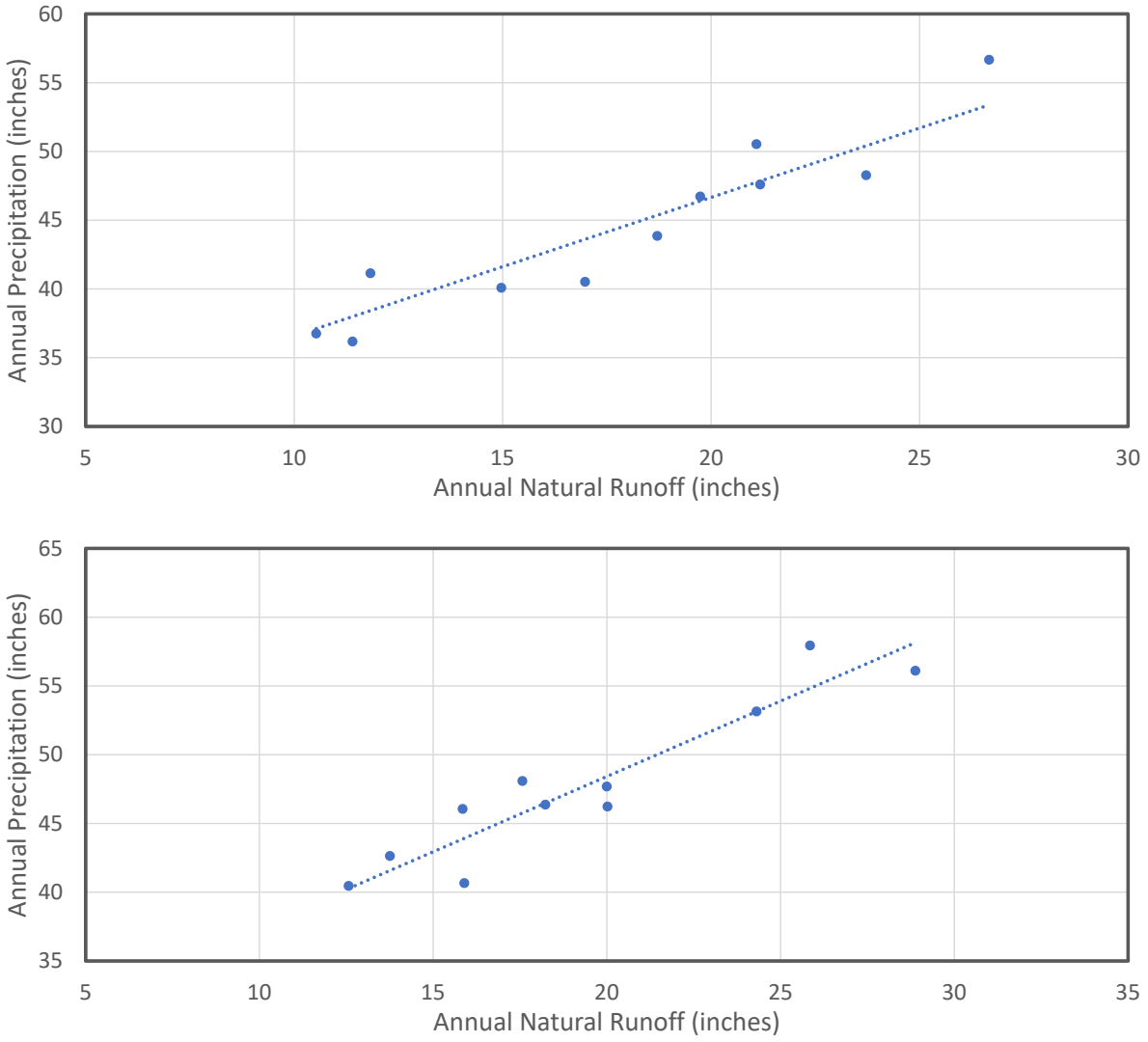


Figure C.9: Relationship between natural runoff and precipitation in Sub-basin 1 (*top*), and Sub-basin 6 (*bottom*) in the White River drainage system.

Table C.5: Comparison of results from the SWB model and natural baseflow (NBF) analysis: annual average recharge and evapotranspiration in the White River drainage system, 2007-2017.

Sub-Basin ID	USGS station at outlet of Sub-Basin	Recharge		Evapotranspiration	
		SWB (inches)	NBF (inches)	SWB (inches)	NBF (inches)
1	03347000 White River at Muncie, IN	4.1	8.4	30.0	26.5
2	03348130 White River at Raible Ave. at Anderson, IN	5.6	11.3	30.1	26.4
3	03349000 White River at Noblesville, IN	5.1	8.3	30.8	27.9
4	03349510 Cicero Creek at Arcadia, IN	7.0	6.7	31.3	28.3
5	03351000 White River near Nora, IN	7.3	12.0	30.0	28.1
6	03351500 Fall Creek near Fortville, IN	6.7	11.3	31.2	28.4
7	03352500 Fall Creek at Millersville, IN	7.6	10.3	30.4	29.5
8	03353000 White River at Indianapolis, IN	11.4	9.6	29.6	29.3
9	03353200 Eagle Creek at Zionsville, IN	5.0	7.4	30.4	26.2
10	03353500 Eagle Creek at Indianapolis, IN	10.7	3.7	30.6	28.9
11	03353611 White River at Stout Gen. Stn., Indianapolis, IN	11.4	9.5	29.7	29.8
12	03353800 White Lick Creek at Mooresville, IN	7.8	8.4	31.3	28.4
13	03354000 White River near Centerton, IN	9.7	9.4	31.2	30.2

Table C.6: Comparison of results from the SWB model and natural baseflow (NBF) analysis: annual average recharge and evapotranspiration in the Wabash River drainage system, 2007-2017.

Sub-Basin ID	USGS station at outlet of Sub-Basin	Recharge		Evapotranspiration	
		SWB (inches)	NBF (inches)	SWB (inches)	NBF (inches)
1	03339280 Prairie Creek near Lebanon, IN	5.2	7.0	30.2	25.8
2	03339500 Sugar Creek at Crawfordsville, IN	5.0	7.4	30.6	27.8
3	03340800 Big Raccoon Creek near Fincastle, IN	6.4	8.4	31.4	29.2
4	03357330 Big Walnut Creek near Roachdale, IN	6.6	8.0	31.3	29.8

Table C.7: Comparison of results from the SWB model and natural baseflow (NBF) analysis: annual average recharge and evapotranspiration in the East Fork White River drainage system, 2007-2017.

Sub-Basin ID	USGS station at outlet of Sub-basin	Recharge		Evapotranspiration	
		SWB (inches)	NBF (inches)	SWB (inches)	NBF (inches)
1	03361500 Big Blue River at Shelbyville, IN	5.6	10.9	31.6	28.4
2	03361650 Sugar Creek at New Palestine, IN	6.2	9.9	31.8	29.4
3	03361850 Buck Creek at Acton, IN	7.6	7.7	31.5	28.6
4	03362000 Youngs Creek near Edinburgh, IN	7.9	7.6	31.5	27.3
5	03362500 Sugar Creek near Edinburgh, IN	6.1	9.9	31.8	29.0
6	03363500 Flatrock River at St. Paul, IN	6.3	8.9	31.6	30.1
7	03363900 Flatrock River at Columbus, IN	4.8	6.4	31.7	30.2
8	03364000 East Fork White River at Columbus, IN	8.5	10.1	32	29.1

over-predicts PET by one to three inches during the months of highest PET. Annually, SWB over-predicts PET by 4 to 10 inches.

C.7 Conclusions

An existing Soil-Water-Budget model (SWB), developed by the USGS has been adapted and modified for estimating recharge in the Central Indiana region for the period 1980-2018. Annual recharge rates estimated with the model are consistently below estimates based on annual natural baseflow in the region. The majority of the difference is attributed to an overestimation of potential and actual evapotranspiration by the SWB model. Although discrete values of recharge obtained from the SWB model consistently underestimates results from more rigorous analyses, the spatial and temporal variations and trends predicted by the SWB model remain useful for interpreting hydrologic data in the region.

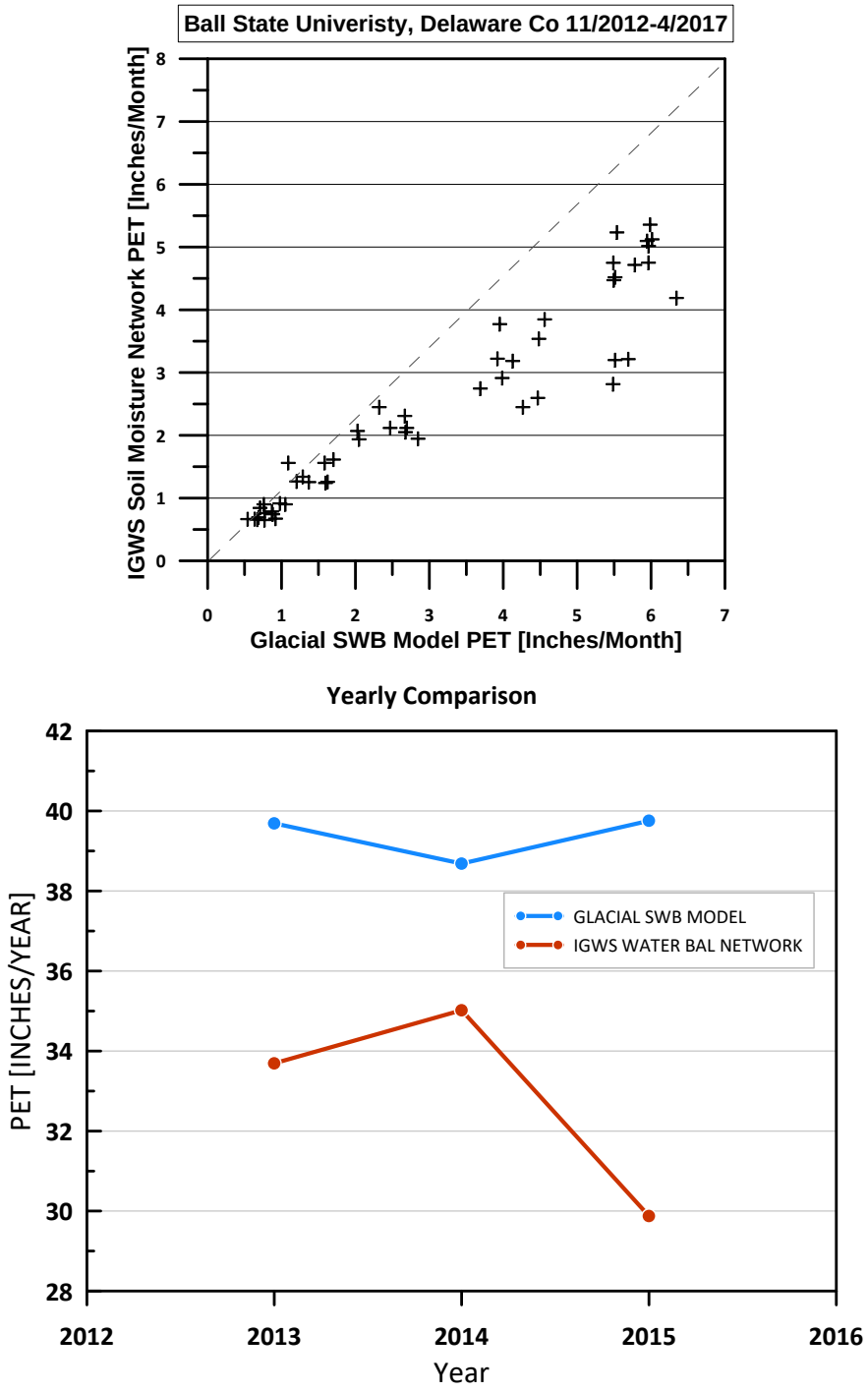


Figure C.10: A comparison of SWB evaluated potential evapotranspiration with IWBN data for the Muncie North station: monthly values (*top*) and annual values (*bottom*).

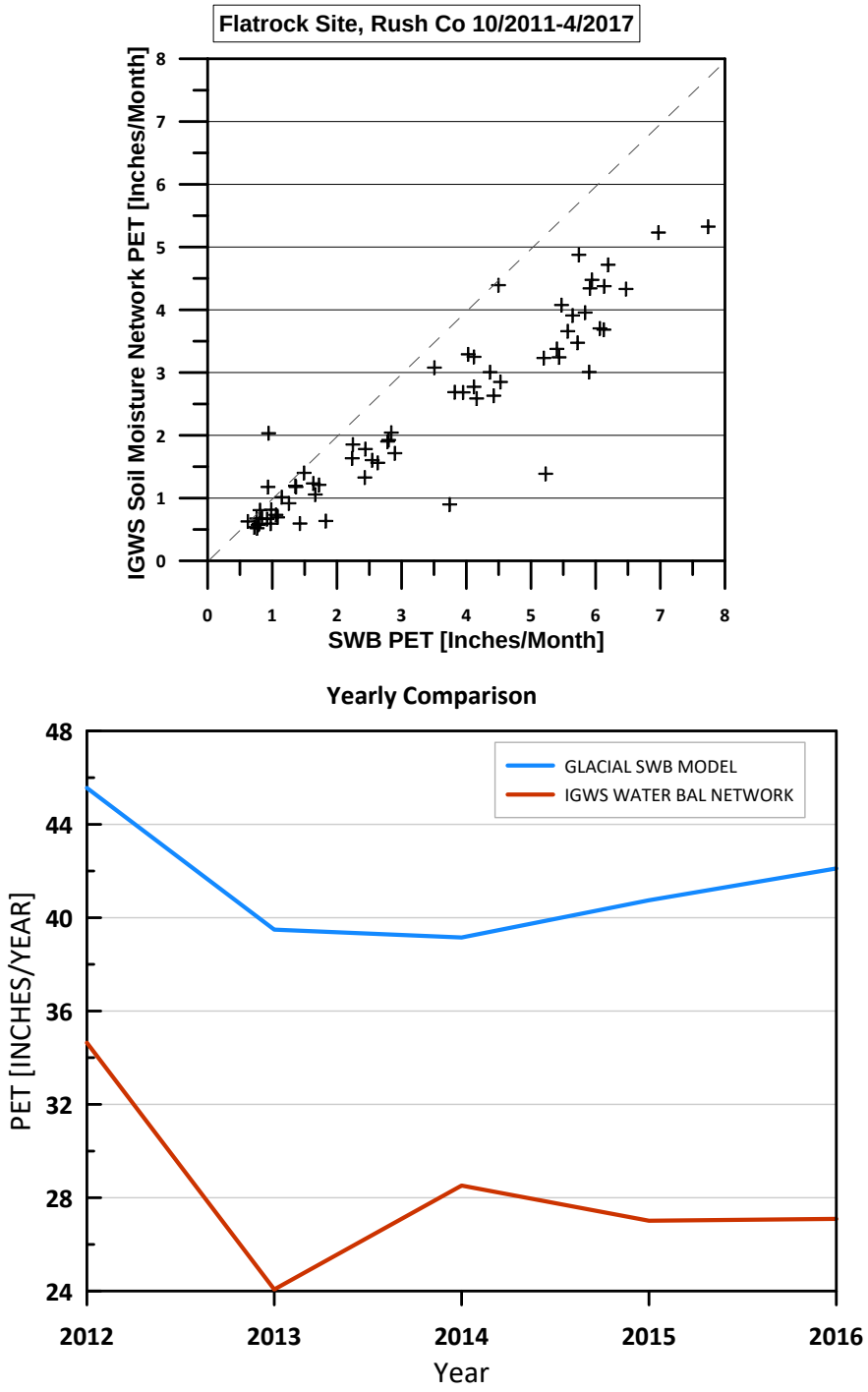


Figure C.11: A comparison of SWB evaluated potential evapotranspiration with IWBN data for the Rushville South station: monthly values (*top*) and annual values (*bottom*).

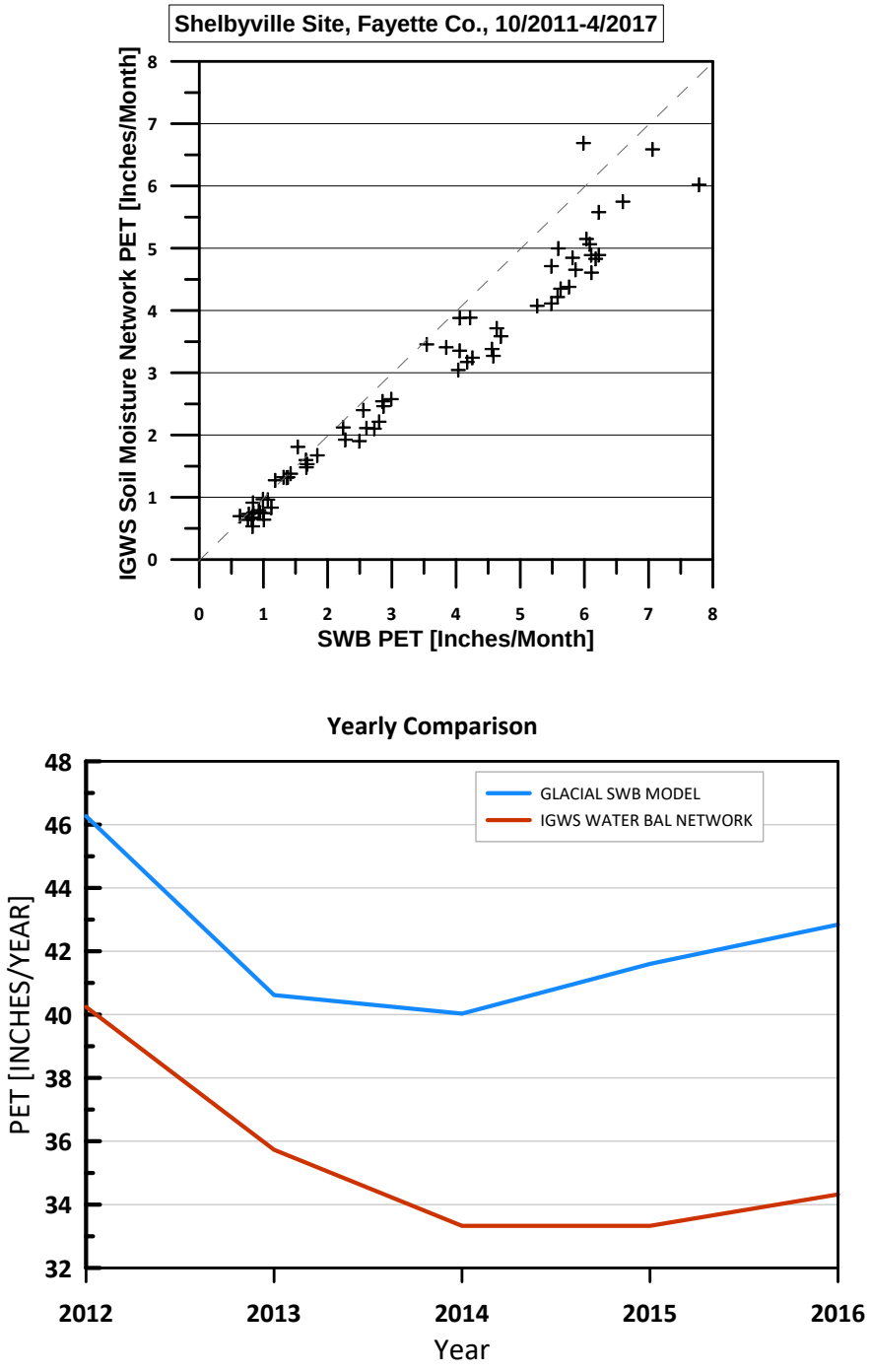


Figure C.12: A comparison of SWB evaluated potential evapotranspiration with IWBN data for the Glenwood North station: monthly values (*top*) and annual values (*bottom*).

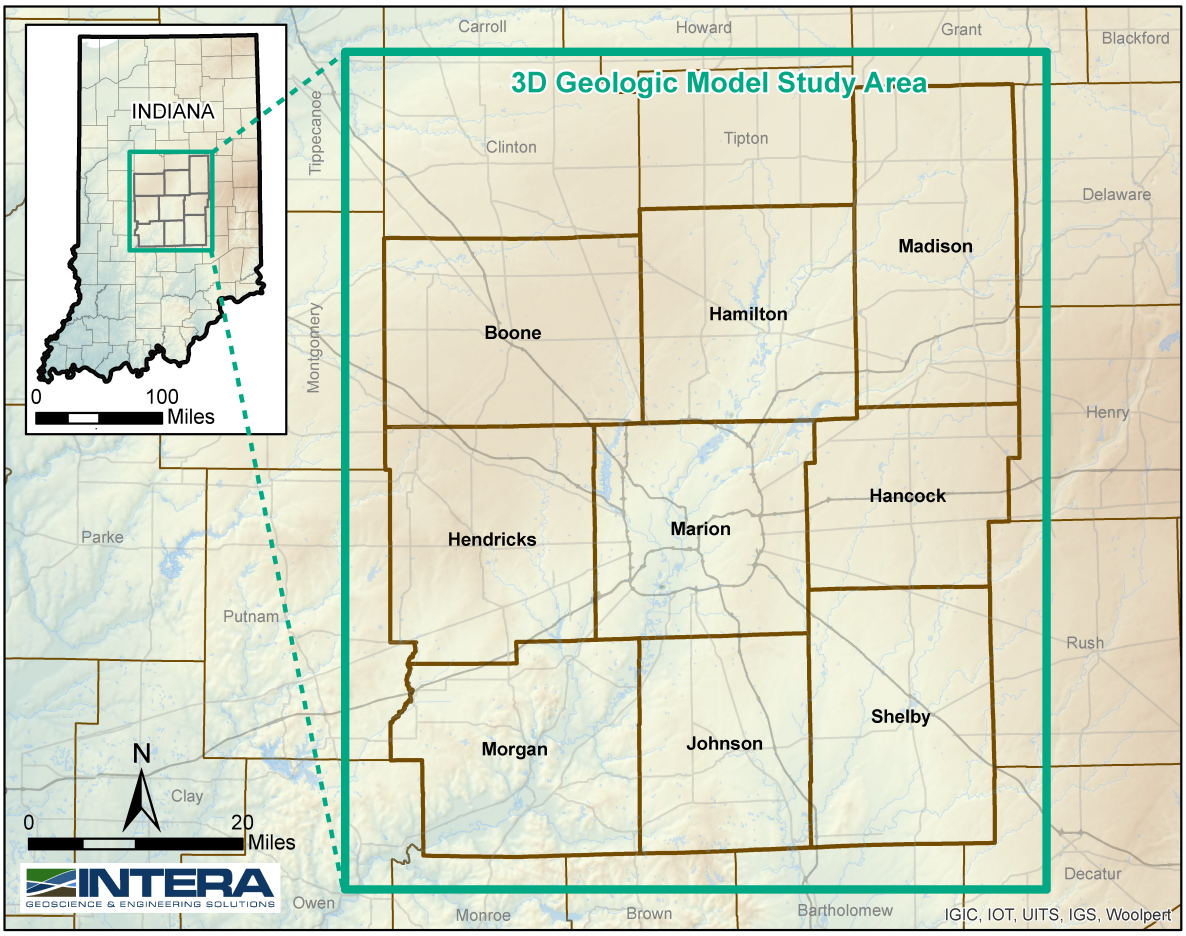


Figure D.1: Extent of the Conceptual Geologic Model.

D Geologic Solid Model

As part of the Central Indiana Water Study, INTERA has constructed a three-dimensional (3D) conceptual geological model (CGM) of the 9-county Study Area (Study Area), including Boone, Hamilton, Hancock, Hendricks, Johnson, Madison, Marion, Morgan, and Shelby Counties. Figure D.1 shows the extent of Study Area.

Water availability cannot be defined solely by the water in the system but must include an interpretation of the interaction of water with its surrounding geology. For groundwater resources in any area to be managed and monitored effectively, a detailed understanding of the geological setting is required. A 3D CGM is a much more effective way than traditional 2D approaches to synthesize large amounts of information and simultaneously analyze multiple data sets. For the Central Indiana water study, along with serving as the CGM, this model was built to: define essential features and extents of select geologic layers, illustrate the principal geometries of the groundwater systems, provide important information about reservoir charac-

teristics and associated properties, better define areas where there are data gaps, be used as a tool to educate the public about Central Indiana's geology and groundwater resources, and as input to better calibrate the groundwater flow model. Also, this model can be used as a tool in future hydrogeological investigations and can be updated as new geologic information becomes available.

This model was built using publicly available data sets gathered from multiple state and federal agencies, including: the Indiana Department of Natural Resources (IDNR), the Indiana Geological and Water Survey (IGWS), and the United States Geological Survey (USGS). These datasets include: Topography derived from USGS digital elevation models (DEM), well logs and associated lithologic data gathered from the IGWS iLITH database (contains information for water-well records provided by the IDNR), surficial and bedrock geological maps from the IGWS, a bedrock elevation model from the IGWS, and a hydrogeologic framework report of Marion County by the IGWS that includes detailed cross sections and maps. The following report gives a brief description of the surficial and bedrock geology of the Study Area and describes how the data was compiled and processed to produce the Central Indiana 3D Conceptual Geological Model.

D.1 Background Geology

The geology of the Central Indiana Study Area can be subdivided into two broad categories, bedrock and unconsolidated. The bedrock category represents the hard rock sedimentary layers that are located mostly below ground as subcrops, although they are sometimes visible as outcrops in road-cuts, quarries, and stream channels throughout the Study Area. The unconsolidated category represents all the material that is sitting on top of the bedrock. These deposits are mainly loose material such as: clay, silt, sand, gravel, and boulders.

D.1.1 Bedrock Geology

The bedrock geology of the study area (to the depth of the study) is generally described as layered beds of limestone, dolostone, shale, sandstone, and siltstone that gently dip to the southwest (Burger, 1986). Within the Study Area, these layered beds make up the geologic units of the Sanders, Borden, New Albany, Muscatatuck, Bainbridge, Maquoketa, and Trenton (from youngest to oldest) (Burger, 1986). The outcrop and subcrop pattern of these bedrock units is shown in Panel A of Figure D.2, with exception of the Trenton, which does not outcrop or subcrop within the Study Area. These units of varying thickness were deposited in shallow sea environments over a span of ~100 million years, from the Late Ordovician Period (Trenton Limestone ~450 mya) to the Early Mississippian Period (Sanders Group ~350 mya). These beds were originally deposited in horizontal layers, but tectonic forces have since tilted these layered beds to their current southwest dipping shallow slope. A generalized stratigraphic column of the Study Area is shown in Figure D.3. This stratigraphic column shows the relationship of the 3D CGM to its: geologic age, general lithology, geologic formation(s), and geologic group.

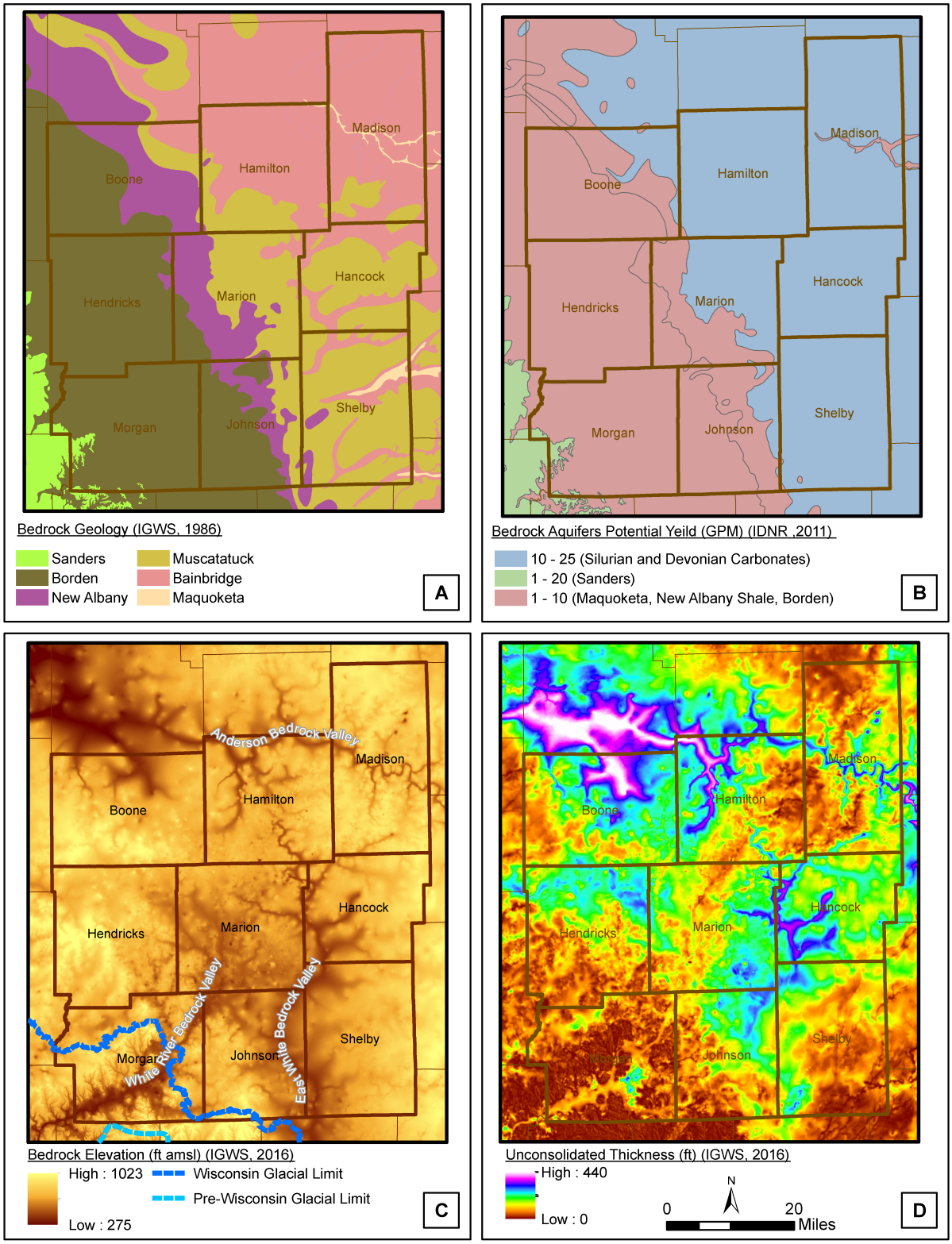


Figure D.2: Features of the bedrock geology in the Central Indiana region.

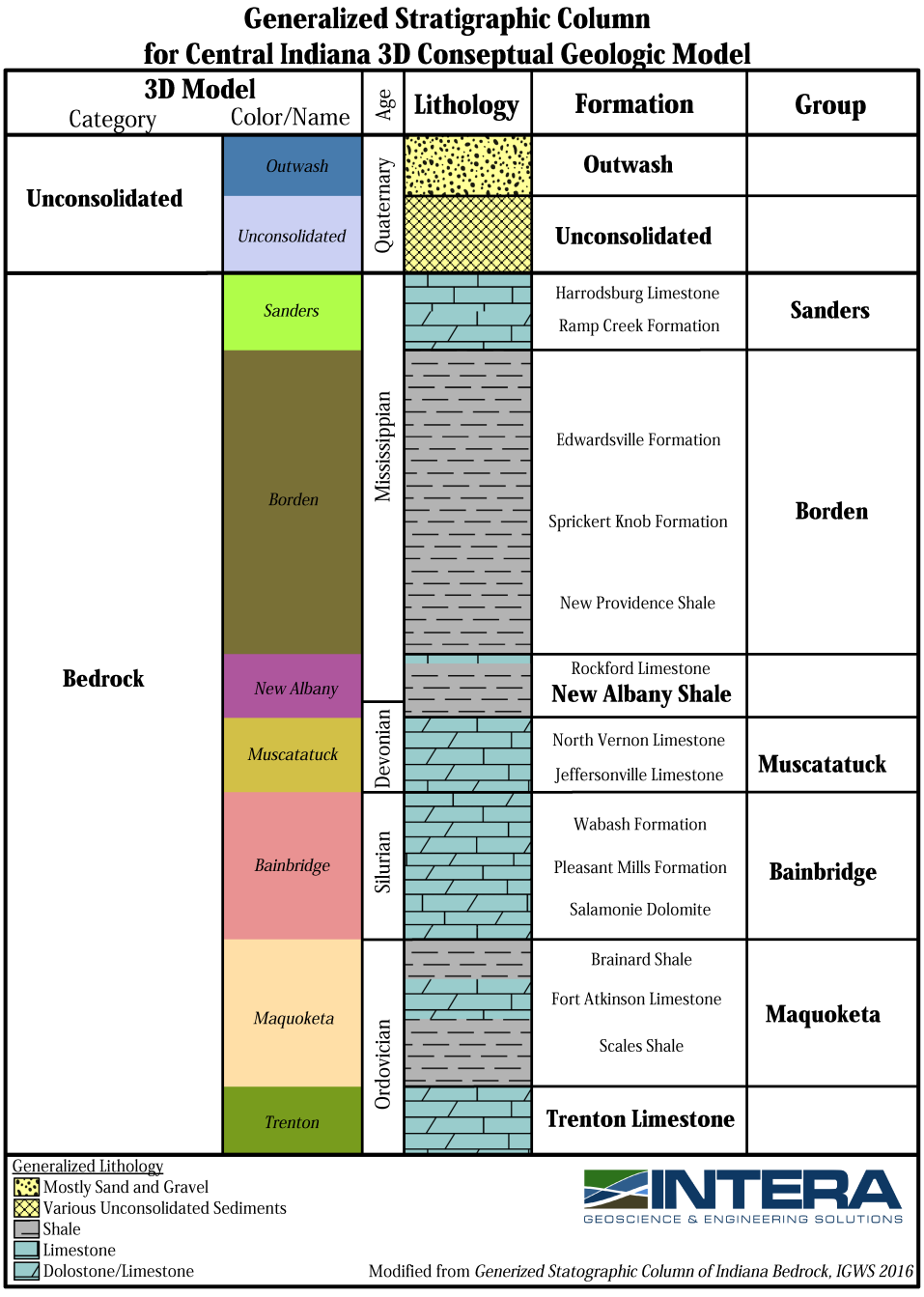


Figure D.3: Generalized stratigraphic column.

Sanders Group Within the Study Area, the Sanders Group contains the Harrodsburg Limestone and the Ramp Creek Formation. These Mississippian aged formations consist of a variety of carbonate rocks that are dominantly a mixture of fine-grained dolostone and limestone (Shaver, 1970). This group outcrops and subcrops in the far southwest corner of the Study Area in Morgan County (Panel A Figure D.2).

Borden Group The Borden Group is a Mississippian aged system that includes three formations within the Study Area: the New Providence Shale, the Sprickert Knob Formation, and the Edwardsville Formation. These formations are composed mainly of siltstone, shale, and some sandstone (Shaver, 1970). There are also discontinuous interbedded limestone lenses present. This group outcrops and subcrops across a large portion of the Study Area in the southwest counties (most of Morgan and Hendricks, southwestern halves of Boone and Johnson, and the southwest corner of Marion) as shown in Panel A of Figure D.2.

New Albany Shale The New Albany Shale is composed of dark carbon-rich shale, with some minor amounts of dolomite and sandstone (Shaver, 1970). It is mostly Late Devonian in age. The New Albany Shale is present in outcrop and subcrop along a relatively narrow strip that runs northwest to southeast through Boone, Marion, and Johnson Counties (Panel A of Figure D.2). The New Albany Shale is overlain by the Rockford Limestone, which represents the boundary between the New Providence Shale and the New Albany Shale.

Muscatatuck Group The Muscatatuck Group includes the Jeffersonville Limestone and the North Vernon Limestone. The formations are light-colored to dark fossiliferous limestones (Shaver, 1970). The group is mostly Middle Devonian in age. This group is present in subcrops in an area from a thin strip in Boone County, southeast through Hamilton and Marion Counties, and broadening out into Johnson, Hancock, Madison, and Shelby Counties as shown in Panel A of Figure D.2.

Bainbridge Group The Bainbridge Group includes all Silurian age carbonate rocks within the Study Area. This group includes the Wabash Formation, the Pleasant Mills Formation, and the Salamonie Dolomite. These formations are mainly dolostone and limestone with multiple reef facies (Shaver, 1970). The reef facies exist in probably thousands of modest-sized to very large so-called patch reefs and pinnacle reefs and are barrier-like, but yet poorly understood, features (Droste and Shaver, 1975). This group is present in outcrop and subcrop in much of Hamilton and Madison Counties, and in thin strips within bedrock valleys in Shelby, Hancock, and Marion Counties as shown in Panel A of Figure D.2.

Maquoketa Group The Maquoketa Group is Late Ordovician in age and consists of mainly shale with some limestone and dolostone (Shaver, 1970). The group contains: the Brainard Shale, the Fort Atkinson Limestone, and the Scales Shale. The group is present in subcrop

Table D.1: Summary of bedrock aquifer data.

3D CGM		SWWF Data			IDNR Aquifer Data		
Model Unit	Color	Total Withdrawal (MGD)	Largest Withdrawal (GPM)	Average Withdrawal (GPM)	IDNR Aquifer Name	Estimated Yield Domestic (GPM)	Estimated Yield High Capacity (GPM)
Outwash		102.1	2313	206	Outwash	50	1000
					Outwash Subsystem	20	300
Unconsolidated		17.5	749	64	Till	10 to 25	200
					Complex	10 to 25	200
					Till Subsystem	< 10	-
					Dissected Till and Residuum	< 5	-
Sanders		-	-	-	Blue River and Sanders	1 to 20	-
Borden		0.1	18	8	Borden	1 to 10	-
New Albany		-	-	-	New Albany Shale	1 to 10	-
Muscatatuck		2.7	515	232	Silurian and Devonian Carbonates	10 to 25	> 70
Bainbridge		7.7	694	100			
Maquoketa		0.5	208	146	Maquoketa Group	1 to 10	-

within bedrock valleys on the eastern edge of the study area, in Madison and Shelby Counties as shown in Panel A of Figure D.2.

Trenton Limestone The Trenton Limestone is a formation of mainly Limestone and Dolostone of Late Ordovician age (Shaver, 1970). This unit does not outcrop or sub crop within the study area. This unit was incorporated into the CGM as the lower bounds due to the extensive exploration of the unit in the late nineteenth century as America's first giant oil field (IGWS, 2020d)).

D.1.2 Bedrock Aquifers

The specific geology (lithology, stratigraphy, chemistry, fractures/faulting, porosity, permeability, etc..) that is exhibited within each of these units defines how it will interact with the groundwater and if it can be utilized as a water source. Within the Study Area three bedrock aquifer zones have been identified by the IDNR as having varied potential for water production: the Silurian and Devonian Carbonates, the New Albany Shale and Borden Group, and the Blue Rivers and Sanders Groups (Panel B of Figure D.2). Bedrock aquifer data is summarized in Table D.1.

Silurian and Devonian Carbonate Aquifers The Bainbridge and Muscatatuck Groups are represented by the IDNR as the Silurian and Devonian Carbonates bedrock aquifer. This aquifer was cited as having the highest potential yield for bedrock aquifers in the Study Area, with a potential yield of typically 10 – 25 gallons per minute (GPM) domestically(Gray et al., 1987). The IDNR estimates are from 2011 and were calculated from values reported on water well records from the IDNR Water Well Database and registered significant water withdrawal facility forms from the Significant Water Withdrawal Facility (SWWF) database. The range

represents the middle 60% statistically for reported domestic yield or reported capacity for registered significant groundwater withdrawal wells. The source of groundwater derived from the Silurian and Devonian aquifer is primarily zones of rock that contain openings along joints, fractures, and bedding planes. The system has been affected by many processes that control the ability of the various geologic units to transmit water. The ability to transmit water can either increase or decrease due to these processes. Also, within these formations, certain facies have a porous and vuggy texture due to reef structures and various diagenetic processes (Droste, J.B., 1975). The Bainbridge Group and the Muscatatuck Groups can be further examined separately as water sources using the SWWF database (IDNR, 2018). The SWWF database contains information for facilities that have the capability of withdrawing more than 100,000 gallons of water in one day. Using the reported depths of the wells, it was determined which unit the well is likely pumping from. Within the 9 Counties in 2018, the Bainbridge Group was responsible for 70% of the reported bedrock withdrawals, with 53 wells producing a total of 7.7 MGD (million gallons per day)(IDNR, 2018). The largest of which reported an average production of .99 MGD (694 GPM) in 2018. Within the Muscatatuck Group, 8 wells produced a total of 2.7 MGD, with the largest producing 0.74 MGD (515 GPM) (IDNR, 2018).

Other Bedrock Aquifers The Maquoketa Group, New Albany Shale, and the Borden Group each have potential yields of typically 1 – 10 GPM for domestic wells (Gray et al., 1987). These units have generally low yields due to the formations being composed primarily of shale, a rock with low porosity and permeability. Within the 9 Counties in 2018, there were 9 total SWWF wells producing from these formations. The Maquoketa Group had 3 wells in 2018 producing a total of 0.6 MGD, with the largest of the 3 produced 0.3 MGD (208 GPM). The Borden Group had the other reported 6 wells which produced a total of 0.07 MGD, the largest of which produced 0.03 MGD (18 GPM). No wells reported producing water from the New Albany Shale in 2018. The Sanders Group has a reported potential of 1 – 20 GPM (Gray et al., 1987), but within the study area this Group is only present at the far southwest corner is mostly exposed outcrop areas, and for these reasons, is not considered to have potential as a water source in the Study Area. Reported potential yields from the IDNR and production data from the SWWF are compiled and presented in Table D.1 for each bedrock unit used in the CGM. Figure D.4 shows the SWWF data, sorted by bedrock formation, as a box and whisker plot.

D.1.3 Bedrock Topography

These bedrock formations have experienced erosion since at least the late Pennsylvanian Period (~300 million years ago) and have only been covered by thick deposits of unconsolidated materials during the past 2 million years, when two (or more) major glacial advances and retreats (referred to as the Pre-Wisconsin and Wisconsin), crossed into the state (IGWS, 2020a). Both glacial advances came from the north and covered most of the Study Area as shown by the

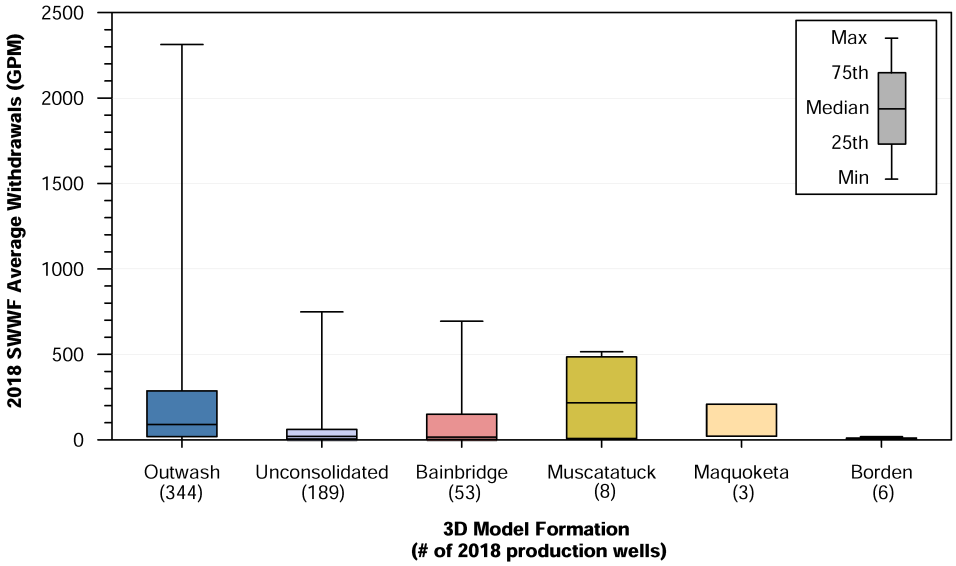


Figure D.4: Pumping well data derived from the SWWF database.

glacial extent boundary lines in Panel C of Figure D.2. This boundary represents the southern extent of glacial advances. The Pre-Wisconsin event(s) covered the entire 9 Counties of the Study Area, stopping just south of Morgan County. The Wisconsin advance(s) also covered most of the Study Area, stopping within the northern and eastern edge of Morgan County and the southern edge of Johnson County. The current shape of the bedrock surface is undulating and uneven with a topographical relief of 748 ft. The Study Area has a bedrock elevation high of 1,023 ft amsl and a low of 275 ft amsl, as seen in Panel C of Figure D.2.

Bedrock Valleys Three main pre-glacial bedrock valleys traverse the study area: The Anderson, the White River, and the East White as shown in Panel C of Figure D.2. In many locations, these valleys were the main drainage ways for the enormous amounts of glacial meltwater produced during the Pre-Wisconsin and Wisconsin events, and in some places, are now filled with permeable glacial outwash (Brown and Laudick, 2003). The Anderson bedrock valley is located in the north of the Study Area and begins as a deep and narrow channel east of Madison County where it meanders west, through the center of Madison County to the north edge of Hamilton County where the valley drastically widens on the north edge of Boone County, eventually connecting to the Teays Bedrock valley a few miles west of Lafayette, IN. The White River bedrock valley begins as a cross cutting set of tributaries in north east corner of Marion County and travels in a southwest direction into the hills of Morgan County, where it emerges as the topographic feature of the White River valley. The East White bedrock valley begins in southern Hamilton and Madison Counties and wanders south, through the border of Johnson and Shelby Counties into Bartholomew County.

Unconsolidated Thickness It is beneficial to contemplate not only the shape of the bedrock surface, but also the amount of material that is on top of the bedrock surface. This can be visualized by mapping the unconsolidated thickness, also described as depth to bedrock, as shown in Panel D of Figure D.2. In the Study Area, unconsolidated deposits are as thick as 440 feet.

D.1.4 Unconsolidated Geology

The two major glacial advances eroded and shaped the pre-glacial bedrock surface, also they are responsible for the deposition of most unconsolidated deposits in the Study Area. These glacial deposits consist of clay, silt, sand, gravel, cobbles, and boulders in various states of layering, sorting, and grading. Also, different pre-glacial and post-glacial environments and processes produced different types of unconsolidated deposits. The surficial unconsolidated deposits are categorized and mapped by the IGWS and are shown in Panel A of Figure D.5.

Outwash Category The CGM combines these unconsolidated deposits into two broad categories, Outwash and Unconsolidated. The Outwash category consists of outwash-fan deposits, undifferentiated outwash, and alluvial deposits as defined by the IGWS and shown in Panel A of Figure D.5 (Gray, 2002). Outwash-fan deposits and undifferentiated outwash are grouped together as Outwash. Outwash is defined as sediment that is transported and deposited by the direct action of glacial meltwater, and usually consists of sorted and stratified sand and gravel. Alluvium is sediment that has deposited from river and stream action, post glacial events, and usually consists of sorted and stratified sand and gravel. Most of the thick alluvial deposits are located on and within the older outwash deposits, sometimes replacing them. Within the Study Area, the alluvial and outwash deposits are regionally connected hydrologically and are thus grouped together for the purposes of this CGM. The Outwash category represents materials with the highest potential for groundwater production in the Study Area.

Unconsolidated Category The Unconsolidated category contains all other unconsolidated deposits that are not in the Outwash category. These deposits are mostly categorized by the IGWS as some form of till: loam till, loam to sandy loam till, and silty clay-loam; with other small mapped deposits of: dune sand, ice-contact stratified drift, lake sand, lake silt and clay, loess, lowland silt complex, mixed drift, muck, and terra rossa (Gray, 2002). Panel A of Figure D.5 shows these surficial deposits as either Till or Other. For this CGM, the Till and Other are grouped together since these 'Other' deposits have similar hydrologic characteristics as till. Till is defined as the material deposited directly from the ice of a glacier and consists of a homogeneous, unsorted mixture of sediments ranging in size from clay to boulders. Within the Study Area, most of unconsolidated material is designated Till/Other as shown if Panel A of Figure D.5. The Till is an intricate system that has been reworked by the complex, multiple glacial advances, creating stacked and interwoven deposits with irregular, hard to define geometries

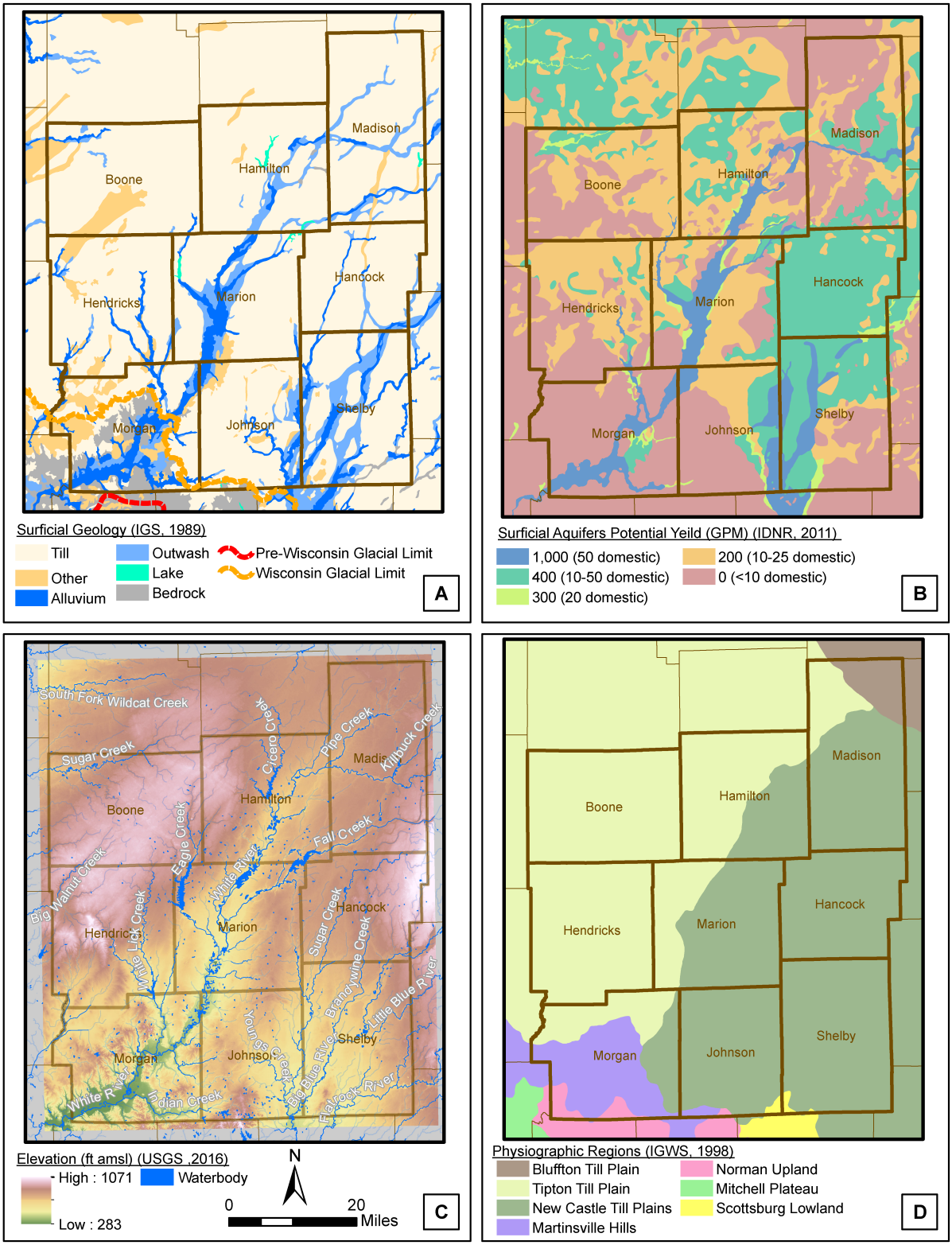


Figure D.5: Features of the surficial geology in the Central Indiana region.

(IGWS, 2020c). Although the till is generally a homogeneous, unsorted mixture of sediments with poor groundwater use potential, these complex geometries are sometimes expressed as pockets of sand and gravel of varying sizes that have potential to produce significant water. Since these pockets are hard to define spatially and their regional extent is usually limited, although they may have a higher groundwater production potential then the surrounding area, they were grouped into the Unconsolidated category for the purposes of the CGM.

D.1.5 Unconsolidated Aquifers

The Outwash category represents the area that has the highest potential for groundwater use as defined by the IDNR and shown in Panel B of Figure D.5. This panel shows the areas surrounding the alluvial and outwash systems have a potential yield of 1,000 GPM for larger diameter high capacity wells and 50 GPM for domestic wells (IDNR, 2011). Outside of these alluvial and outwash channels, the potential sharply decreases to 400 GPM for high capacity wells and 10 – 50 GPM for domestic wells which are in complex areas where continuous deposits of intertill and basal sand and gravel or buried outwash sands and gravels are present. Areas defined as outwash subsystems, which are located on the extremities and edges of the main outwash channels, have a potential yield of 300 GPM for high capacity wells and 20 GPM for domestic wells. Areas mapped as till have potential yields of 200 GPM for high capacity wells and 10 – 25 GPM for domestic wells, where regionally discontinuous intertill or basal sand and/or gravel is present. Areas mapped as Dissected Till and Residuum/Till Veneer have a little to no potential yield for high capacity wells and less than 10 GPM for domestic wells where residual, intertill, or basal fine-grained sand and gravel are present. An overview of this data is shown in Table 1. The Outwash and Unconsolidated categories can be further examined using the SWWF database (IDNR, 2018). Locations of non-bedrock wells within the database were mapped within the CGM and categorized as either an Outwash well or an Unconsolidated well based on their location and depth. The Outwash category had 344 wells in 2018 which produced a total of 102.1 MGD, with the largest producing 3.3 MGD (2313 GPM). The Unconsolidated category had 189 wells which produced 17.5 MGD in total, with the largest well producing 1.1 MGD (749 GPM). Figure D.4 shows the SWWF data, sorted by formation, as a box and whisker plot.

D.1.6 Rivers and Drainageways/Topography

The outwash was deposited in major drainage-way channels shaped by the very meltwater which it transported. Most of these channels remain and house the drainage ways where the larger streams and rivers flow today, such as: White River, Indiana Creek, White Lick Creek, Eagle Creek, Fall Creek, Pipe Creek, Killbuck Creek, Sugar Creek, East Fork White River, Flatrock River, Big Blue River, Little Blue River, Brandywine Creek, Sugar Creek, and Youngs Creek. These major drainage ways are shown in Panel C of Figure D.5. The topography of the Study Area is characterized primarily by low, gently rolling hills and shallow valleys. To the

southwest, in Morgan County, the topography becomes rugged and hilly as shown in Panel C of Figure D.5. The Study Area has a topographic relief of 788 feet with an elevation high of 1,071 ft amsl and a low of 283 ft amsl.

D.1.7 Physiographic Regions

Physiographic regions are geographic areas with similar landforms that are distinctively different form the landforms in adjacent areas. There are two main physiographic regions within the Study Area, as defined by the IGWS (IGWS, 2000): the Central Till Plain, and the Southern Hills and Lowlands (Panel D of Figure D.5). These two regions show the dominance of glaciations on Central Indiana's natural landscape as demonstrated by the glaciated Central Till Plain and relatively unglaciated Southern Hills and Lowlands.

Central Till Plain The Central Till Plain is a region of limited topographic diversity that extends across Ohio, Illinois, and Indiana. Within the Study Area, the Central Till Plain can be subdivided into three regions: The Bluffton Till Plain, The Tipton Till Plain, and the New Castle Till Plains and Drainageways, as shown in Panel D of Figure D.5 (IGWS, 2000).

The Bluffton Till Plane is located at the far northeast corner of the Study Area, in the northeast of Madison County. This region is defined by large areas of till plain of low relief with a concentric series of end moraines, with the outermost moraine visible as the boundary of the Bluffton Till Plain with the Tipton Till Plain and the New Castle Till Plains and Drainageways as shown in Panel D of Figure D.5 (IGWS, 2000).

The Tipton Till Plain is located west of White River valley, between the Bluffton Till Plain to the northeast and the Martinsville Hills to the southwest. This area covers all of Boone and Hendricks Counties, northern Morgan, western Marion, western Hamilton, and northwest Madison Counties (Panel D of Figure D.5). The Tipton Till plain is of low relief with extensive areas of ice-disintegration features. The topography is relatively uniform and of very low relief, with a few irregularities (outwash fans, kames, and moraines). The till plain owes its uniformity to the way in which it was constructed: by relatively narrow tongues of ice that surged across a flat, wet, and slippery substrate, then stagnated and melted in place (IGWS, 2000).

The New Castle Till Plain is located east of the White River valley, between the Bluffton Till Plain to the northeast and the Martinsville Hills to the southwest (Panel D of Figure D.5). This area covers all of Hancock County, most of Johnson and Shelby Counties, east Morgan County, east Marion County, southeast Hamilton County, and south Madison County. This till plain is defined by its low relief crossed by many major tunnel-valleys. During glaciation events, these tunnel valleys fed the White River, the East Fork of White River and several of its tributaries, and the several forks of the Whitewater River. In some places drainageways now abandoned cut across the till plains from one of these drainage lines to another. This crisscross pattern of meltwater features dissects a relatively featureless plain of low relief that would otherwise be indistinguishable from the Tipton Till Plain (IGWS, 2000).

Southern Hills and Lowlands The Wisconsin glacial boundary is clearly defined and makes a useful line of division between the Central Till Plain Region and the Southern Hills and Lowlands Region. This region is part of the state that has not been profoundly affected by the latest (Wisconsin) glaciation and in which bedrock is at or near the surface in much of the region (IGWS, 2000). Within the Study Area the Southern Hills and Lowlands can be subdivided into four separate regions: the Martinsville Hills, the Norman Upland, the Mitchel Plateau, and the Scottsburg Lowland.

The Martinsville Hills are described as bedrock hills of high relief strongly modified by pre-Wisconsin glacial activity. This region is in central and south Morgan County, representing most of the County (Panel D of Figure D.5). The region is distinguished from the other three by the strong glacial modification of the underlying bedrock topography due to pre-Wisconsin glaciations (IGWS, 2000).

The Normand Upland is only present in southern Morgan County and a very small amount in south Johnson County (Panel D of Figure D.5). This region is defined as bedrock hills of high relief. It is distinguishable from the Martinsville Hills due to its lack of glacial modifications (IGWS, 2000).

The Mitchel Plateau is not present within the 9 Counties but does have a small area within the CGM Study Area at the far southwest corner (Panel D of Figure D.5). The Mitchel Plateau is described as rolling clay-covered upland of low relief and large areas of karst (IGWS, 2000).

The Scottsburg Lowland Is located in small areas in southeast Johnson and southwest Shelby Counties (Panel D of Figure D.5). The Scottsburg Lowlands is defined by its broad terraced valleys and low till-covered hills (IGWS, 2000).

D.2 Three-Dimensional Geologic Model

The 3D Conceptual Geologic Model was developed to provide a generalized representation of the geologic framework within the Study Area. This was accomplished by assembling publicly available data sets and reports into a 3D geologic modeling software package and analyzing the data. The following is a summary of the process and attributes used to construct the 3D CGM and a presentation of the results.

The 3D CGM was built using the Leapfrog Works software (©Seequent Limited). Leapfrog Works is a dynamic 3D subsurface modeling software that turns complex data into clear, easy to interpret models. Leapfrog Works allows for easy export of data which can be imported into other various software. This software also includes a free viewing tool that can be shared with any interested party. The viewing tool, Leapfrog Viewer, allows the user to view and manipulate the Central Indiana CGM. The viewer and instructions for use may be downloaded from https://www.seequent.com/products-solutions/leapfrog-viewer/.

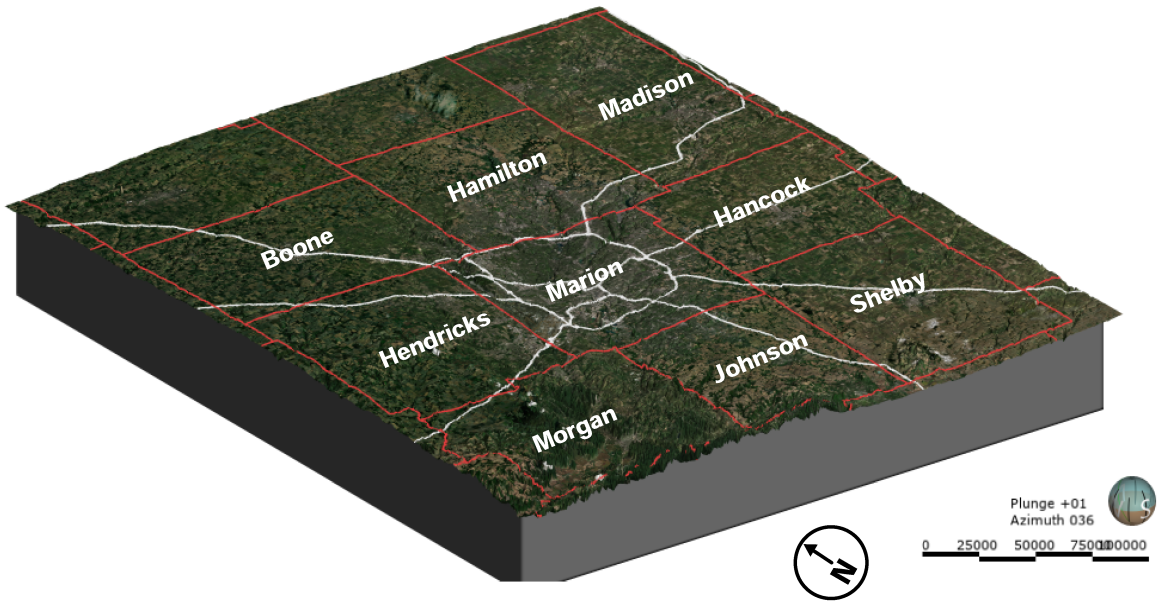


Figure D.6: Bounds of the geologic model.

D.2.1 Model Properties – Bounds, grid size, Layers

The horizontal "X" (east-west) and "Y" (north-south) extents of the model bounds were set to fully encompass the 9 Counties of the Central Indiana Study within a rectangular shape, along with a margin outside of the County boundaries as seen in Figure 1. The X-Y model bounds area is also referred to as the Study Area within this report. The vertical "Z" (elevation) extents of the model were set to the topography as the upper bounds, and the deepest well that reached the Trenton Limestone in the iLITH database as the lower bounds. The model represents an area of 4,569 square miles, 61.8 miles east to west and 73.9 miles from north to south. The model represents a vertical profile of 1,993 feet from the highest topographic point of 1,071 ft amsl to the lower bounds of -922 ft amsl. The model bounds are shown in 3D in Figure D.6. This, and all other 3D images of the model in this report, are shown with a vertical exaggeration of 25x. The vertical exaggeration is enhanced to emphasize vertical features, which are too small to identify relative to the large horizontal scale of this study.

Figure D.7 shows the difference between viewing the model with no vertical exaggeration opposed to 25x vertical exaggeration. A horizontal projection of NAD 1983 StatePlane Indiana East FIPS 1301 Feet was applied to all mapped data. This projection was used to standardize all location data (X,Y, and Z) to feet, while keeping distortions and exaggerations of horizontal data to a minimum. The model uses meshes to represent surfaces in the form of vertices and triangles that define the 3D shape of the surface. The grid size defines the distance between mesh points. Due to the large regional scale of this study, a grid size of 500 feet was used to maximize detail without making the file size too large. The CGM includes nine modeled geologic layers;

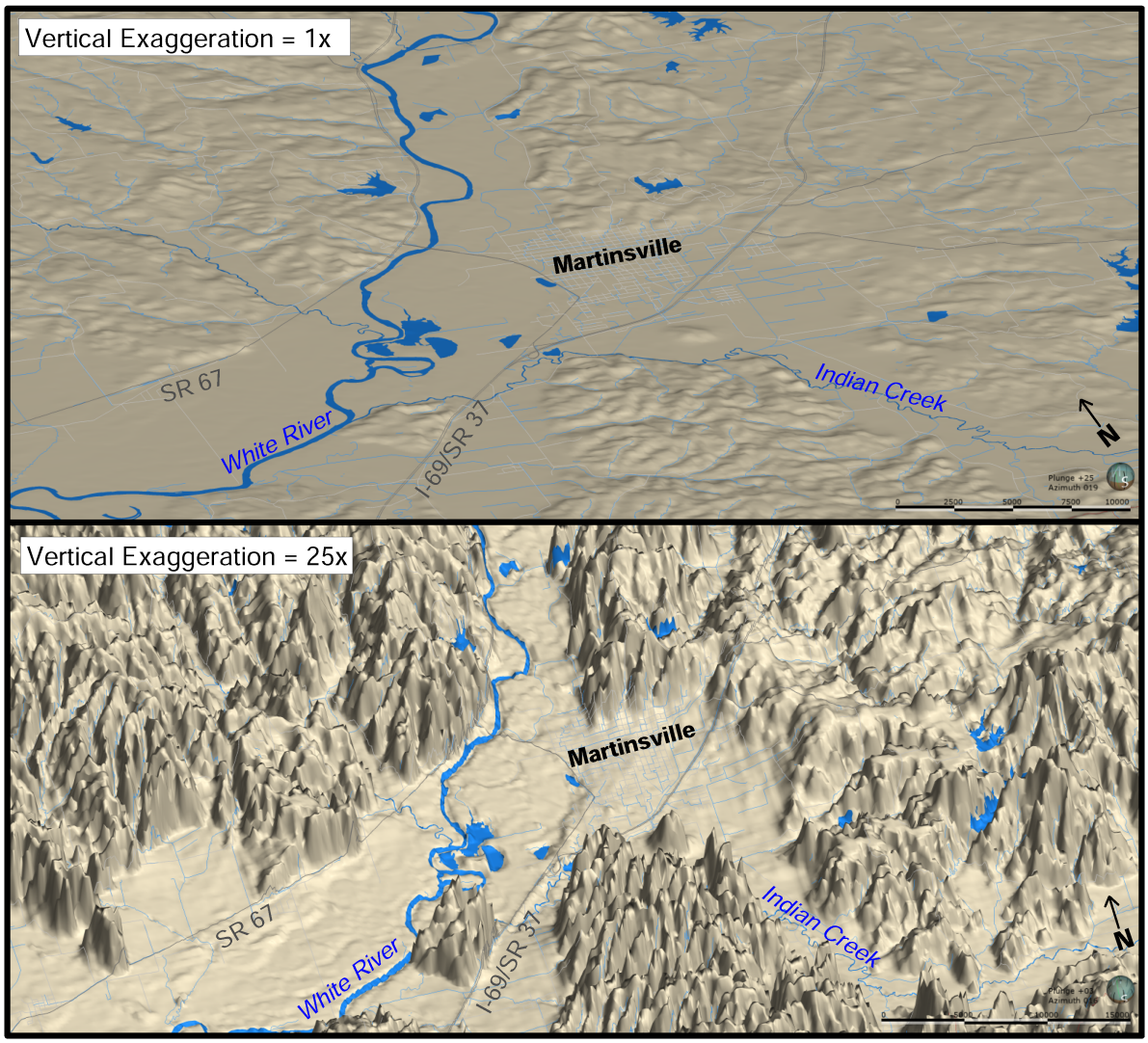


Figure D.7: Model views with and without vertical exaggeration.

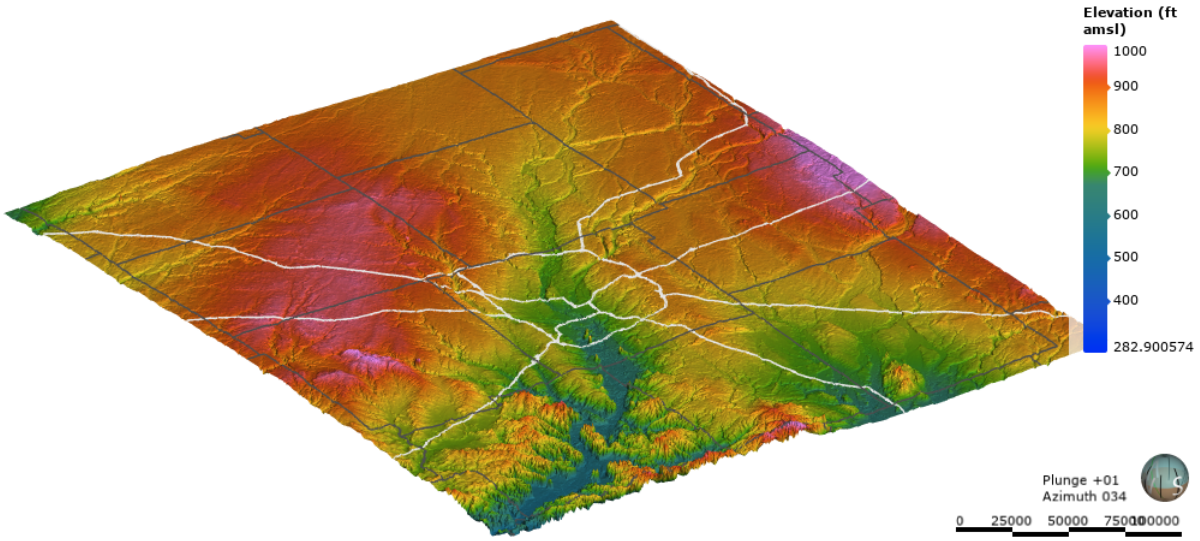


Figure D.8: Topography of the geologic model.

two unconsolidated groups, and seven bedrock groups. For this study, these groups are referred to as: Outwash, Unconsolidated, Sanders, Borden, New Albany, Muscatatuck, Bainbridge, Maquoketa, and Trenton. This is shown in the generalized stratigraphic column shown as Figure D.3.

D.2.2 Model Data Input

Topography The topography was imported from four USGS 1/3 arc second resolution (10 meter, 32.8 feet) DEM rasters (USGS, 2019). The rasters were merged together and converted by the software to a triangulated mesh at a resolution of 500 feet. The mesh was imported into the CGM as the topography. The topography is shown in Figure D.8 as a 3D surface with a color flood to emphasize elevations. The topography represents the ground surface as well as the upper bounds of the 3D model.

Bedrock Surface The bedrock surface was imported from the IGWS bedrock elevation surface raster (IGWS, 2015). The IGWS bedrock surface map was developed using 120,000 water well records, petroleum-well logs, geotechnical investigations, and soil surveys (IGWS, 2015). The IGWS bedrock elevation map is shown in Panel C of Figure D.2. This raster was imported as a mesh layer that was used to define the bedrock interface where iLITH bedrock well log data were not present within the CGM.

Geologic Maps, Reports, Cross Sections

Bedrock Map The bedrock outcrop and subcrop contacts were refined using the IGWS Bedrock Geology map from the Regional Geologic Map (RGM) series, which was mapped at a scale of 1:250,000 (Burger, 1986). This map was imported and draped over the bedrock elevation surface to define bedrock contacts where well log data was sparse. This map is shown in Panel A of Figure D.2.

Surficial Map The boundaries of the Outwash and Unconsolidated units were initially defined using the IGWS Glacial Quaternary Geology map, which was created at a scale of 1:500,000 (Gray, 2002). The map was imported and draped over the topography to define the surficial contacts of the outwash deposits with the surrounding materials. This map is shown in Panel A of Figure D.5. These boundaries were further refined using the topography in areas where the outwash or alluvial valley was clearly visible.

Marion County Hydrogeologic Report An IGWS Open-File Study, Hydrogeologic Framework of Marion County, Indiana, contains detailed surficial and bedrock geologic maps of Marion County (Brown and Laudick, 2003). The report also presents 5 detailed geologic cross sections of Marion County. This extensive geologic study provided a background to refine the geometries within Marion County and provide a template for analysis of the other 8 counties. The surficial and bedrock geologic maps presented in the study were imported into the model and used as the primary data source for Marion County. The 5 cross-sections were also imported into the 3D model. These cross-sections were used to define the vertical geometries of the outwash channel within Marion County, as well as provide a template to define geometries throughout the rest of the Study Area. The 5 cross-sections are shown in Figure D.9, along with a visualization of the iLITH well log data. Cross-section C-C' from the report is shown in comparison to a cross-section from the 3D CGM in Figure D.10.

Well Logs Well logs were imported from the IGWS iLITH database. The database contains information from water-well records provided by the IDNR Division of Water. These records contain both location and lithologic data reviewed and edited by the IGWS (Brown et al., 2001). The location information was verified by the IGWS. The reported horizontal location (X, Y) of these well logs was used as the collars in the 3D model. The collar sets the 'zero' location for the lithologic data that is input into the model. The lithologic information contained in the database was standardized by the IGWS into a series of tables, separating geologic attributes such as color, hardness, texture, consistency, and simplified sediment type. These tables were used to categorize the sediment/rock type described into one of the 9 modeled layers within the CGM.

Collars The collar of each well log is the horizontal and vertical location that represents the 'zero' point where the lithologic information begins. The horizontal location of the collars was defined by the data within the iLITH database. The vertical location of the collars was

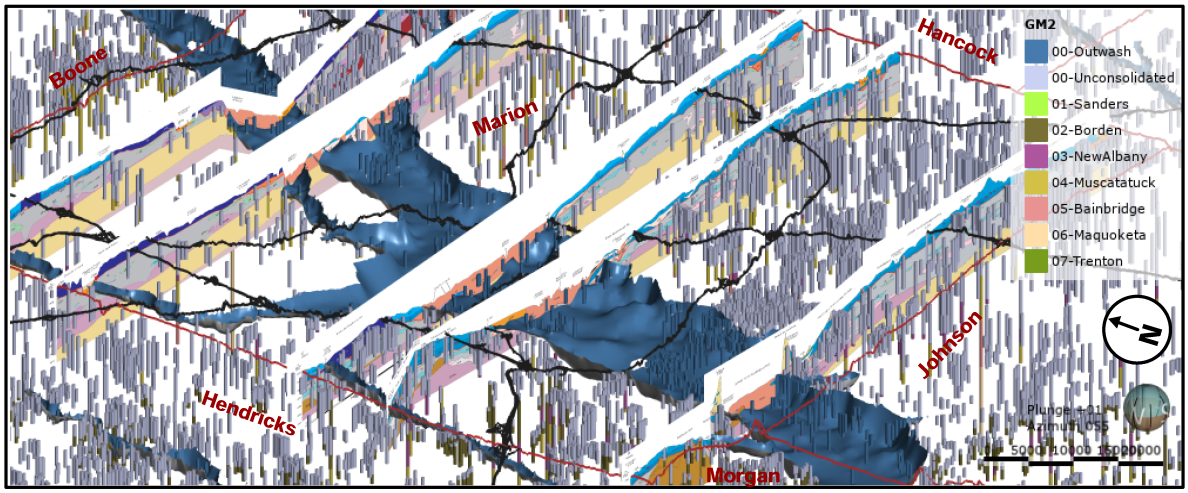


Figure D.9: Marion County cross sections.

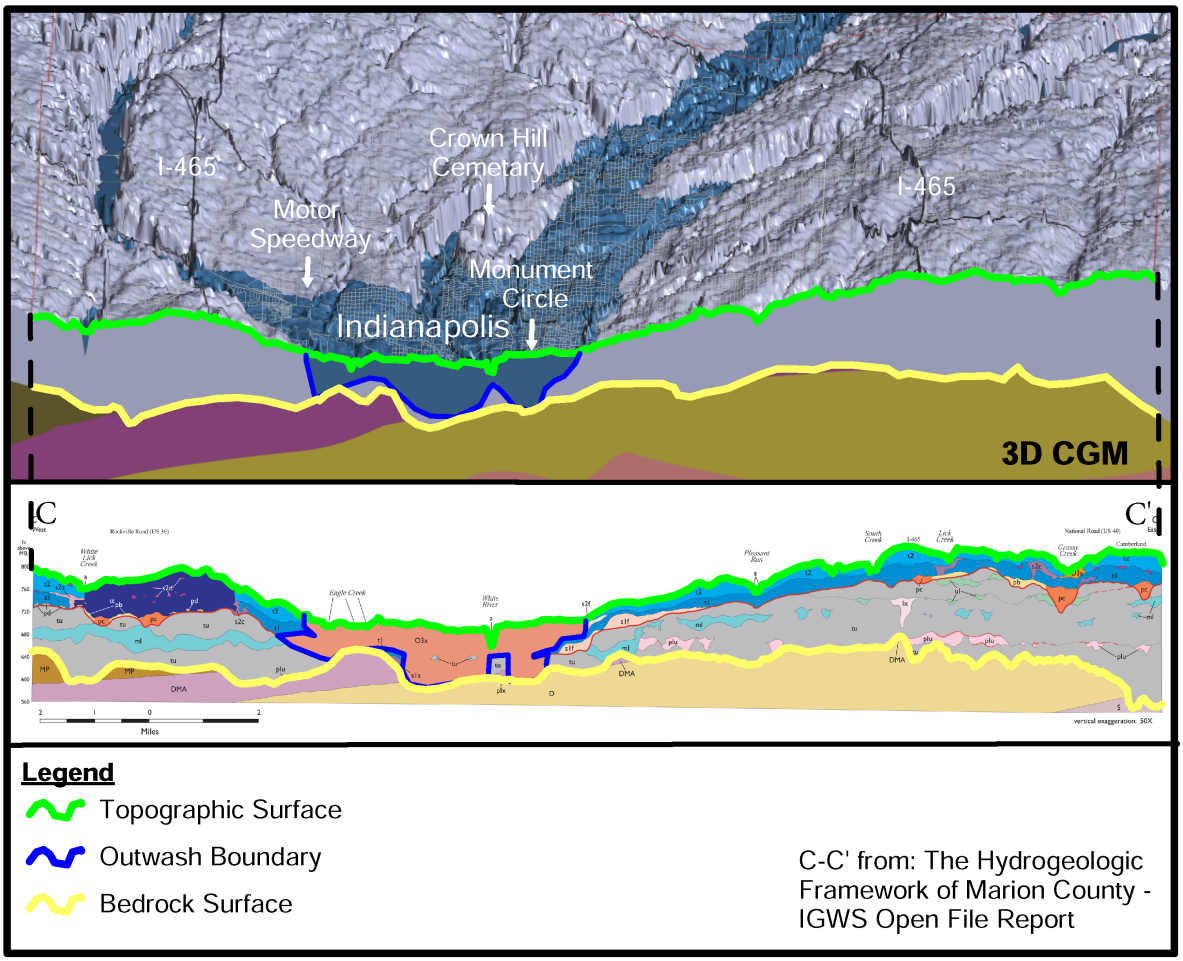


Figure D.10: Topography of the geologic model.

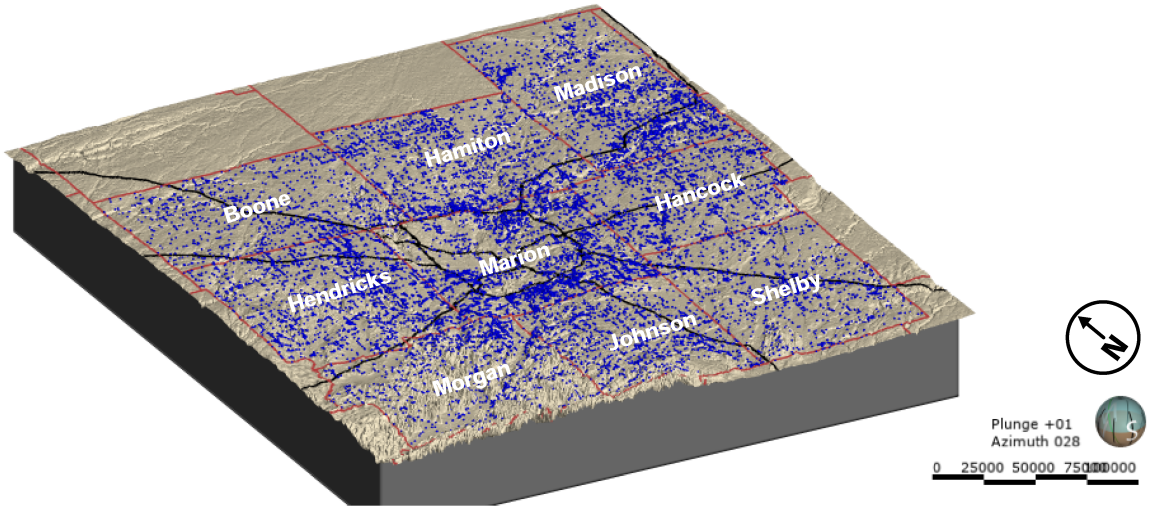


Figure D.11: Illustration of collars applied to iLITH data.

snapped to topographic surface at the reported X-Y locations. The collars used in the study are shown as blue dots on the topography in Figure D.11.

Lithologies Lithologic categories defined by the iLITH database, including Clay, Silt, Sand and Gravel, Limestone, Shale, and others, were displayed and analyzed in 3D. With the aid of the published geologic maps and cross sections, each logged lithologic section in the iLITH database was grouped into one of the 9 modeled categories.

Well logs lithologies located within the mapped outwash channels were categorized as Outwash, starting at the ground surface, up to a certain depth, depending on the surrounding geologic setting. In some settings the outwash/alluvial deposits sit directly on bedrock, in other settings they are deposited on top of older, unconsolidated sediments. Outwash channel boundaries were revised from mapped areas using the topography as a guide. When viewed with a vertical exaggeration, the Outwash channel boundaries become clearly apparent within the 3D space. These boundaries were edited using manually entered structural disks, which define a location and slope that the Outwash surface with snap to. An example of these structural disk edits is shown in Figure D.12, where the topography defines Outwash boundaries. In general, the Outwash category contains more sand and gravel deposits. Using this generalization, the lithologies described on the well logs were used to further define the Outwash category. Also, within Marion County, the 5 cross-sections were used as the main data source to define the bottom of the Outwash channel. This can be seen in Figure D.10, where the modeled bottom of the Outwash channel is shown along with the well logs, cross sections.

The Unconsolidated category was defined in the well logs as all unconsolidated deposits that were not grouped as Outwash. This is displayed in Figure D.13, where Outwash and Unconsolidated category selections are shown throughout the study area.

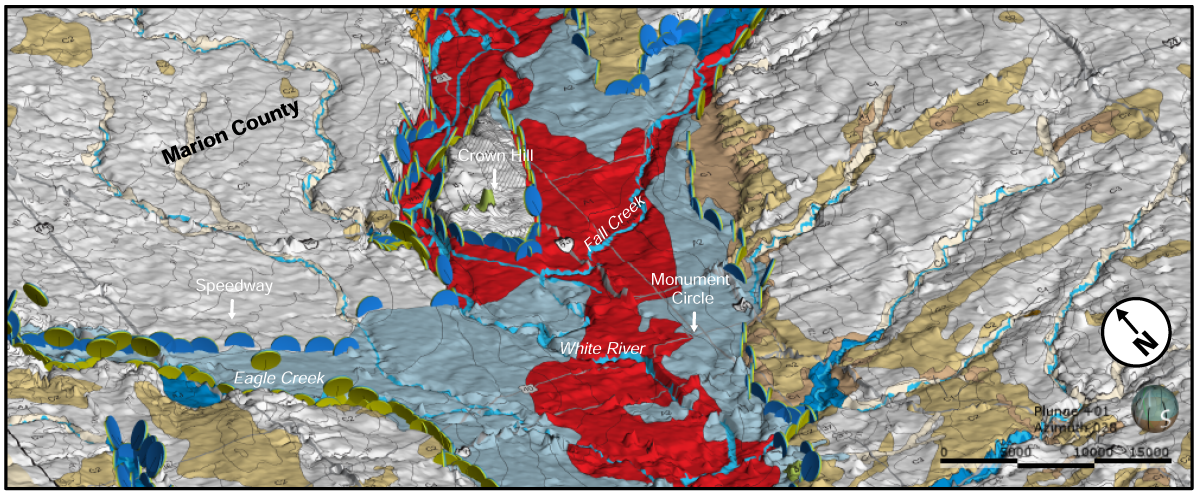


Figure D.12: Illustration of structural disks to define outwash boundaries.

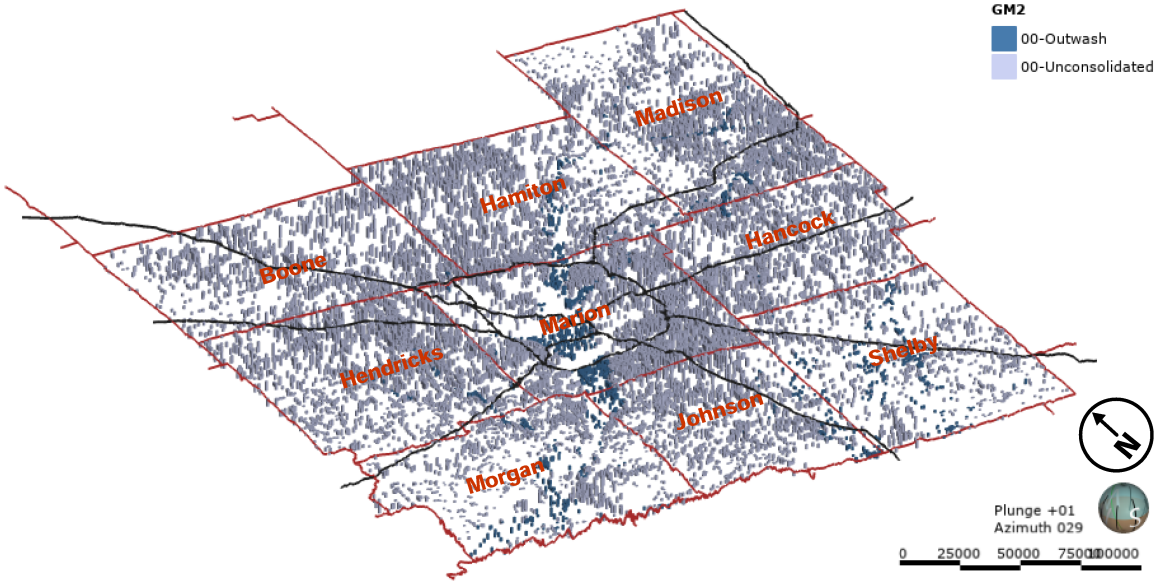


Figure D.13: Unconsolidated lithology defined in the geologic model.

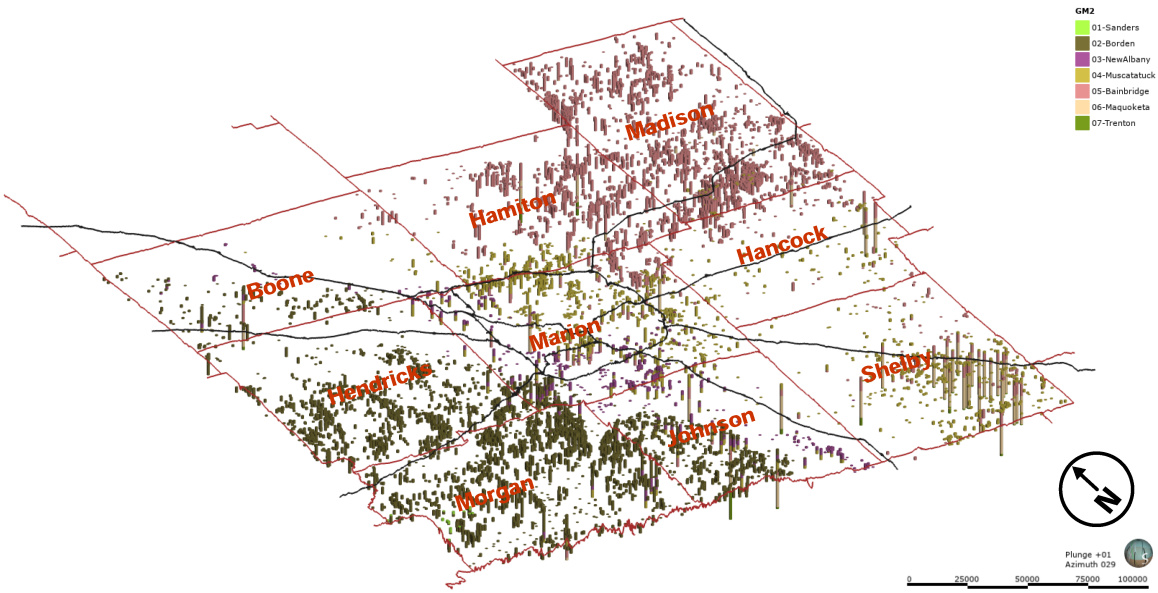


Figure D.14: Bedrock lithology defined in the geologic model.

Bedrock lithologies we grouped into one of the 7 modeled bedrock units: Sanders, Borden, New Albany, Muscatatuck, Bainbridge, Maquoketa, and Trenton (Figure D.3). Within the CGM, the Trenton layer represents the Trenton limestone and anything below (geologically older). Due to its use in oil and gas exploration and its distinct characteristics, the deepest well logs clearly identify when they encounter this unit. This provides a bottom contact point to use as a control point to work up from when categorizing the other bedrock lithologies. The IGWS bedrock map was overlaid on the 3D model. Generally, the map was used to define the first lithology reported on the well log. This upper bedrock lithology represents a top contact point to work down from when categorizing the younger bedrock lithologies. In most cases within the Study Area, a change in formation represents a change in lithology from a shale dominated system to a limestone/dolostone dominated system, as shown in Figure D.3, the generalized stratigraphic column. In some cases, well logs indicate the formational change by name, in most cases a lithologic change reported on a well log was used to define the contact between units. Using these methods, each bedrock lithology reported on well logs was categorized into one of the 7 modeled bedrock units. Well logs with bedrock lithologies logged are displayed in Figure D.14 according to their model color. The contacts between these categorized well logs was used to create mesh layers that represent the boundary between the units in 3D space, this is shown in Figure D.15.

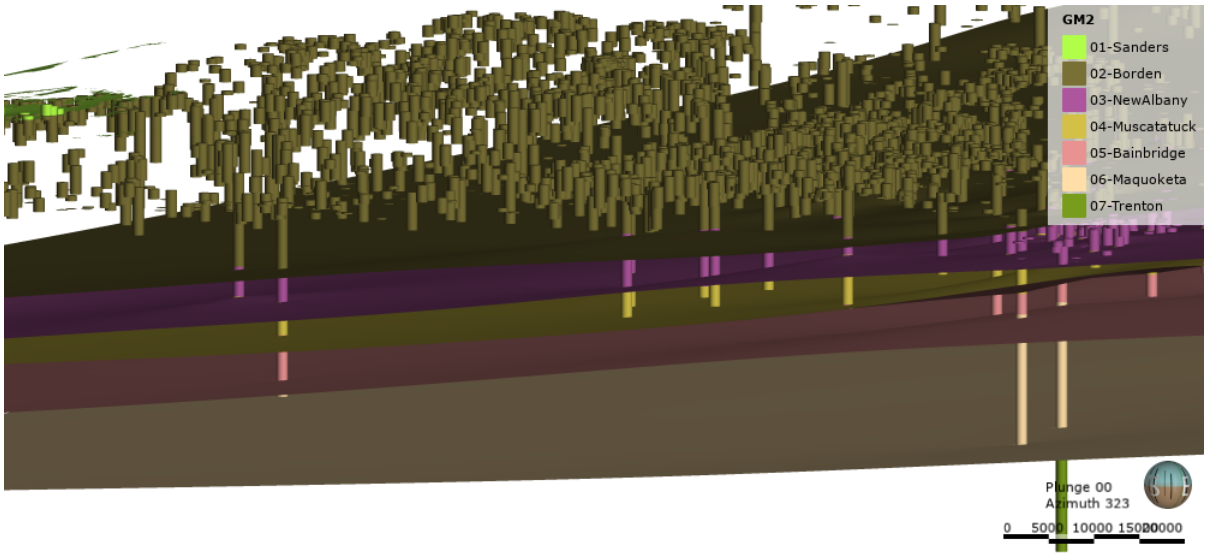


Figure D.15: Bedrock boundaries defined in the geologic model.

D.3 Model Results

Model results are presented below as images of the 3D model and cross sections. The model results are also available as a Leapfrog Viewer file. To better envision the area is real 3D space, Figure D.16 shows a view of a limestone quarry from Google Earth and one from the 3D CGM. This view may help give some perspective of what features may look like in the real world while viewing the 3D CGM.

D.3.1 3D Views

Figure D.17 shows the full 3D model. These figures show the final output volumes for the 9 modeled units, as viewed from different directions: the top left panel shows the model looking down from southwest to northeast, the top right panel shows the model looking down from southeast to northwest, the bottom left panel shows the model looking down from northeast to southwest, and the bottom right shows the model looking down from northwest to southeast.

D.3.2 Map Views

Figure D.18 shows a map view of the bedrock geology from the 3D CGM. Figure D.19 shows a map view of the bedrock elevation from the 3D CGM. Figure D.20 shows a map view of the unconsolidated thickness in the CGM. Figure D.21 shows a map view of the surficial geology defined by the 3D CGM.

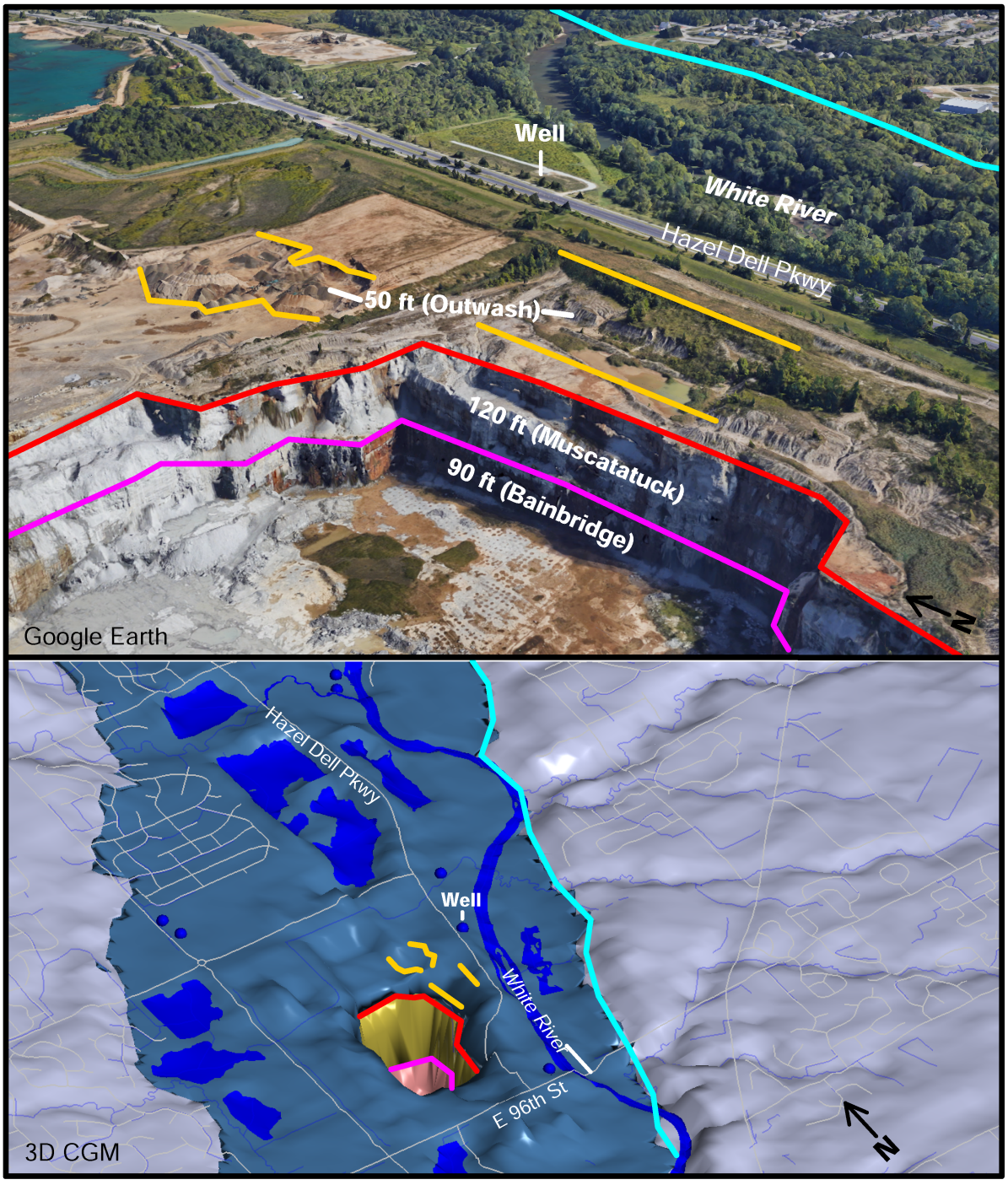


Figure D.16: Three-dimensional perspective view of limestone quarry.

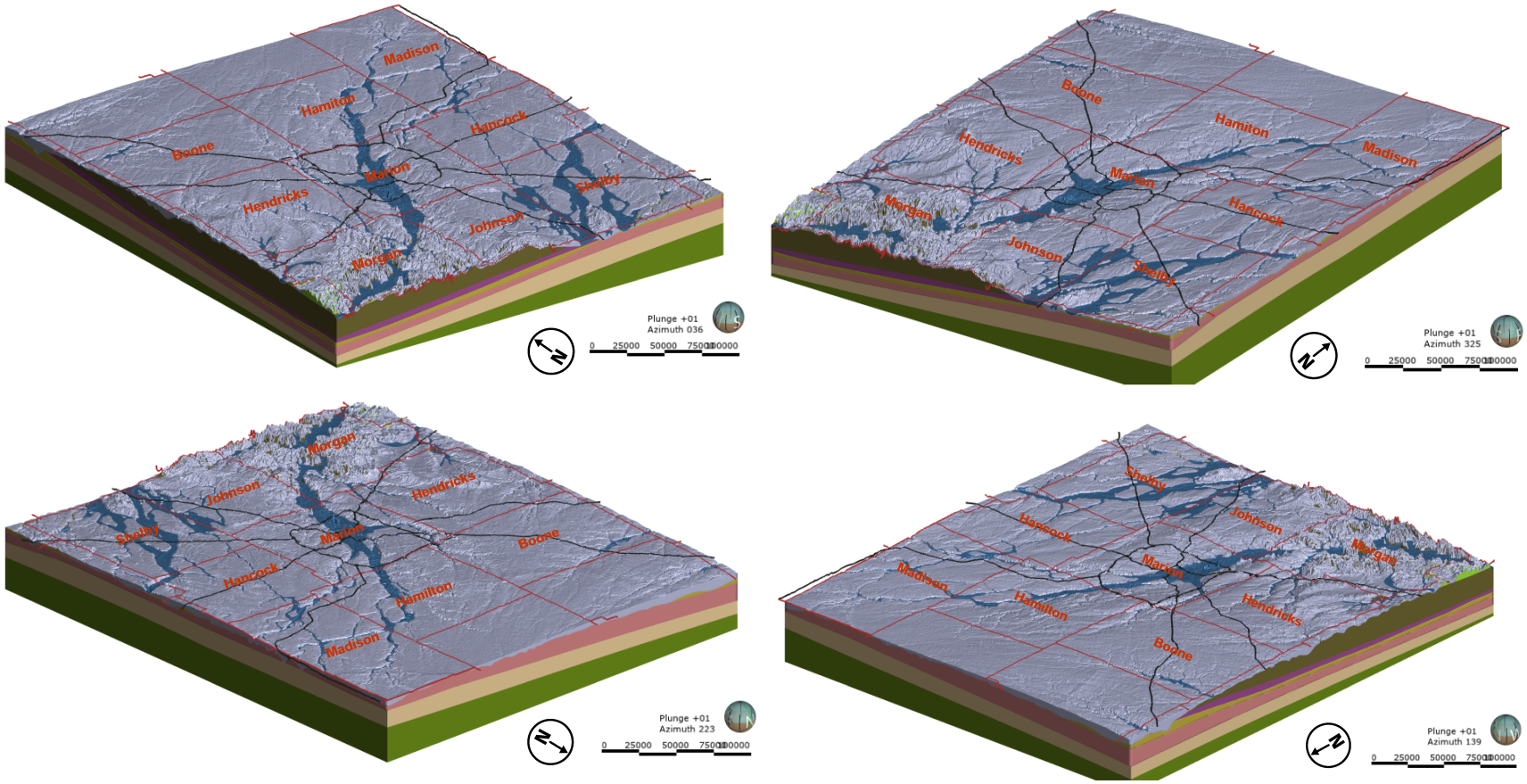


Figure D.17: Three-dimensional model viewed from different directions.

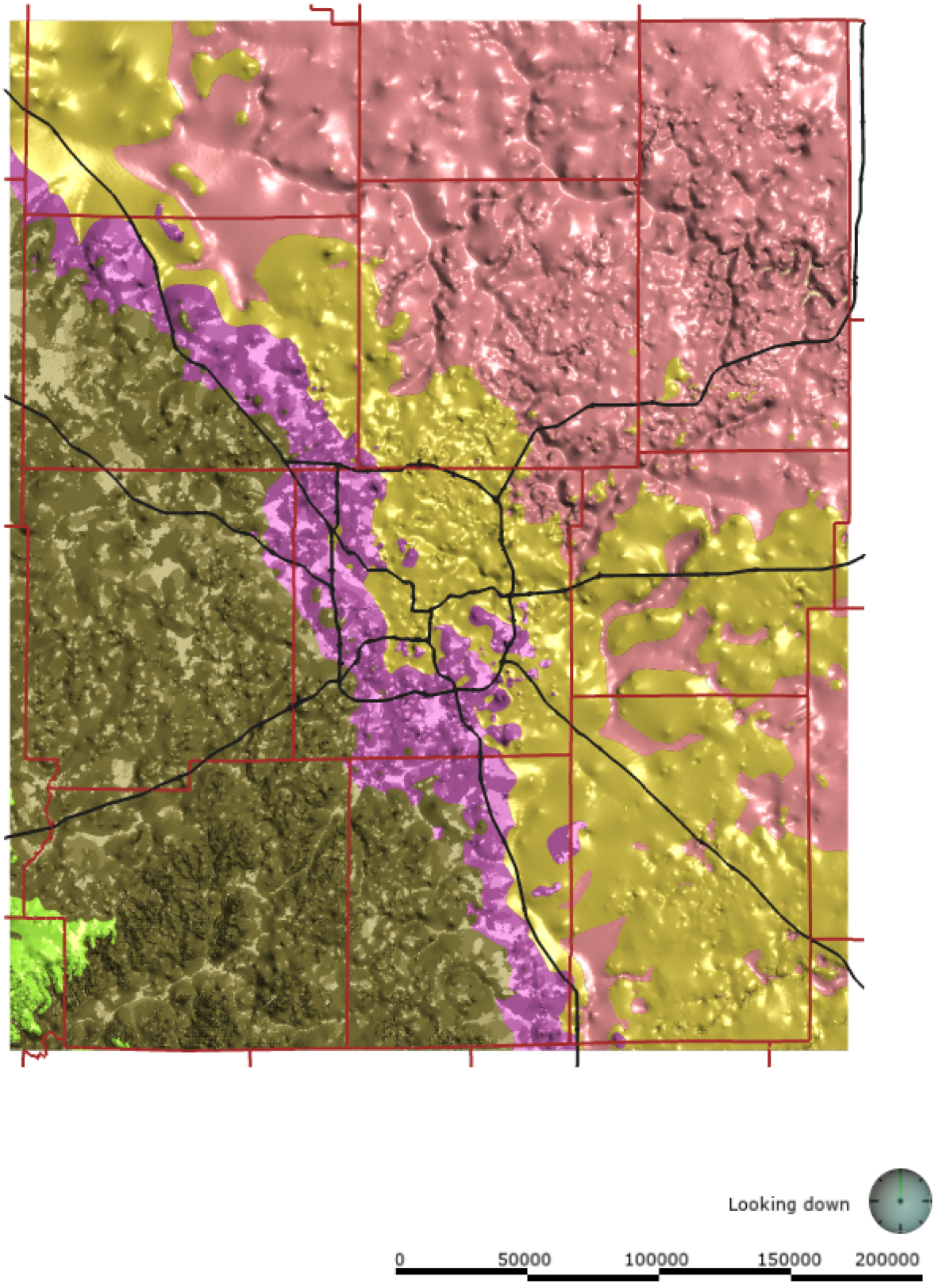


Figure D.18: Plan view of the geologic model showing bedrock geology .

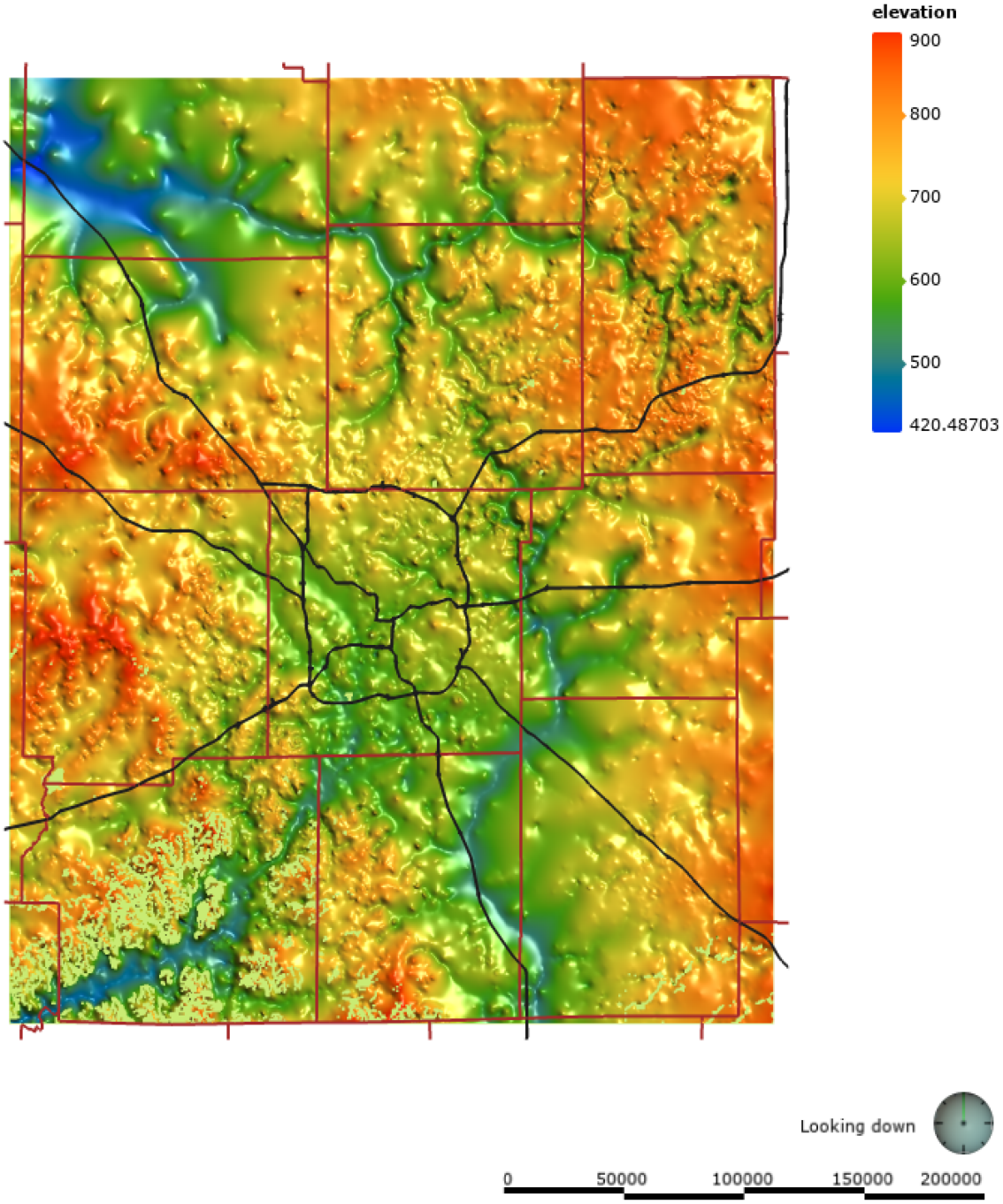


Figure D.19: Map of the bedrock elevation.

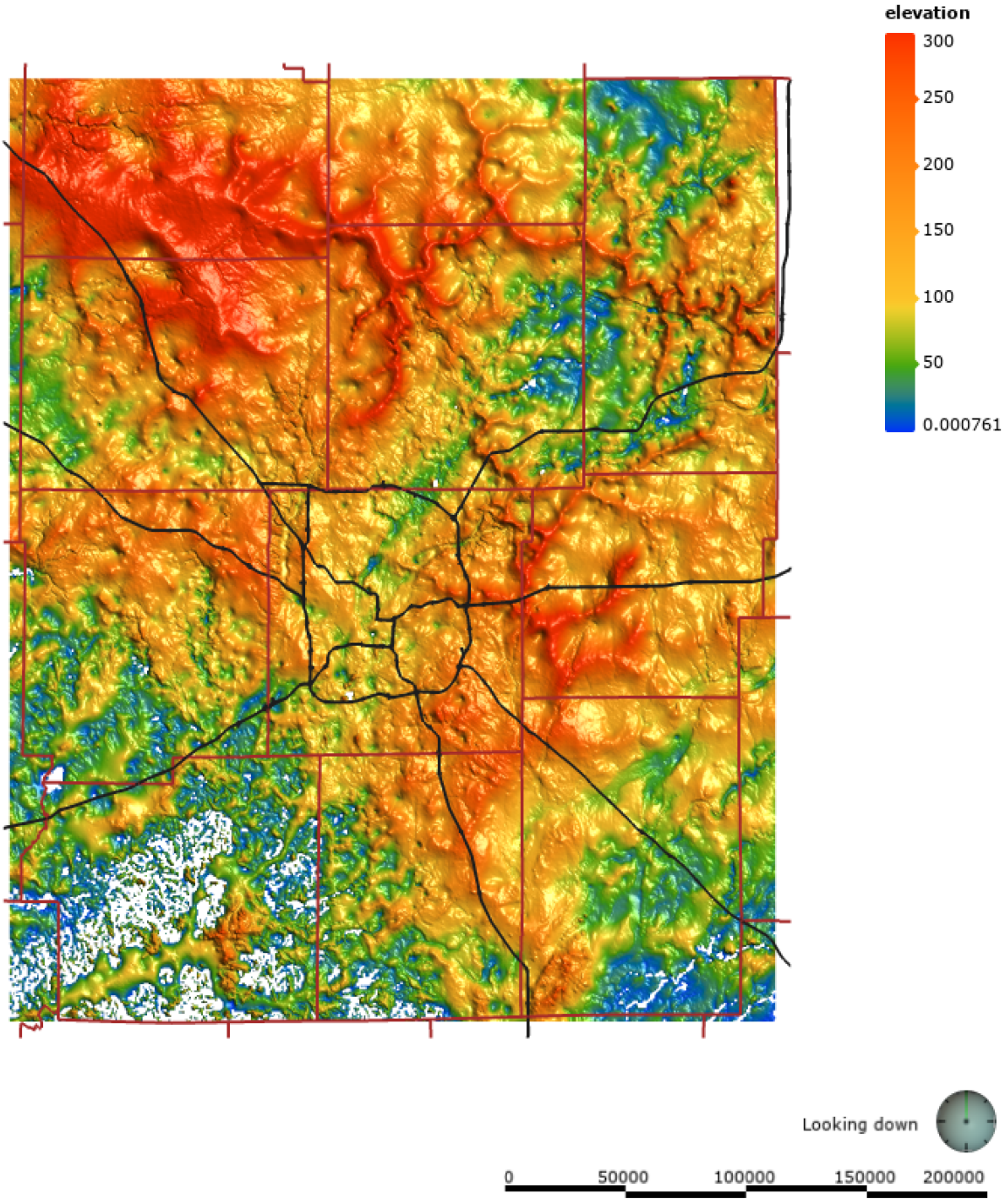


Figure D.20: Thickness of unconsolidated deposits.

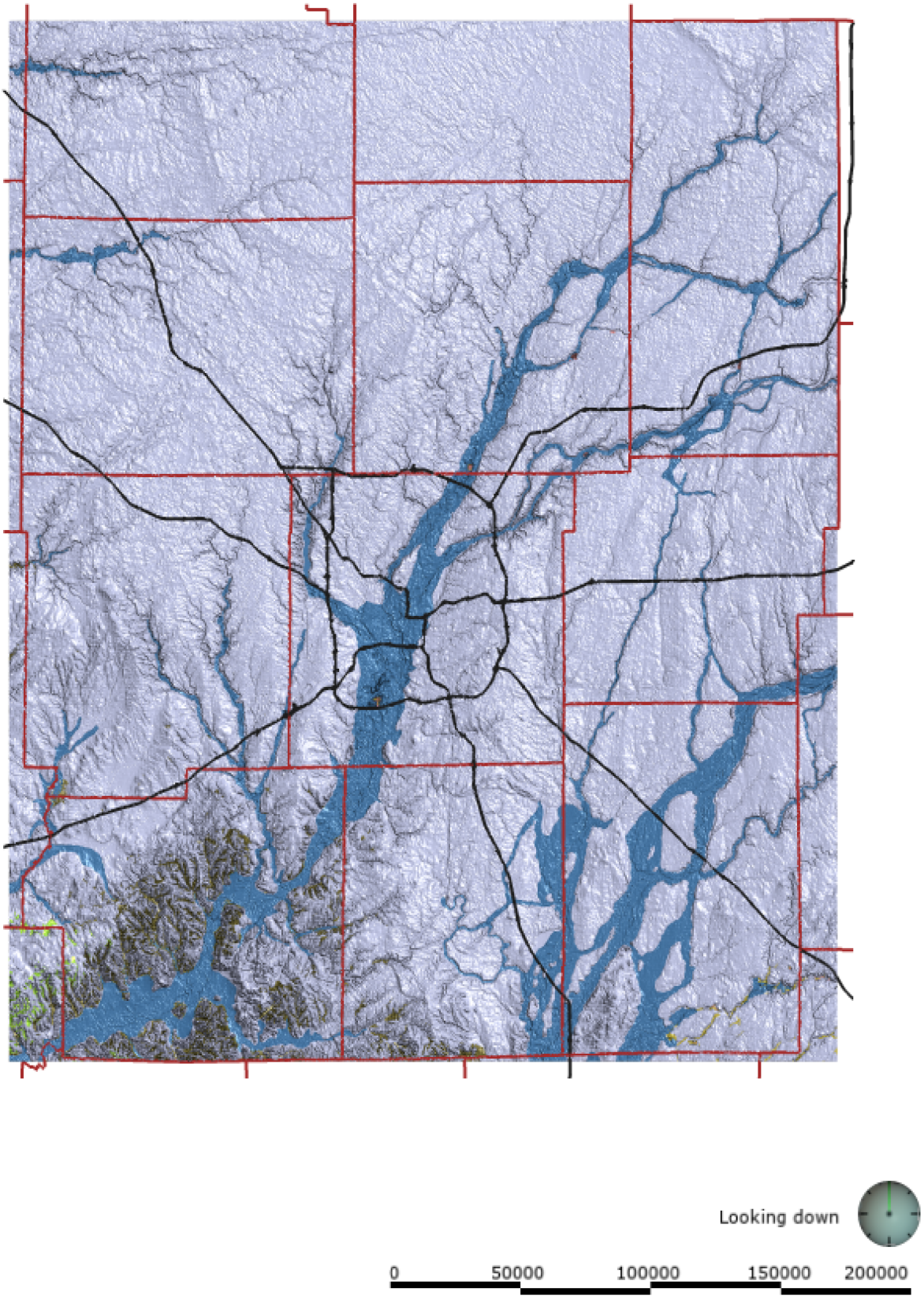


Figure D.21: Surficial geology.

D.3.3 Cross-Sections

19 cross-sections were created throughout the Study Area. There are 10 east to west cross-sections (A-A', B-B', C-C', D-D', E-E', F-F', G-G', H-H', I-I', and J-J'), and 9 north to south cross-sections (K-K', L-L', M-M', N-N', O-O', P-P', Q-Q, R-R', and S-S'). These cross-sections are presented as Figures D.22 through D.40.

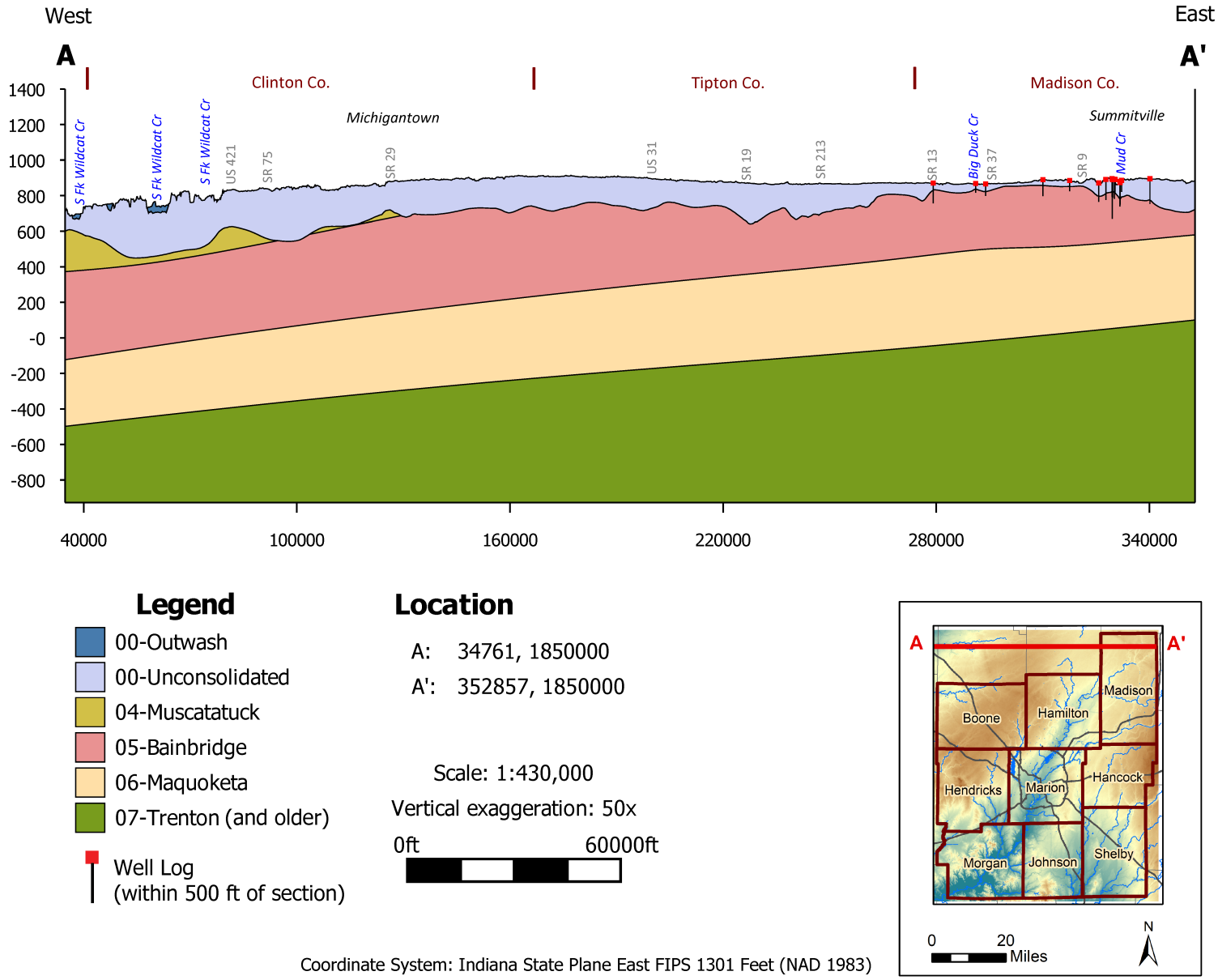


Figure D.22: Geologic section A-A'.

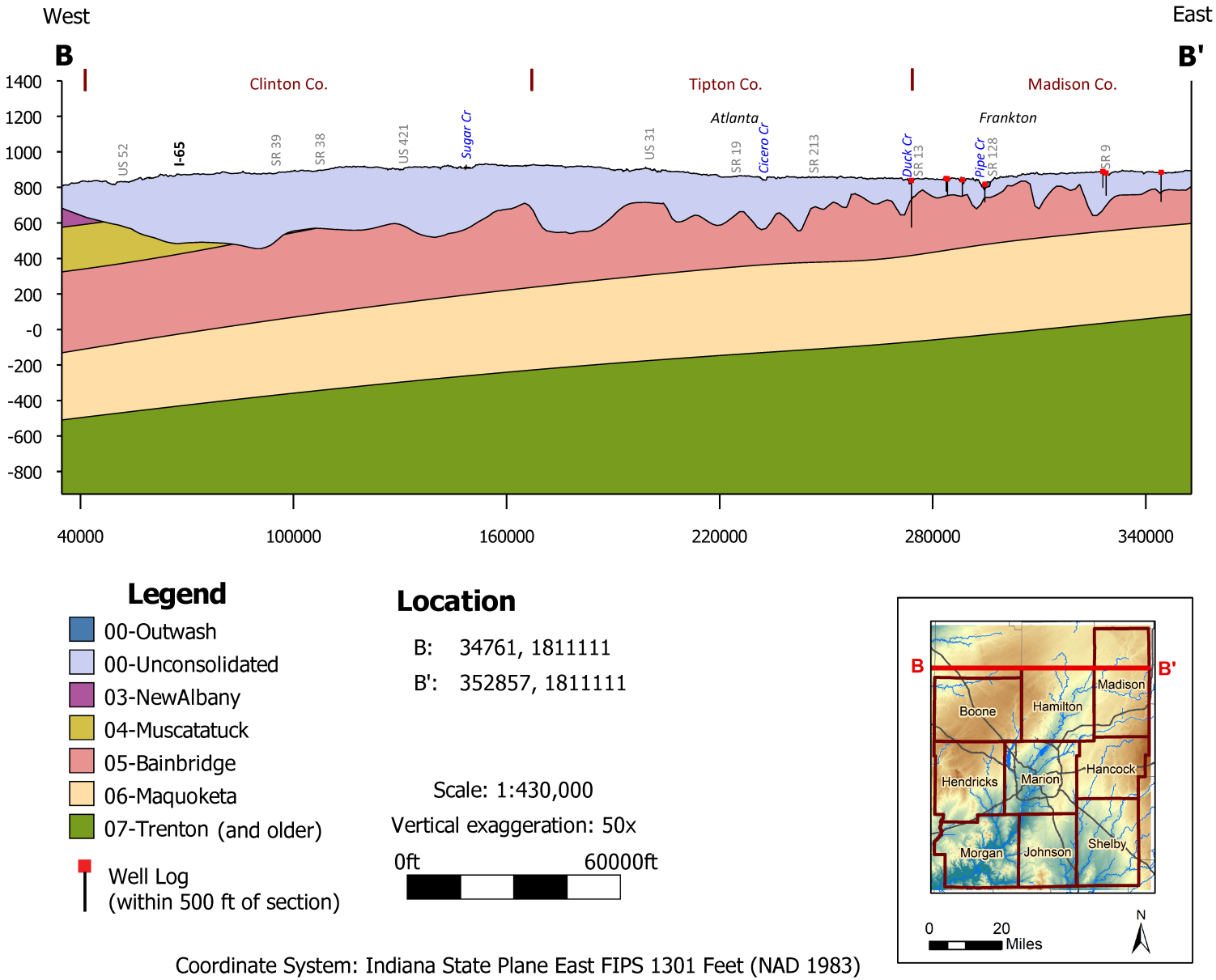


Figure D.23: Geologic section B-B'.

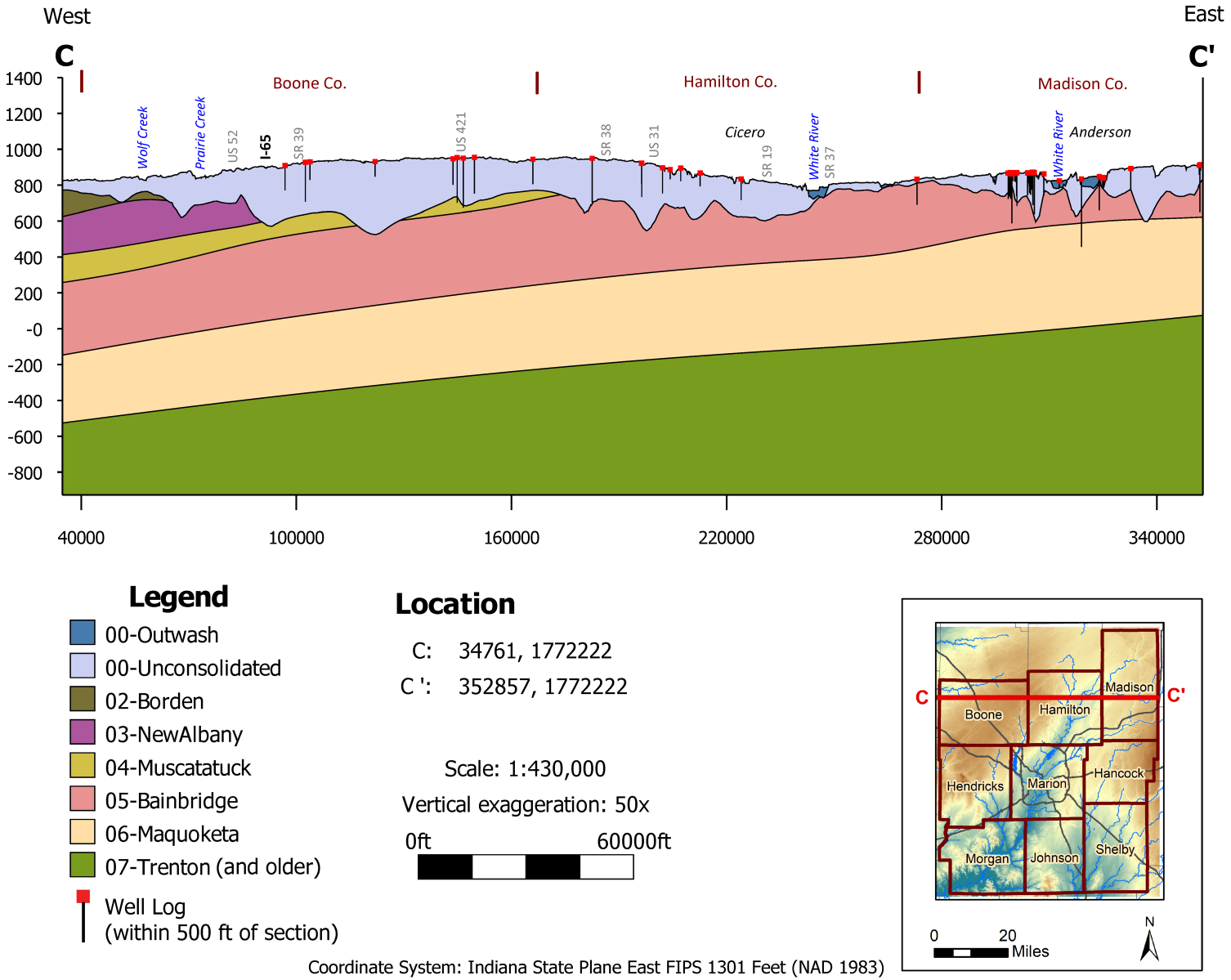


Figure D.24: Geologic section C-C'.

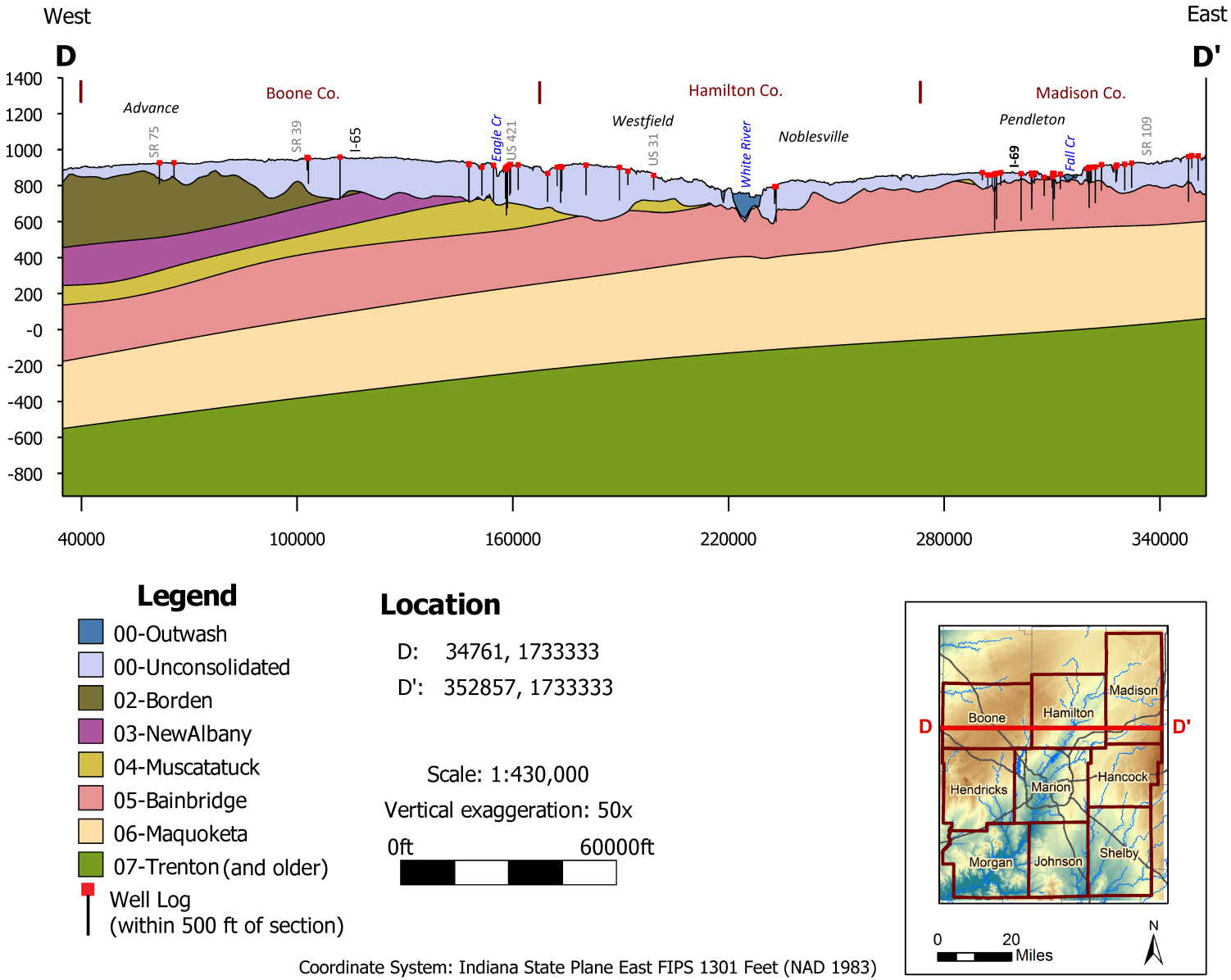


Figure D.25: Geologic section D-D'.

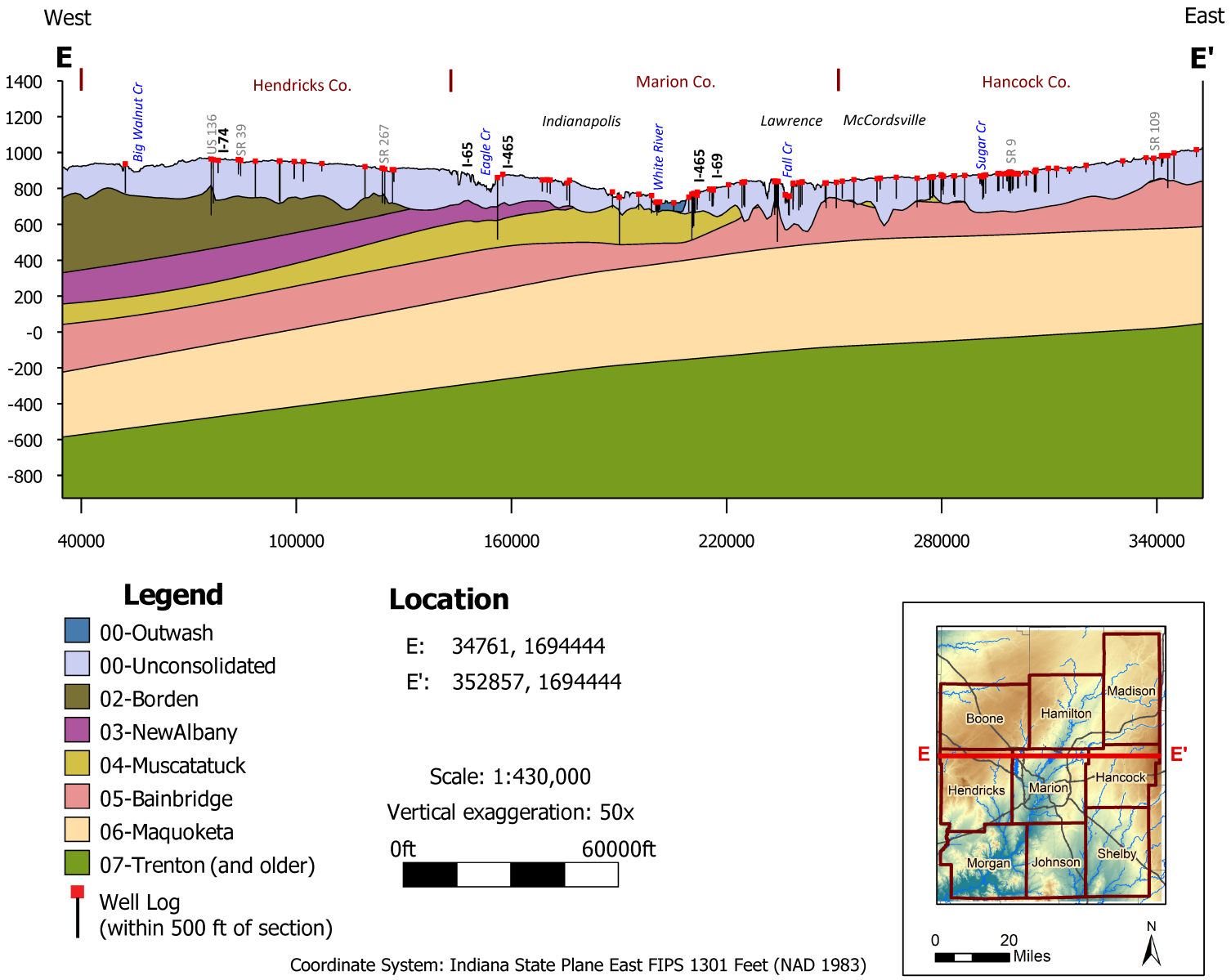


Figure D.26: Geologic section E-E'.

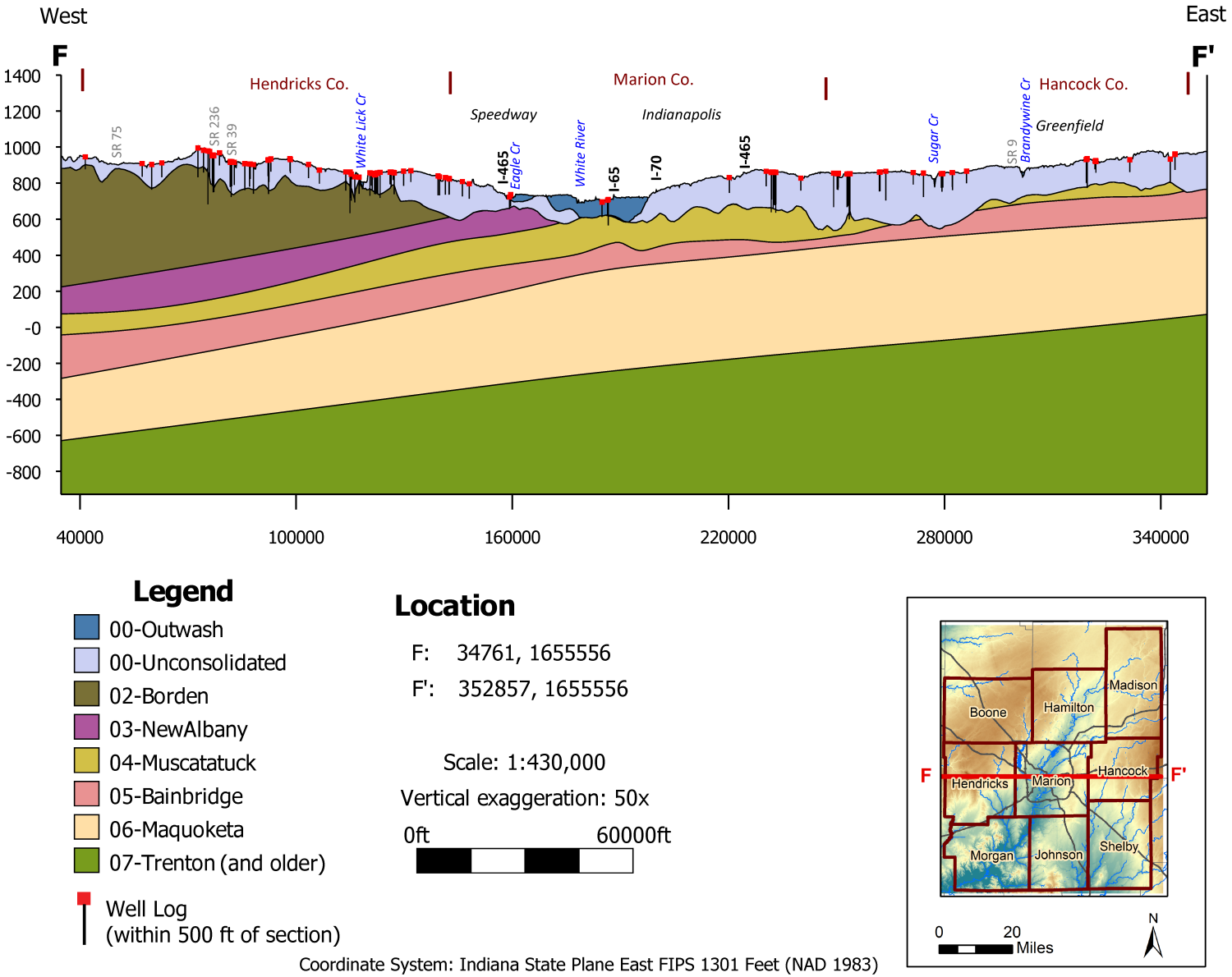


Figure D.27: Geologic section F-F'.

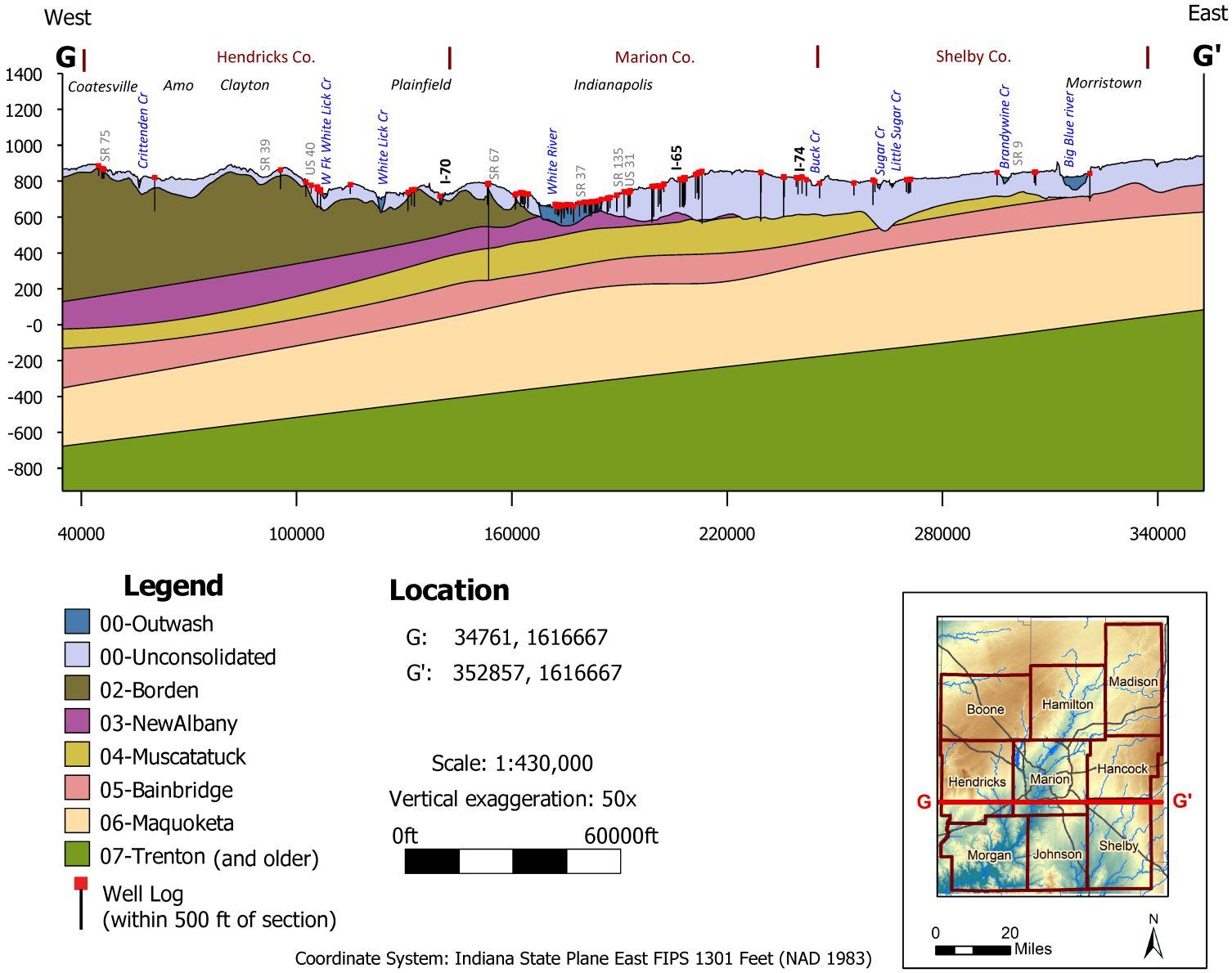


Figure D.28: Geologic section G-G'.

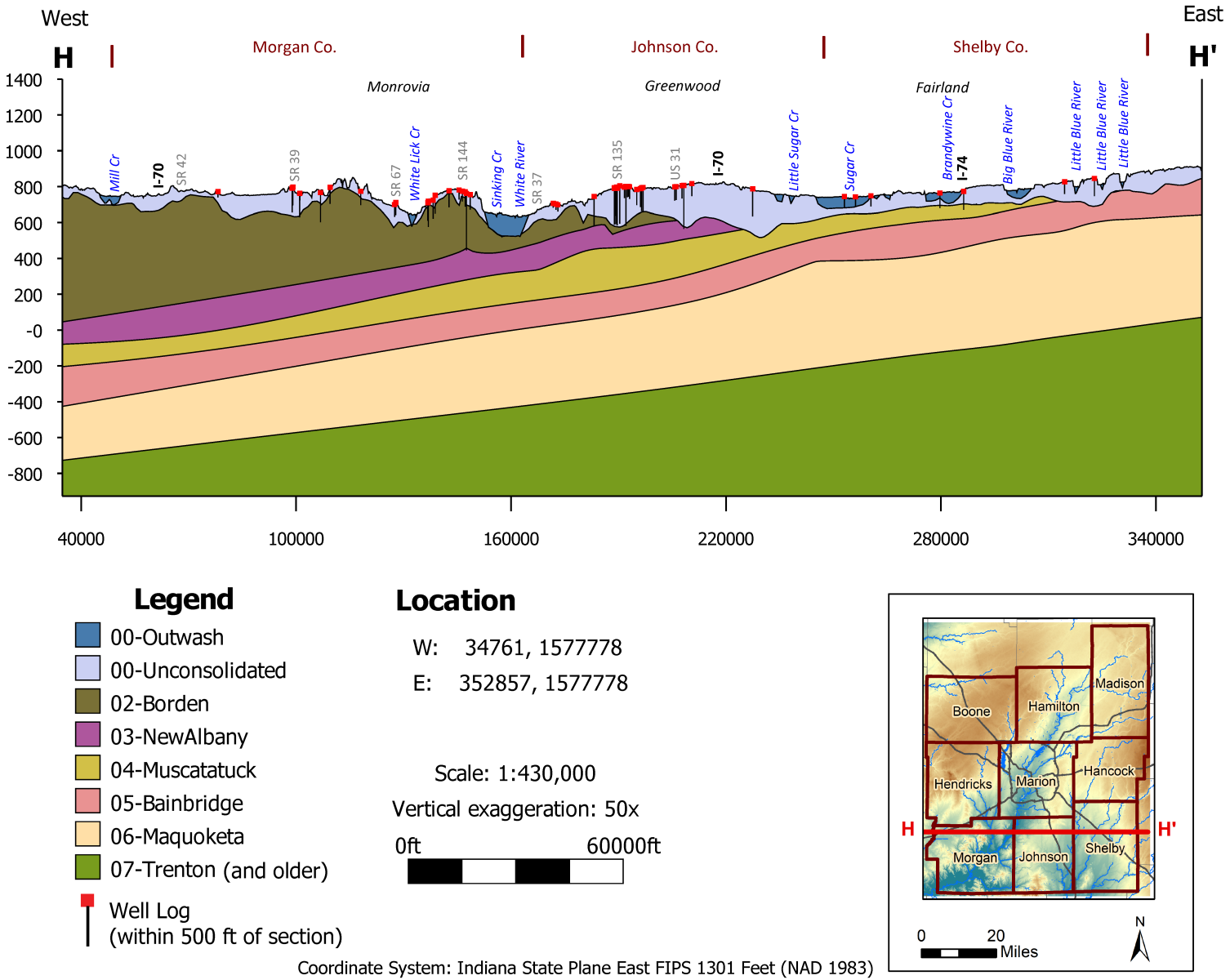


Figure D.29: Geologic section H-H'.

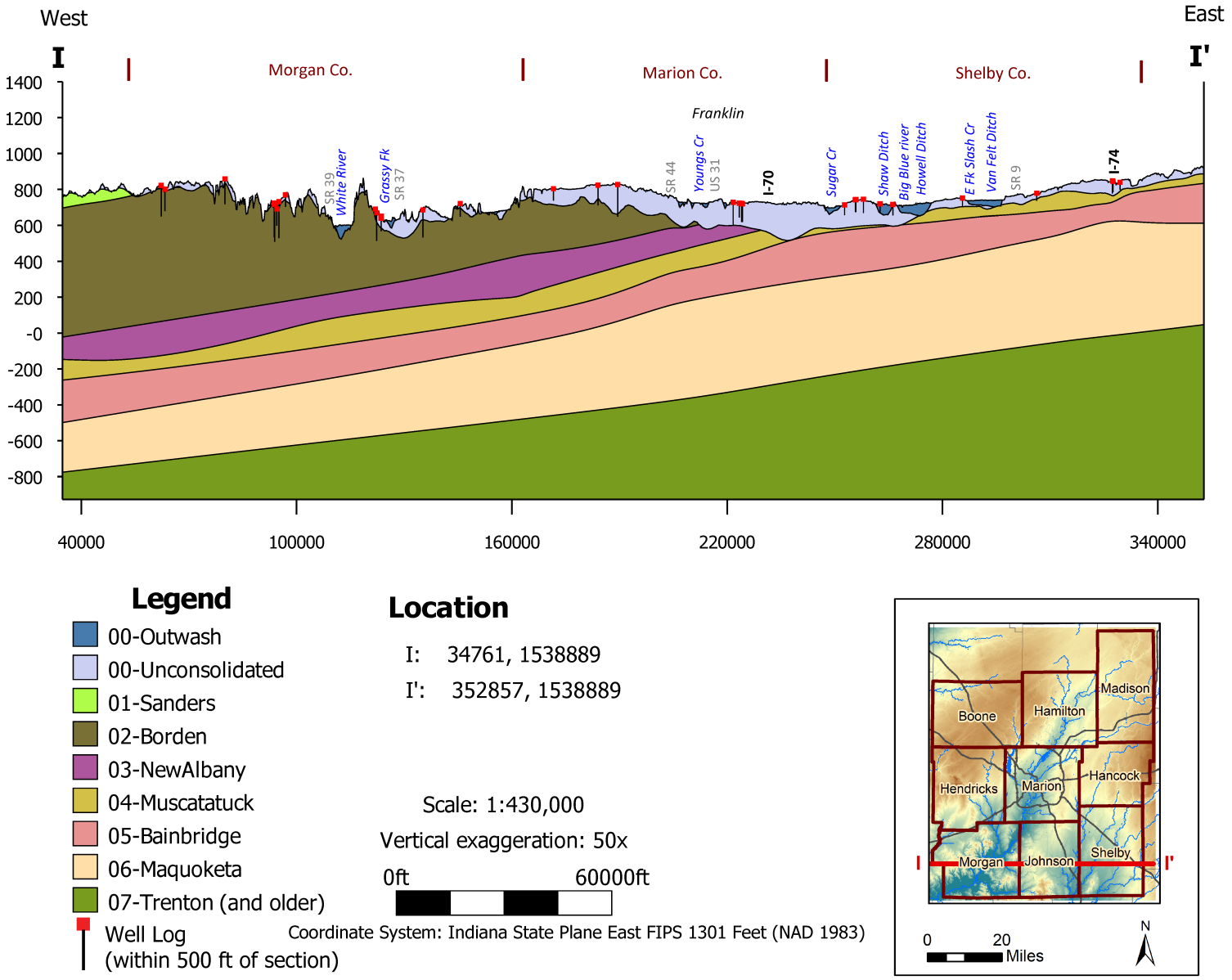


Figure D.30: Geologic section I-I'.

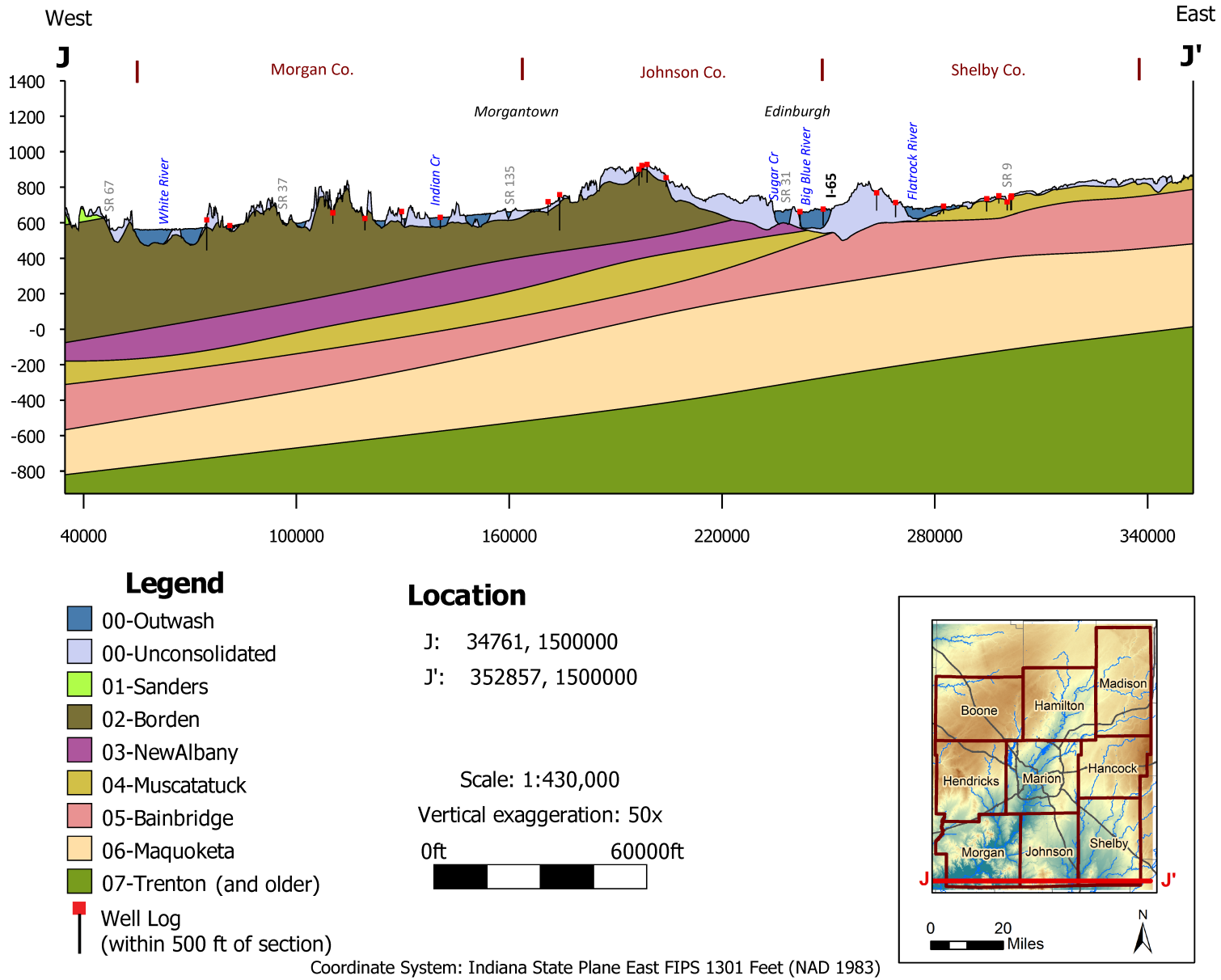


Figure D.31: Geologic section J-J'.

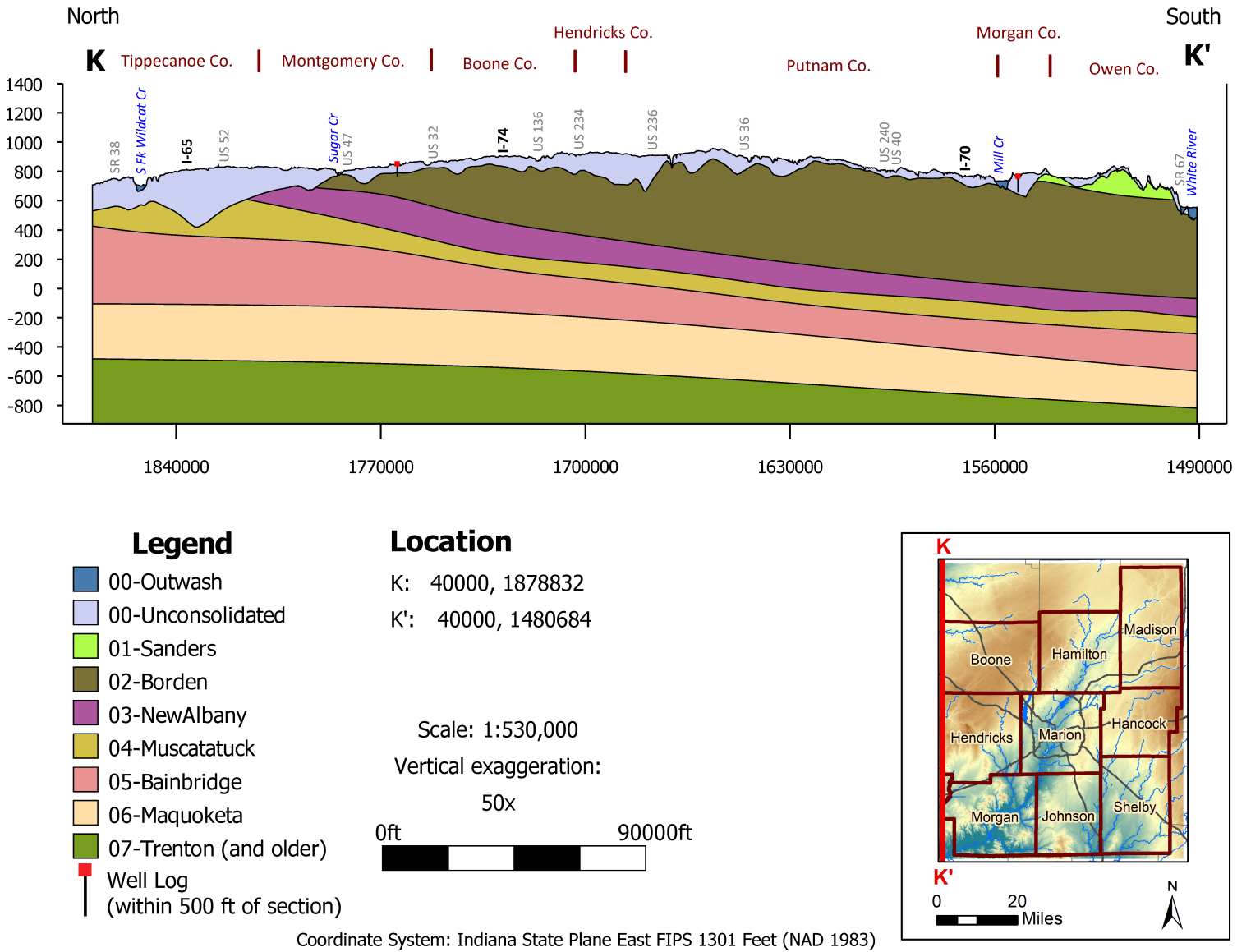


Figure D.32: Geologic section K-K'.

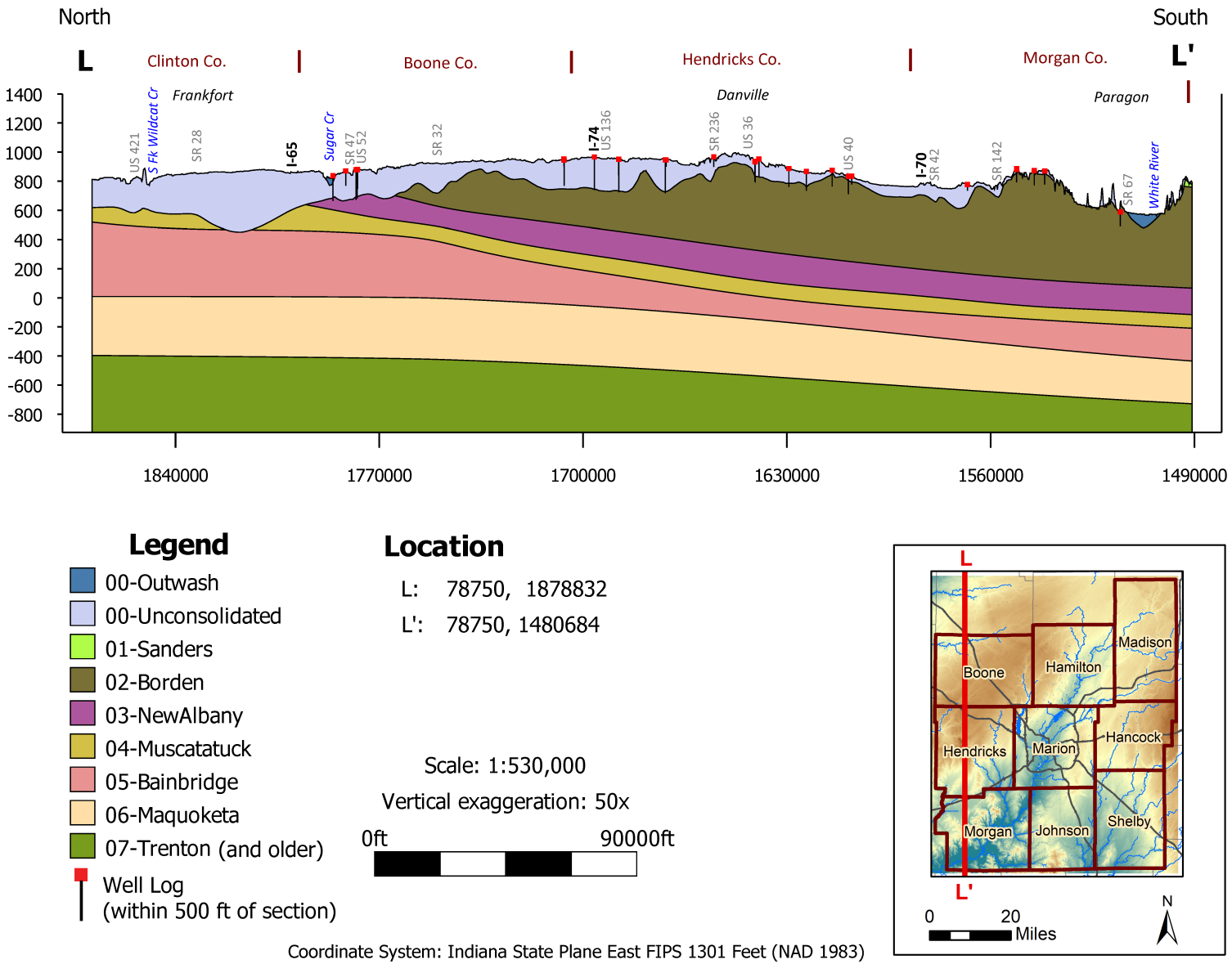


Figure D.33: Geologic section L-L'.

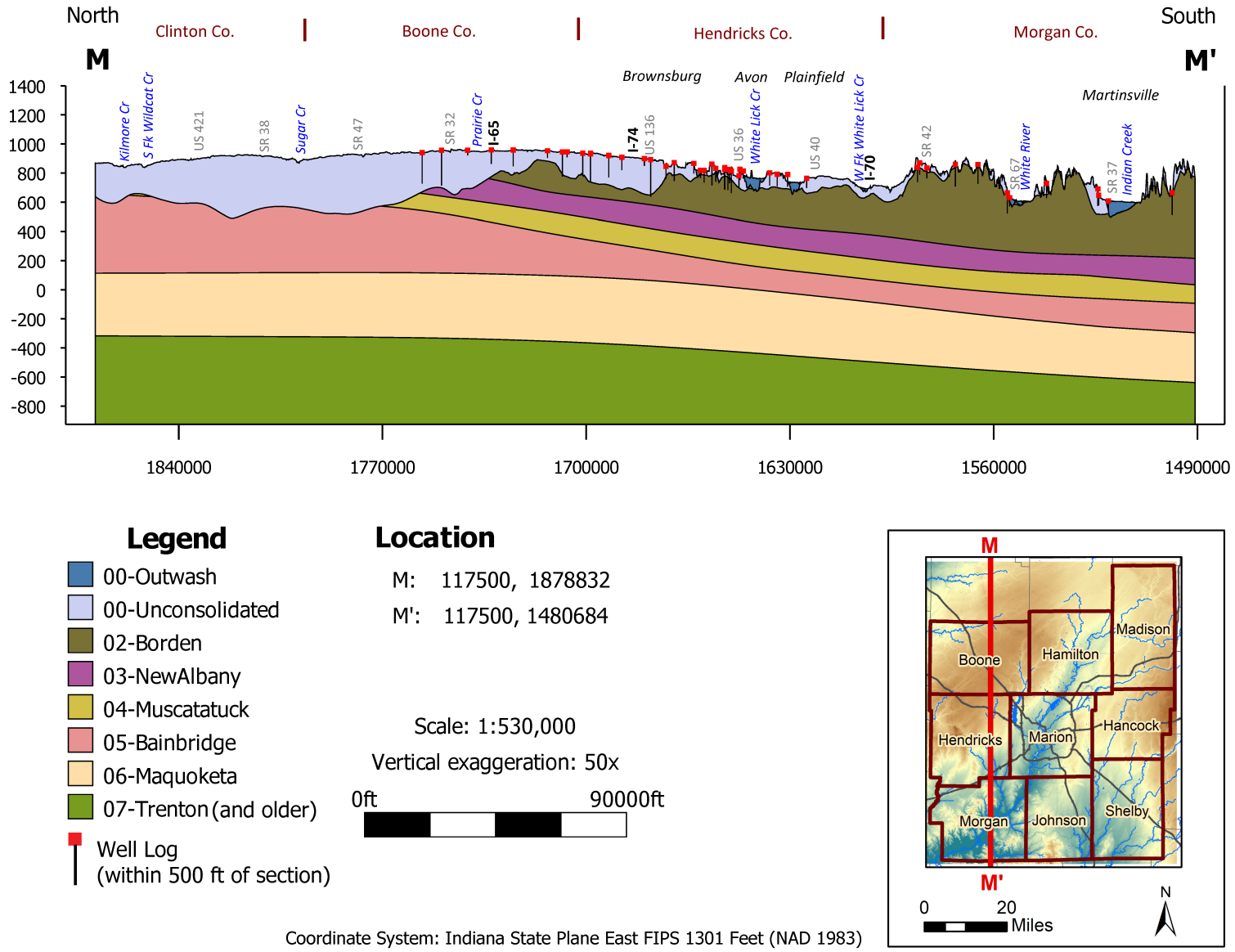


Figure D.34: Geologic section M-M'.

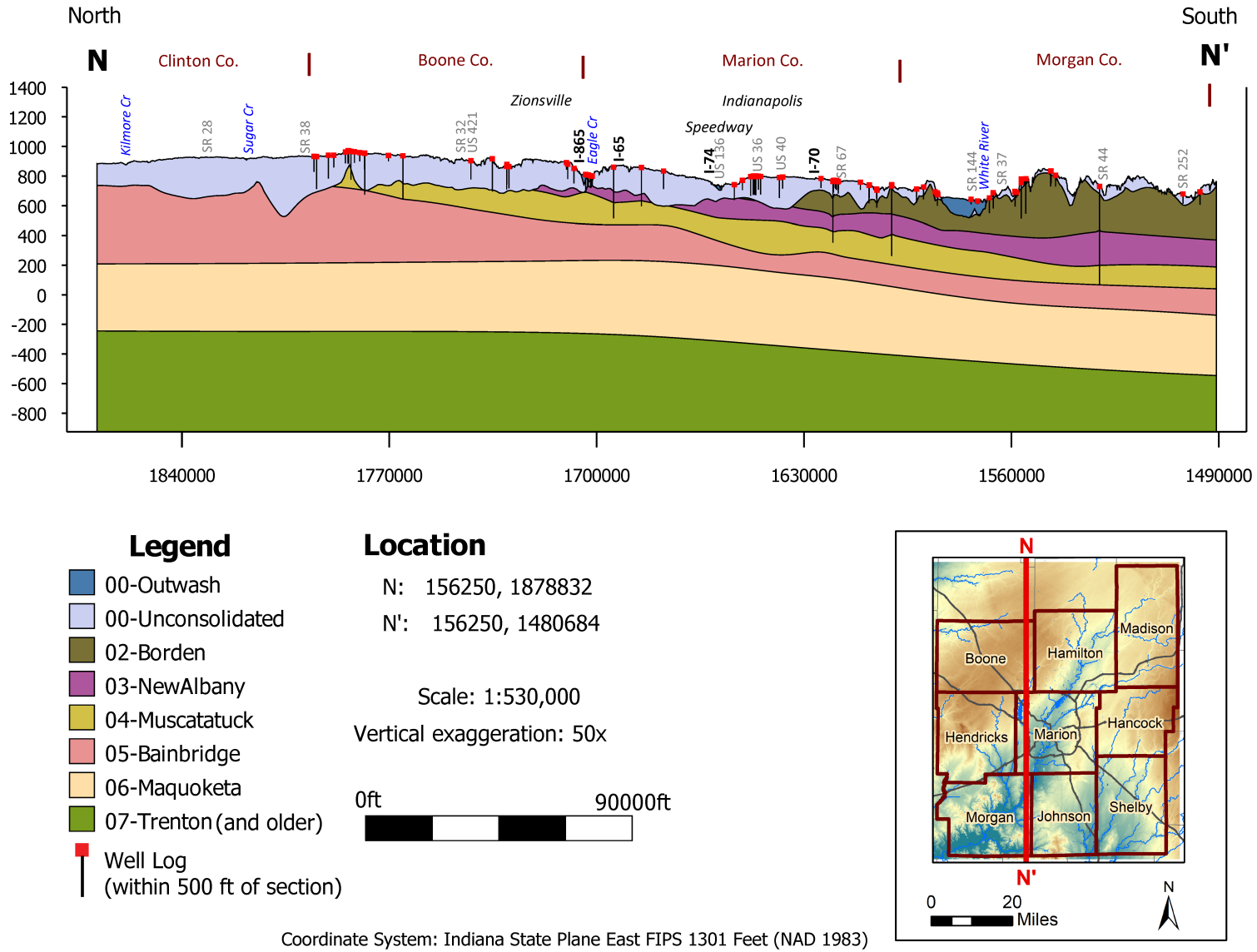


Figure D.35: Geologic section N-N'.

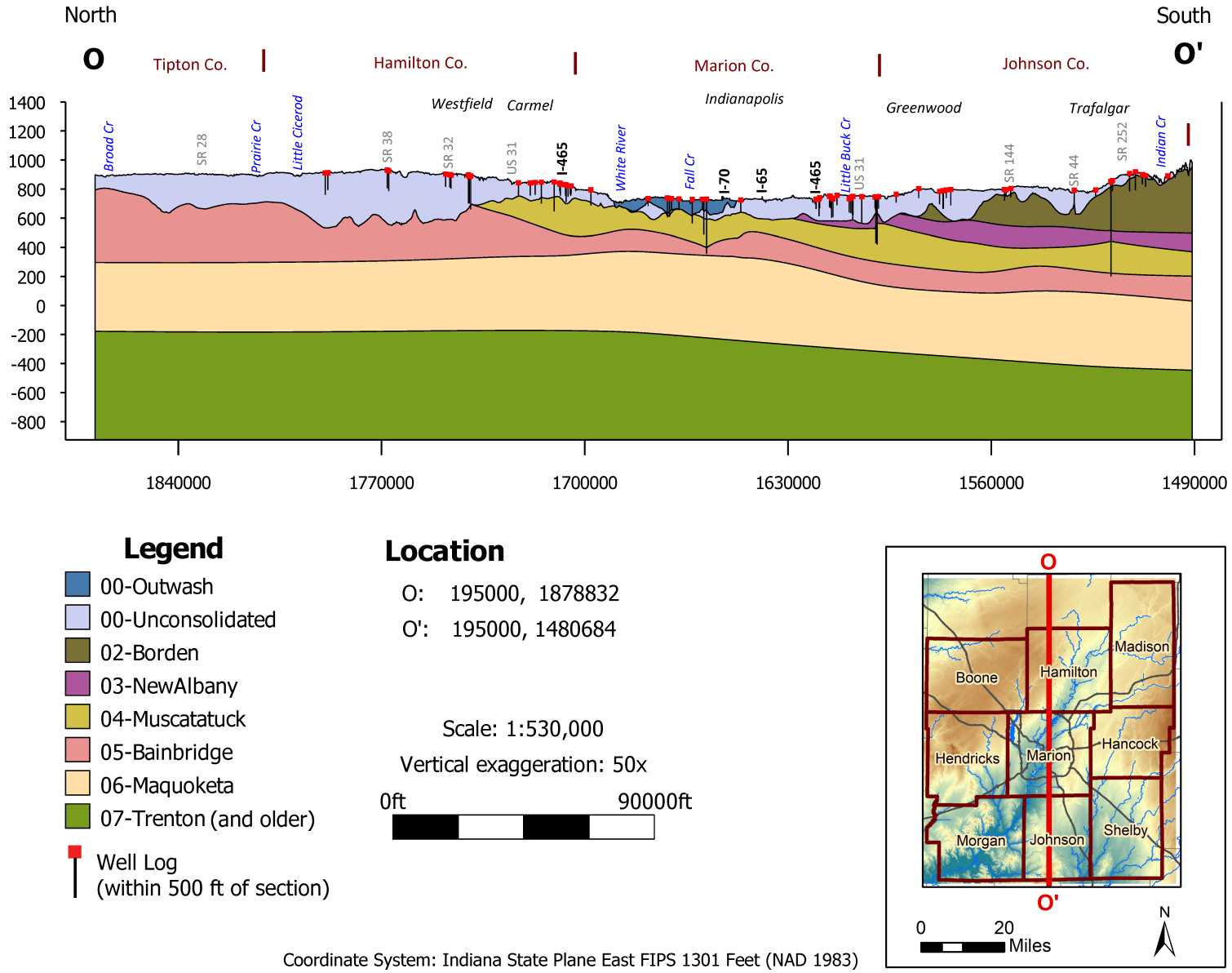


Figure D.36: Geologic section O-O'.

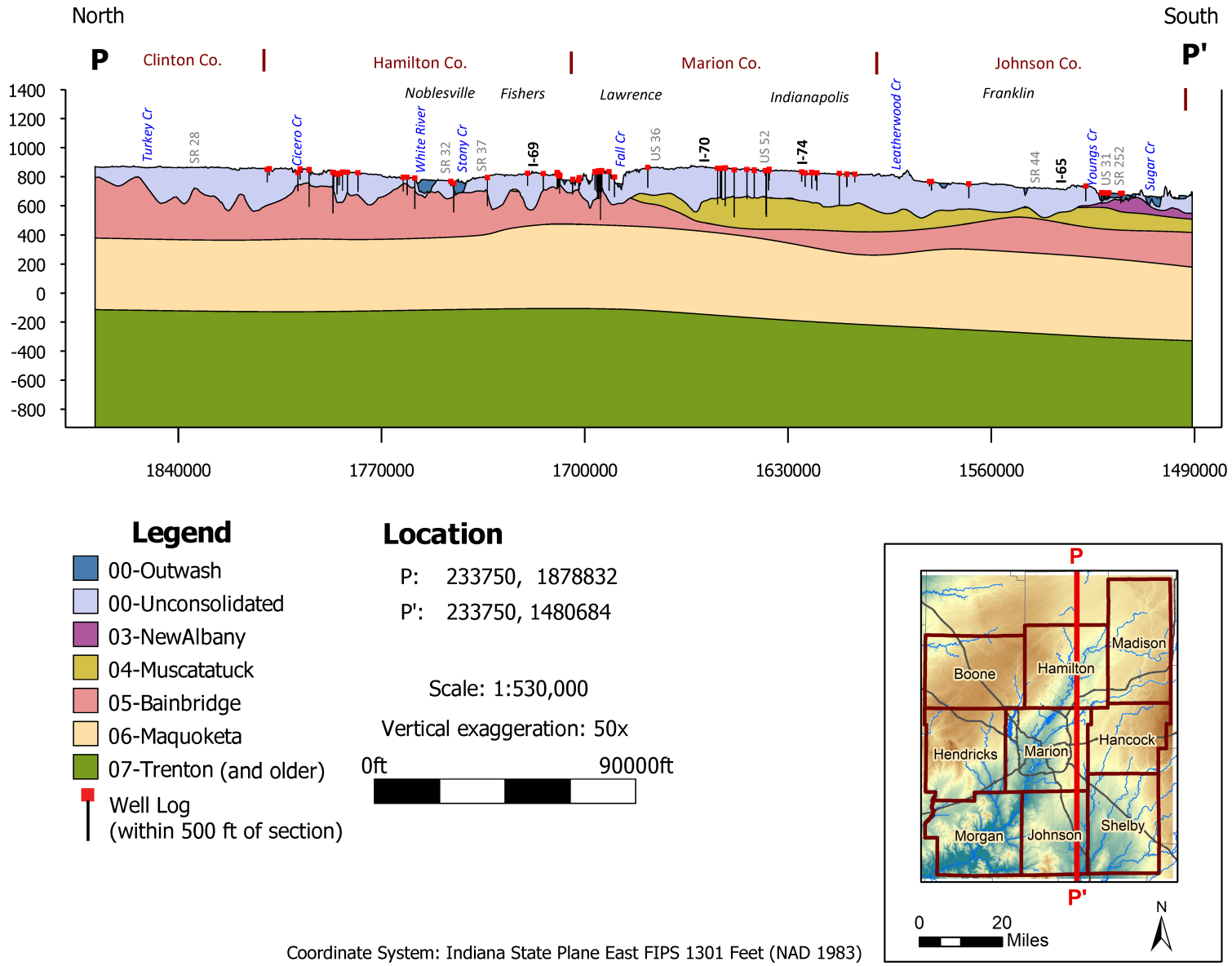


Figure D.37: Geologic section P-P'.

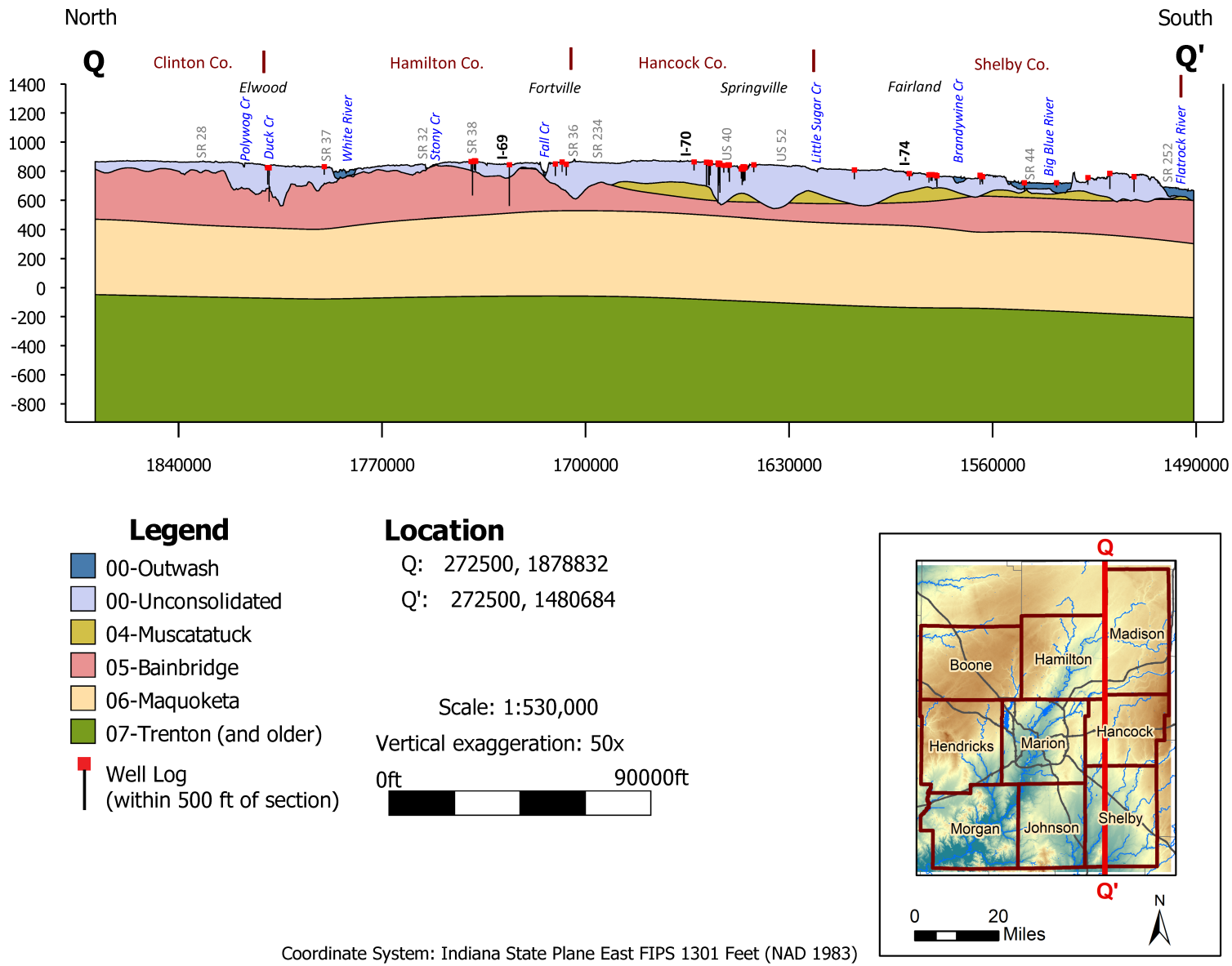


Figure D.38: Geologic section Q-Q'.

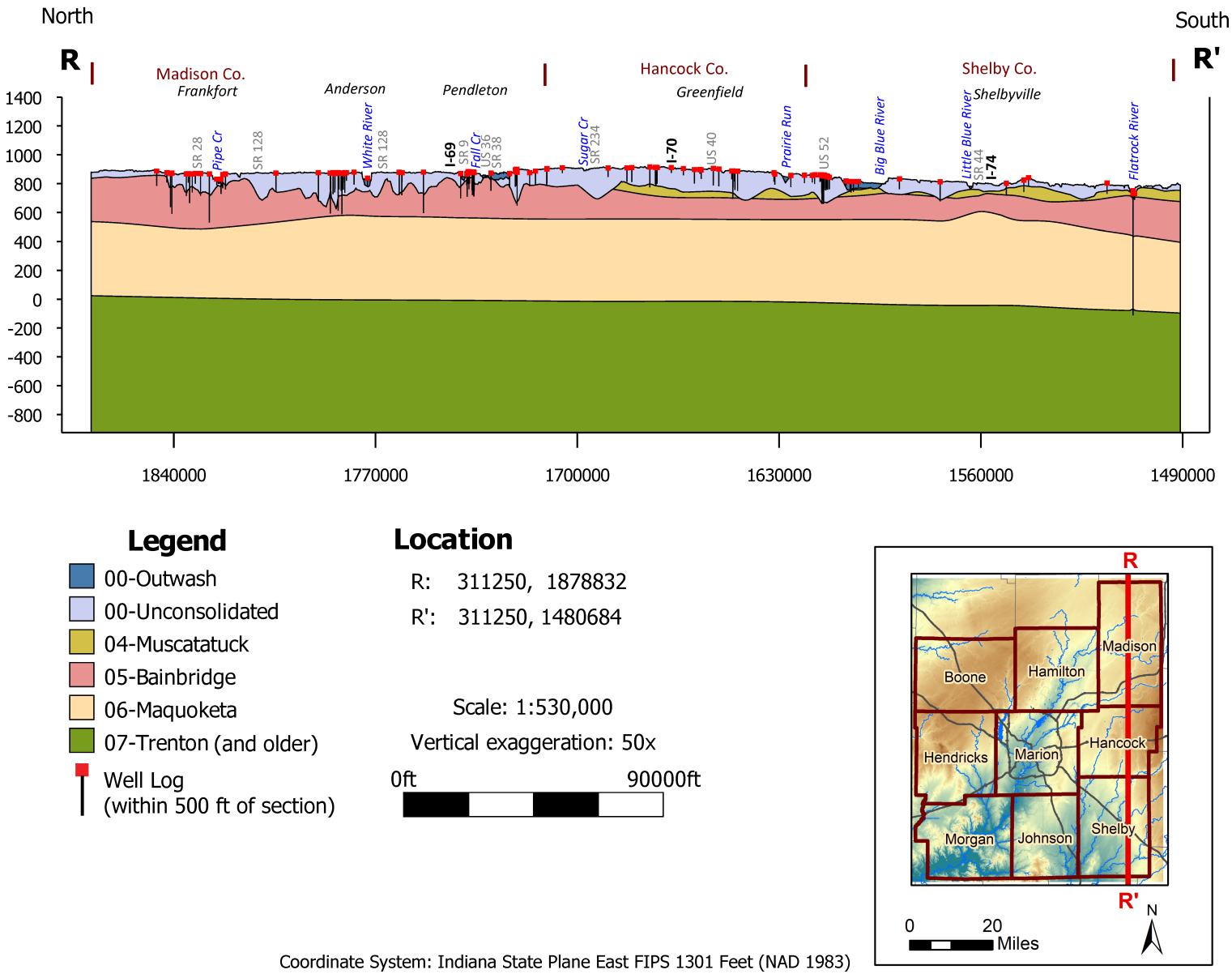


Figure D.39: Geologic section R-R'.

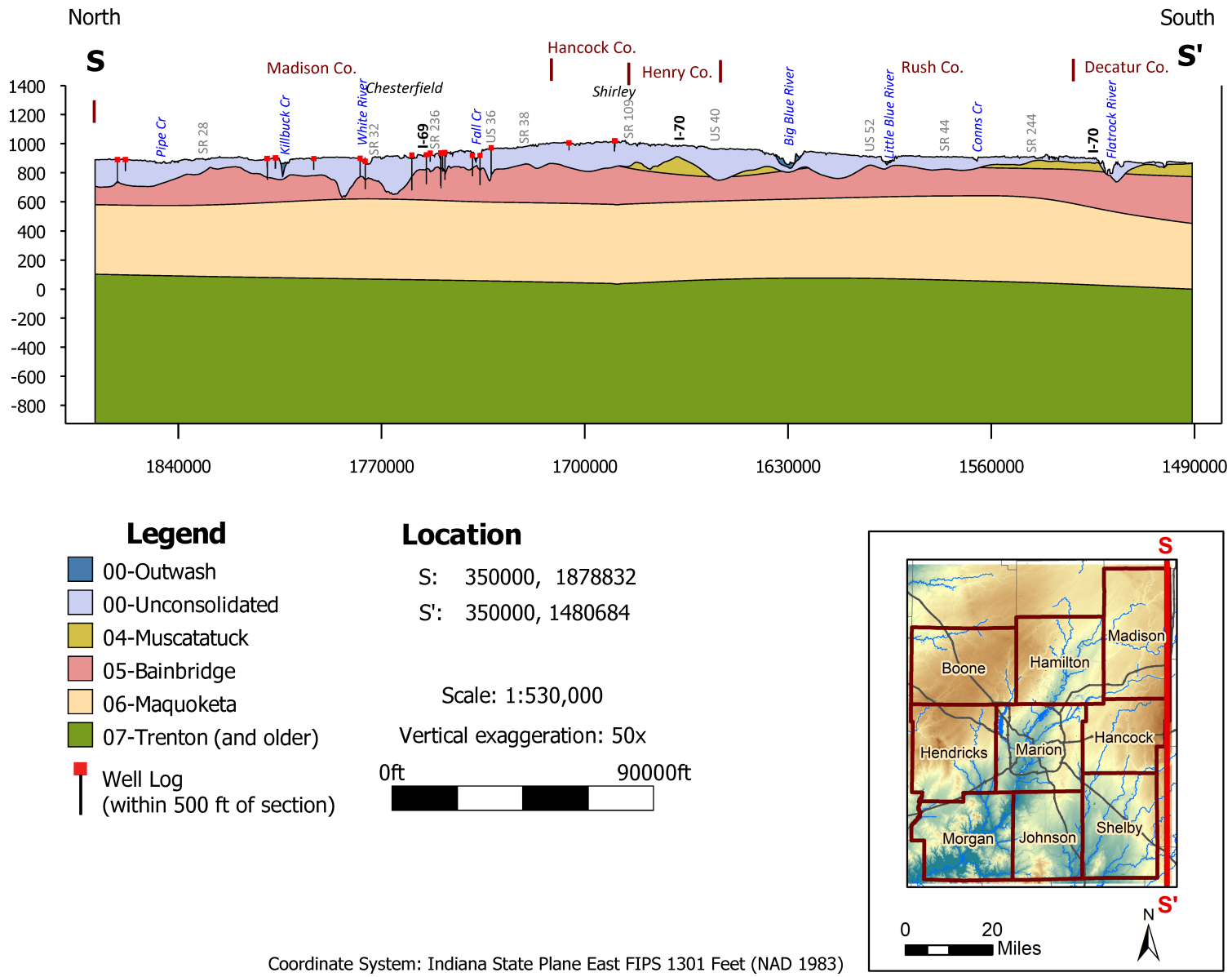


Figure D.40: Geologic section S-S'.

E Field Testing

The importance of considering groundwater and surface water as a single resource has become increasingly evident as concern over water quality and availability have increased. Effective water management requires a clear understanding of the linkages between ground water and surface water (Winter et al., 1998; Stonestrom and Constantz, 2003). The purpose of this study was to gain insight into the interaction between surface water and groundwater at representative sites within the Study Area.

E.1 Groundwater/Surface-Water Interaction

Groundwater and surface water are essentially one resource, physically connected by the hydrologic cycle and functionally inter-dependent. Groundwater naturally flows from higher elevation, often discharging to surface waters, including streams, lakes, springs, and wetlands (Figure E.1A). If the ground water table is in physical contact with the stream bed, it is a hydraulically connected system.The exchange of water between groundwater system and a stream is controlled by the difference in elevation between groundwater table and the water level in the stream and the hydraulic properties of the streambed. Fine-grained sediments in the streambed or layered in the aquifer between the stream and the well screen can inhibit or prohibit groundwater/surface-water exchange.

Pumping groundwater from aquifers that discharge to hydraulically connected streams can reduce flows and water levels by intercepting groundwater that would normally discharge to the stream (Figure E.1B) or if conditions are right, induce recharge from the stream (Figure E.1C). The conditions for inducing recharge depend on the pumping rate, distance from the stream, and aquifer properties, including the hydraulic properties of the streambed.

There have been a few studies of the hydraulic connection between the sand and gravel aquifers and the streams in the Study Area, including site-specific (Meyer, 1978, 1979) and regional studies (IDNR, 2002; Arihood, 1982). The general conclusion of these investigations is that the hydraulic connection varies locally depending on the grain size of the riverbed materials and the presence of intervening clay layers in the aquifer. The glacial outwash aquifers in the Study Area are often capped and/or divided by an intervening clay confining layer that inhibits flow between the stream and the lower sand and gravel units that are a common source for public supply.

E.2 Objective

The objective of the field program was to characterize the hydraulic interaction between key well fields and adjacent surface water bodies. Three utilities volunteered access to their well field for a topical study of the interaction between the aquifer and the river, including the City of Carmel Utilities (Carmel), Indiana American Water Company (INAWC), and the City of

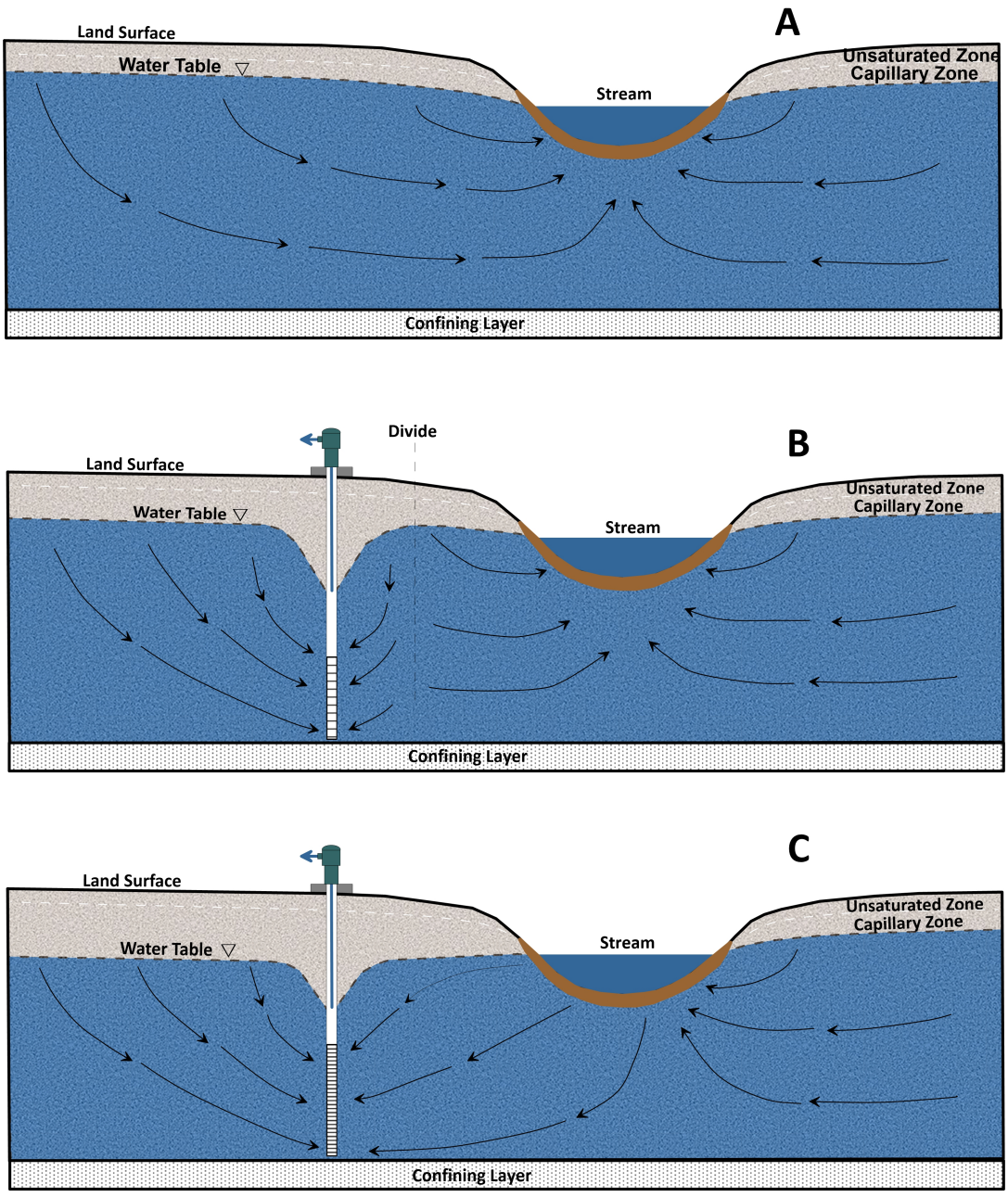


Figure E.1: Schematic showing (A) groundwater discharging to a stream, (B) a production well pumping near a stream that intercepts groundwater discharging to the stream, and (C) well pumping near a stream that intercepts groundwater and induces recharge through the streambed. *The conditions for inducing recharge depend on the pumping rate, distance from the stream, and aquifer properties, including the hydraulic connection between the stream and aquifer.*

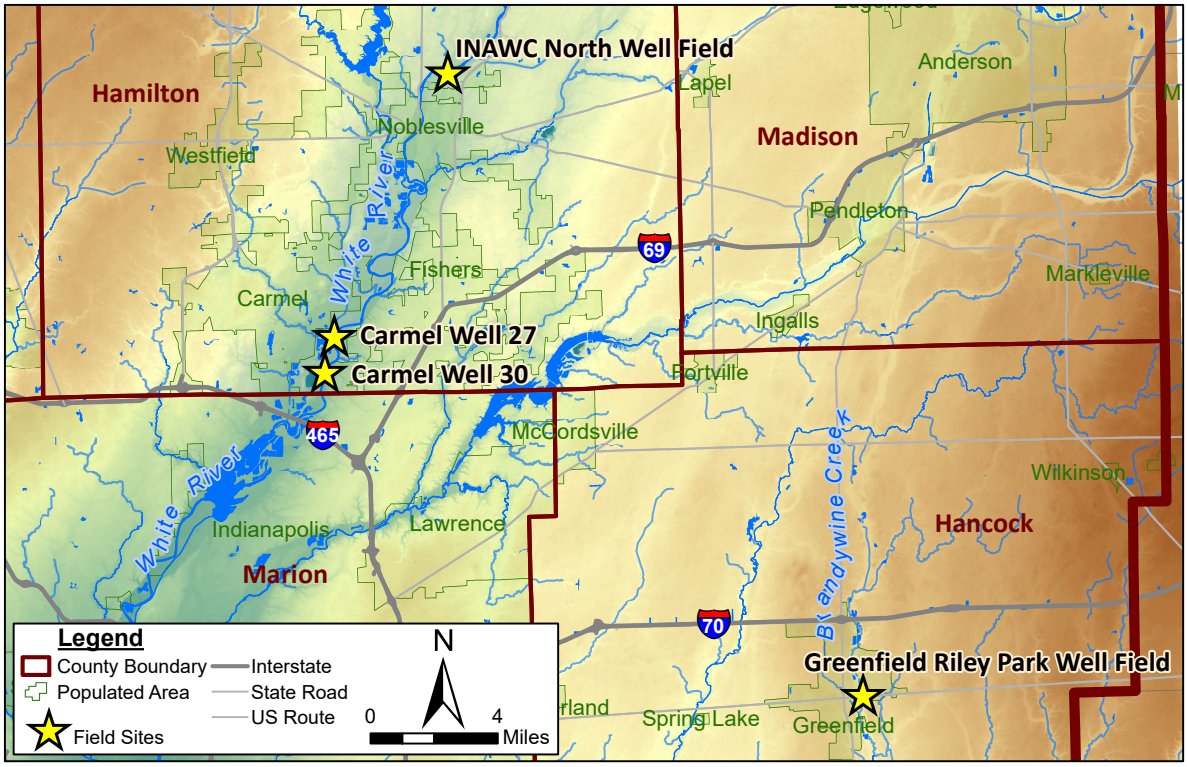


Figure E.2: Location of well fields in infiltration study.

Greenfield Water Utility (Greenfield) (Figure E.2). Shallow piezometers were installed in the White River (Carmel and INAWC well fields) and Brandywine Creek (Greenfield) to characterize the hydraulic connection between the river and the aquifer. Heat tracing techniques were used to examine fluxes.

E.3 Heat as Tracer

Various methods have been developed to estimate fluxes between groundwater and surface water . Because these exchanges are typically slow and diffuse, they are difficult to measure directly. Of various methods that are available for estimating fluxes between groundwater and surface water, temperature-based methods provide an efficient way to delineate the direction and rate of vertical fluid movement (flux) (Cremeans et al., 2020). Heat is an effective tracer because it is naturally occurring, ubiquitous, and readily measured.

Methods to quantify surface water-groundwater exchange using heat as a tracer have been developed over the last sixty years (Suzuki, 1960). In general, temperature-based methods use naturally occurring variations in temperature to track the heat carried by flowing water (Constantz, 2008). Flux at the riverbed surface can be in either direction, downward movement of surface water into shallow groundwater (infiltration or downwelling) or upward movement of groundwater into surface water (exfiltration or upwelling).

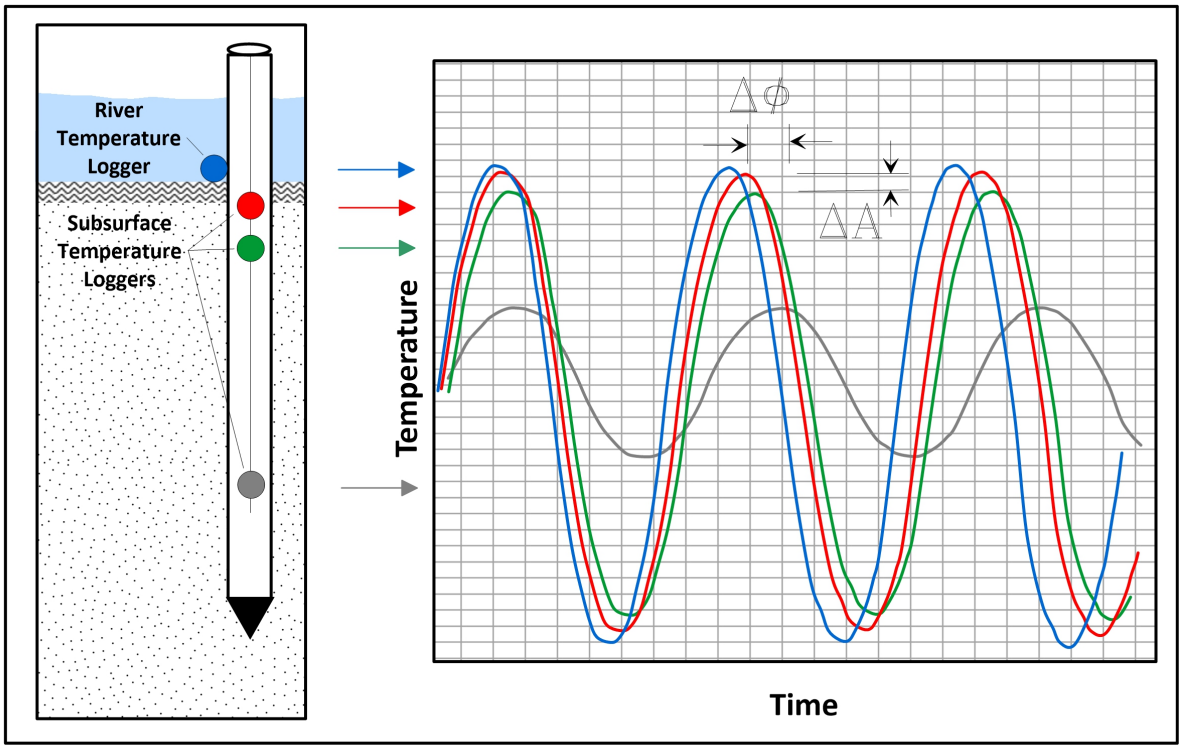


Figure E.3: Diagram showing acquisition of riverbed temperature measurements and resulting reduction reduction in amplitude (ΔA) and shift in phase ($\Delta\phi$)with depth.

More recently developed methods based on timeseries analysis techniques with diurnal temperature signals (Hatch et al., 2006; Keery et al., 2007) have become well established because they provide vertical flux estimates through time with minimal field effort and relatively low cost. Compared to other methods, time-series approaches offer lower data requirements, require less setup and data handling, and are considerably faster (Hatch et al., 2006).

When surface water is infiltrating into shallow groundwater beneath the riverbed, diurnal variations in surface-water temperature are transported downward by conduction and advection. This combination of heat transport results in observable diurnal signals below the riverbed. In the case of exfiltration, diurnal temperature signals are only transported downward by conduction. Because the temperature of groundwater is relatively constant, this usually results in a muted temperature signal below the riverbed. Timeseries methods to estimate fluxes use changes in phase and attenuation of the diurnal temperature signals measured between pairs of sensors at different depths to quantify fluxes (Figure E.3).

E.4 Methods

Diurnal temperature methods were used to estimates point fluxes at the four well field sites. At each of the four sites, high-capacity wells are located adjacent to a surface water body, the

White River for the Carmel and INAWC wells and Brandywine Creek for the Greenfield wells. Shallow piezometers were installed in the riverbed adjacent to each well field to measure water levels and temperature profiles. Where available, onsite observation wells were monitored to provide additional insight into interaction between the aquifer and surface water. All measuring points were instrumented as described below and deployed to measure and record data for over two months.

E.4.1 Piezometers

Each piezometer was generally constructed of a 0.6 ft long steel drivehead, a short screen, and 3-5 ft sections of casing consisting of 1.25 in diameter galvanized steel pipe. The assembly was driven into the riverbed with a pneumatic or gas-powered hammer until refusal. Because the piezometers at Carmel Well 30 consistently met refusal at approximately 1.5 ft below bed of the White River, these piezometers were not equipped with a screen. All of the other piezometers were constructed with a screen connected to the the drivehead, consisting of 1.25 in diameter, 0.5 ft long stainless-steel, wire-wrapped screen with 0.010 in slots. With the exception of the piezometers installed at Carmel Well 30, all piezometers were driven to depths ranging from 2.9-7.0 ft below the river bed (Table E.1). The piezometers were instrumented with temperature loggers at multiple depths within the piezometers to record the vertical temperature profile through time in each piezometer. Construction logs for the piezometers are included in Section E.10.

E.4.2 Existing Observation Wells

Existing observation wells were used in the study, where possible. Water levels were observed in the observation wells to gain insight into operation of the well field and interaction between the production wells and the river.

E.4.3 Instrumentation

Diurnal signals are required at a minimum of two depths from a vertical profile to estimate fluxes using heat tracing methods. Temperature loggers were placed at specific depths within each piezometer as summarized in Table E.1. For the case of infiltration, diurnal signals are commonly damped out at depths of less than 1.5 ft (Irvine et al., 2017). For the case of exfiltration, where the diurnal signals are transported downward only by conduction, the diurnal signal is usually limited to the approximately 0.66 ft below the riverbed (Briggs et al., 2012)

All piezometers were outfitted with a temperature logger at depths of 3 in and 6 in below the riverbed. An additional temperature logger was placed at 1 ft below the riverbed in the four piezometers installed at Well 30. A temperature and pressure logger was installed in the bottom of each piezometer with a screen. At each well field, a temperature and pressure logger was installed on the riverbed surface to record river temperature and stage.

Table E.1: Piezometer construction and instrumentation.

Well Field	Piezometer ID	Total Depth (ft below bed)	Screen Interval (ft below bed)	River	Instrumentation: 3 in below Bed	Instrumentation: 6 in below Bed	Instrumentation: 12 in below Bed	Instrumentation: Piezo Bottom
Carmel Well 30	P-1	1.5	–	–	T	T	T	–
	P-2	1.8	–	T,P	T	T	T	–
	P-3	1.5	–	–	T	T	T	–
	P-4	2.2	–	–	T	T	T	–
Carmel Well 27	P-5	4.4	3.3-3.8	–	T	T	–	T,P
	P-6	3.7	2.6-3.1	–	T	T	–	T,P
	P-7	4.4	3.3-3.8	T,P	T	T	–	T,P
	P-8	2.9	1.8-2.3	–	T	T	–	T,P
INAWC North Well Field	P-9	6.6	5.5-6.0	–	T	T	–	T,P
	P-10	4.7	3.6-4.1	T,P	T	T	–	T,P
	P-11	3.6	2.5-3.0	–	T	T	–	T,P
	P-12	3.7	2.6-3.1	–	T	T	–	T,P
Greenfield Riley Park Well Field	P-13	6.5	5.4-5.9	T,P	T	T	–	T,P
	P-14	5.1	4.0-4.5	–	T	T	–	T,P
	P-15	5.4	4.3-4.8	–	T	T	–	T,P
	P-16	7.0	5.9-6.4	–	T	T	–	T,P

Notes: in=inches. ft=feet. T=temperature logger. P=pressure logger.

The temperature loggers deployed on the surface of the riverbed were Hobo U12 Stainless Steel loggers. The temperature loggers installed in the piezometers were a mix of Onset Hobo U12 loggers and Onset TidBit Stowaway V2 loggers. Temperature and pressure loggers installed in existing monitoring wells were In-Situ Level Troll 400s. All pressure transducers installed in the piezometers were non-vented models. All piezometer pressure data was corrected with barometric data recorded by a designated pressure logger placed above ground at each site. All loggers were set to record data at five minute intervals, beginning with deployment in mid- to late November, 2019 and ending in January, 2020.

E.4.4 Analysis

We used the riverbed temperature measurements recorded in the piezometers to estimate fluxes at the four well field sites. Specifically, we analyzed the diurnal response of the the temperature loggers with a method developed by Keery et al. (2007), which uses an analytical extension to a numerical solution of the heat-flow equation combined with signal processing techniques. The analysis was facilitated by VFLUX, a MATLAB toolbox developed to facilitate the estimation of fluxes from time-series temperature data collected in the subsurface (Hatch et al., 2012; Irvine et al., 2015). Timeseries methods to estimate fluxes assume that, between two temperature sensors, fluid flow is vertical and one dimensional; the porous medium is homogeneous; the change in temperature of the sediment and fluid phases occurs simultaneously; there is no mean thermal gradient with depth; and that thermal properties are not temperature dependent (Irvine et al., 2017).

For the best results, VFLUX requires raw data sets that exhibit a strong periodic temperature signal for a long enough time period to filter the signals and discard the edge effects (Irvine et al., 2015). Typically, this means at least one week of continuous time-series data with a pronounced duirnal temperature signal. Based on the period of record, we chose a twelve-day stretch to analyze based on flow and the observed temperature in the White River. Figure E.4 shows the daily discharge in the White River at the USGS gage in Noblesville and in Brandywine Creek at the USGS gage in Greenfield. Figure E.4 also shows the temperature observed in the White River and Brandywine Creek at the four well field sites. Between December 15-26, flow in the White River and Brandywine Creek was low and stable and the observed temperature fluctuations at all four well field sites exhibited a diurnal signal.

The temperature time series for all piezometers were analyzed for the analysis period, December 15-26, 2019. Results from the beginning and end of the analysis period were discarded to account for edge effects; VFLUX results are reported for December 18-24. All physical parameters assumed in the VFLUX analysis, summarized in Table E.2, are typical values (Irvine et al., 2015).

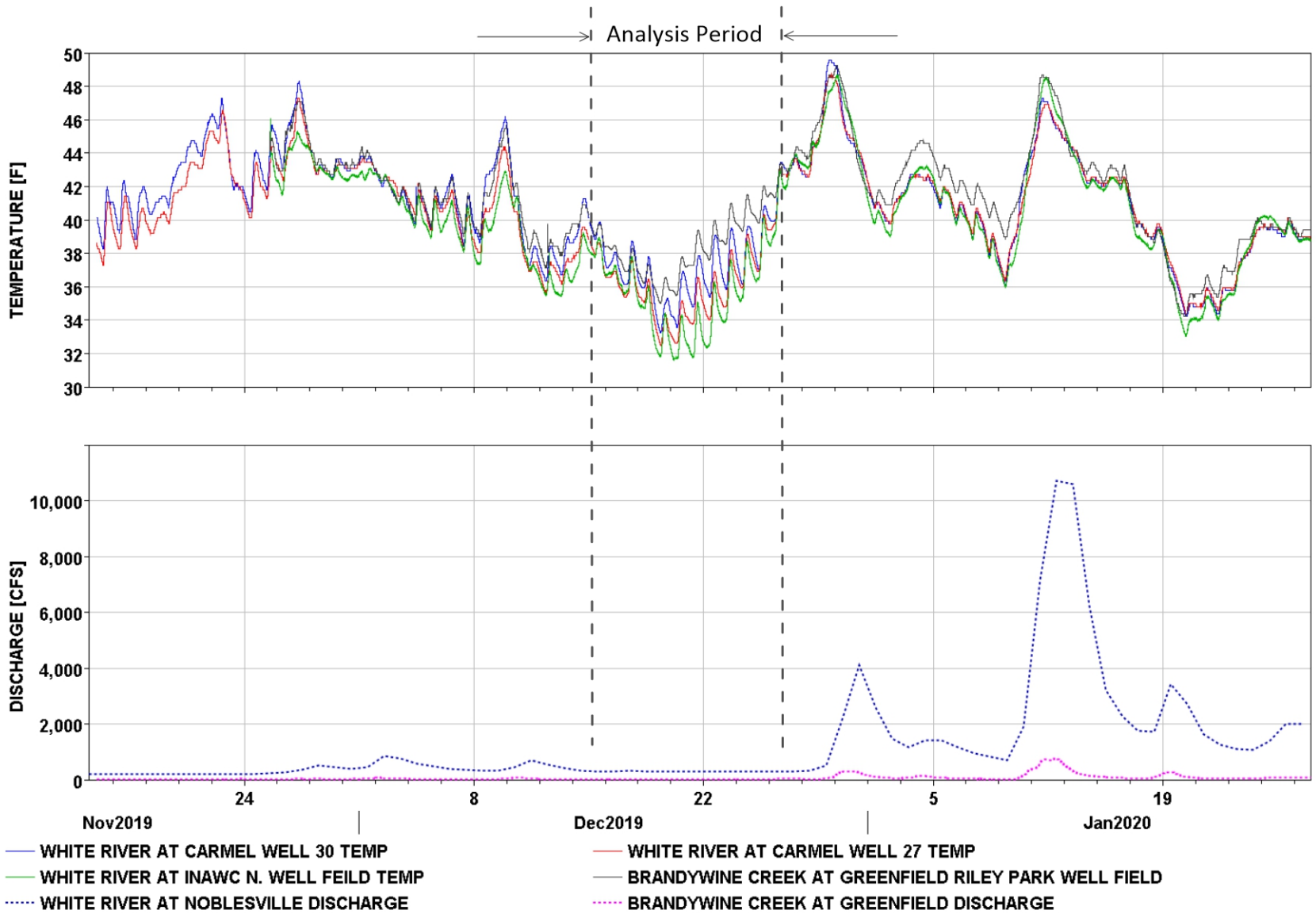


Figure E.4: Observed temperature *(top)* and discharge *(bottom)* and in the White River and Brandywine Creek during the data collection period. *The dashed line indicates the period that was analyzed.*

Table E.2: Summary of parameter values used in VFLUX analysis.

Parameter	Units	Value
n : total porosity of the sediment	–	0.25
beta : dispersivity	meters	0.001
c Kcal : thermal conductivity	cal/(s · cm · C)	0.0045
Cscal : vol. heat capacity of sediment	cal/(cm^3 · C)	0.5
Cwcal : vol, heat capacity of the water	cal/(cm^3 · C)	1.0

Notes: cal=calorie. cm=centimeters. C=degree Celsius.

E.5 Carmel Well 30

Well 30 is one of several Carmel production wells located between 96th Street and 106th Street on the west side of the White River (Figure E.5). This well is one of three Carmel wells, including Well 20 to the north and Well 23 to the south, that are located along Hazel Dell Parkway across the street from Martin Marietta's North Indianapolis Mine. At the mine, the unconsolidated sediments that compose the aquifer have been removed as well as approximately 150-200 ft of the bedrock surface (Figure E.6).Well 30 is located approximately 300 ft from the edge of the White River, and pumps from a productive area of the outwash aquifer, consistent with thick sections of sand, gravel, and cobbles (Figure E.6). Well 30 was installed in 2013, is 92 ft deep, and has a rated capacity of 2,500 gpm.

Four piezometers (P1-P4) were installed in the river 5-10 ft from the west bank, adjacent to Well 30 (Figure E.5). The piezometers at this site could only be driven to depths of 1.5-2.2 ft below the bed. This could be due to the presence a consistent layer of cobbles or fine sediment. Because of this constraint, the four piezometers at this site were not outfitted with a pressure/temperature logger at the bottom. Instead, a third temperature logger was placed at a depth of 1 ft below the bed (summarized in Table E.1).

Diurnal temperature signals recorded below the riverbed in piezometers at Well 30 were damped with depth (Figure E.7). The VFLUX results show consistency between the piezometers, with all four piezometers indicating infiltration at rate between approximately 0.2 and 0.4 ft/day (Figure E.8). Water levels recorded in existing monitoring wells at the site indicate that water levels in the aquifer are well below the bottom of the river. Figure E.9 shows water levels in the monitoring points in relation to the riverbed, rising and falling through time in response to Well 30 cycling and and off.

The disconnected water table at Well 30 appears to be a characteristic of the river reach between 106th street and 96th street and appears to be an impact of adjacent mining operations. The disconnect was noted by the City of Carmel's consultant prior to placing Well 20 into service at 106th Street (WHPA, 2005) and confirmed in 2007 when the City was considering adding a production well in the vicinity of Well 20 in 2007 (JHE, 2007).

The disconnected water table at this site is may be due to a combination of factors related

to mining. The presence of a fine-grain layer of sediment in the bottom of the river that restricts infiltration could be caused by or exacerbated by years of highly-silted wash water discharged into Blue Woods Creek (JHE, 2007), which flows into the White River adjacent to Well 20. The regional lowering of the water table could also be due to dewatering activities by Martin Marietta. The open pit limestone quarry near 96th Street and Hazel Dell Parkway has been excavated well below the overlying outwash formation. The pit and horizontal shafts are continuously dewatered as part of mining operations. The extent of mine dewatering has not been quantified.

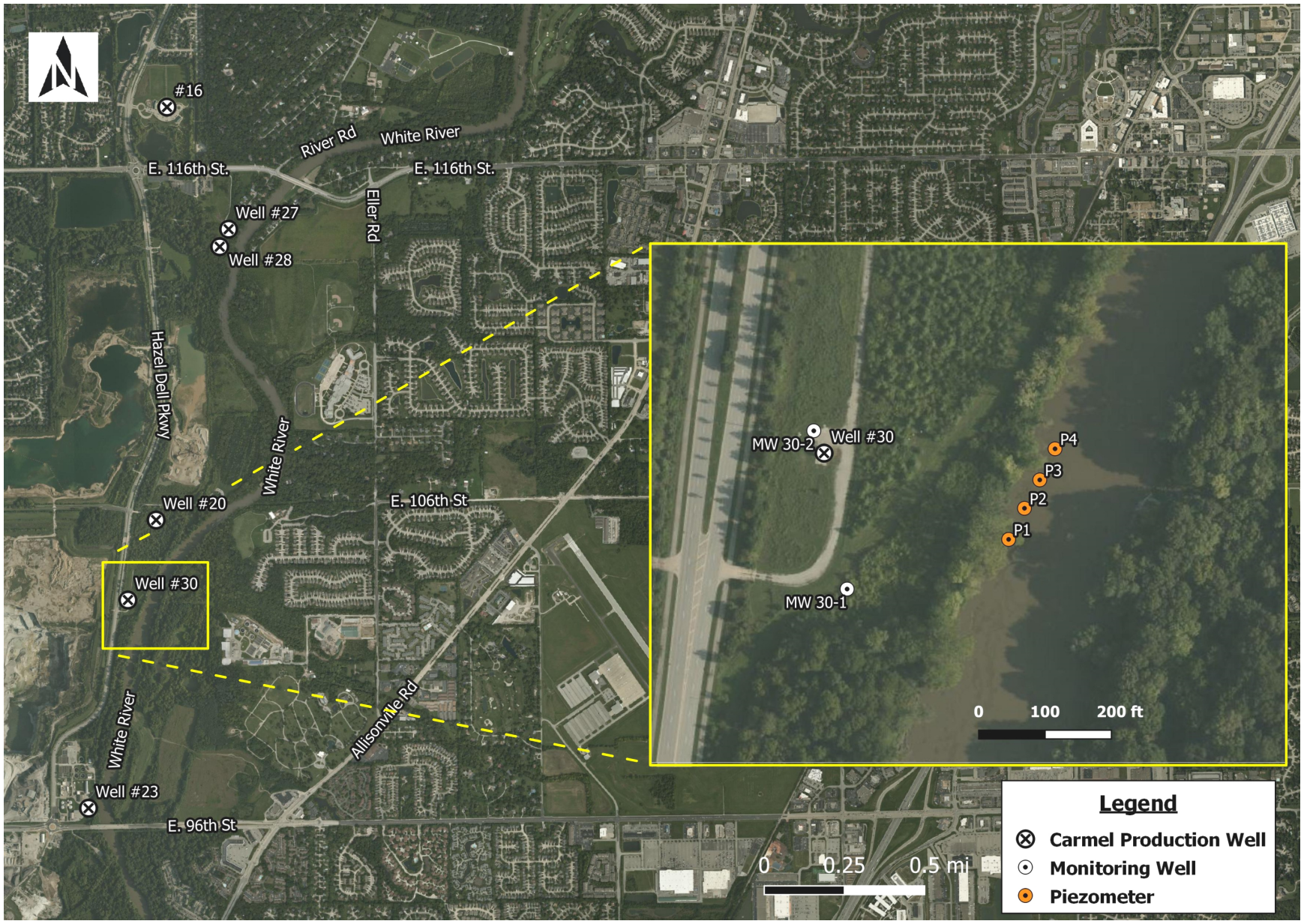


Figure E.5: Carmel Well 30 location and monitoring layout.

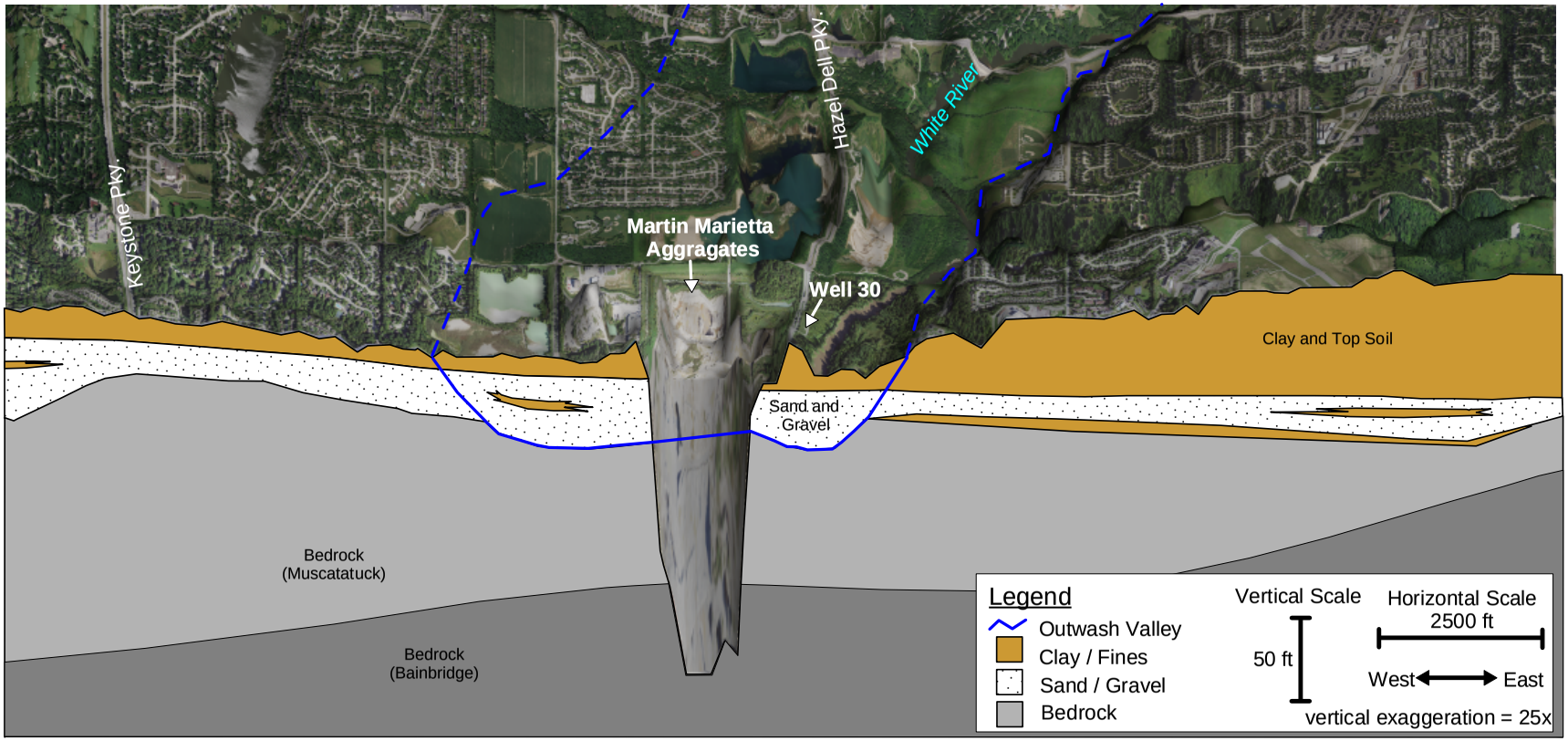


Figure E.6: Geologic cross section at Well 30.

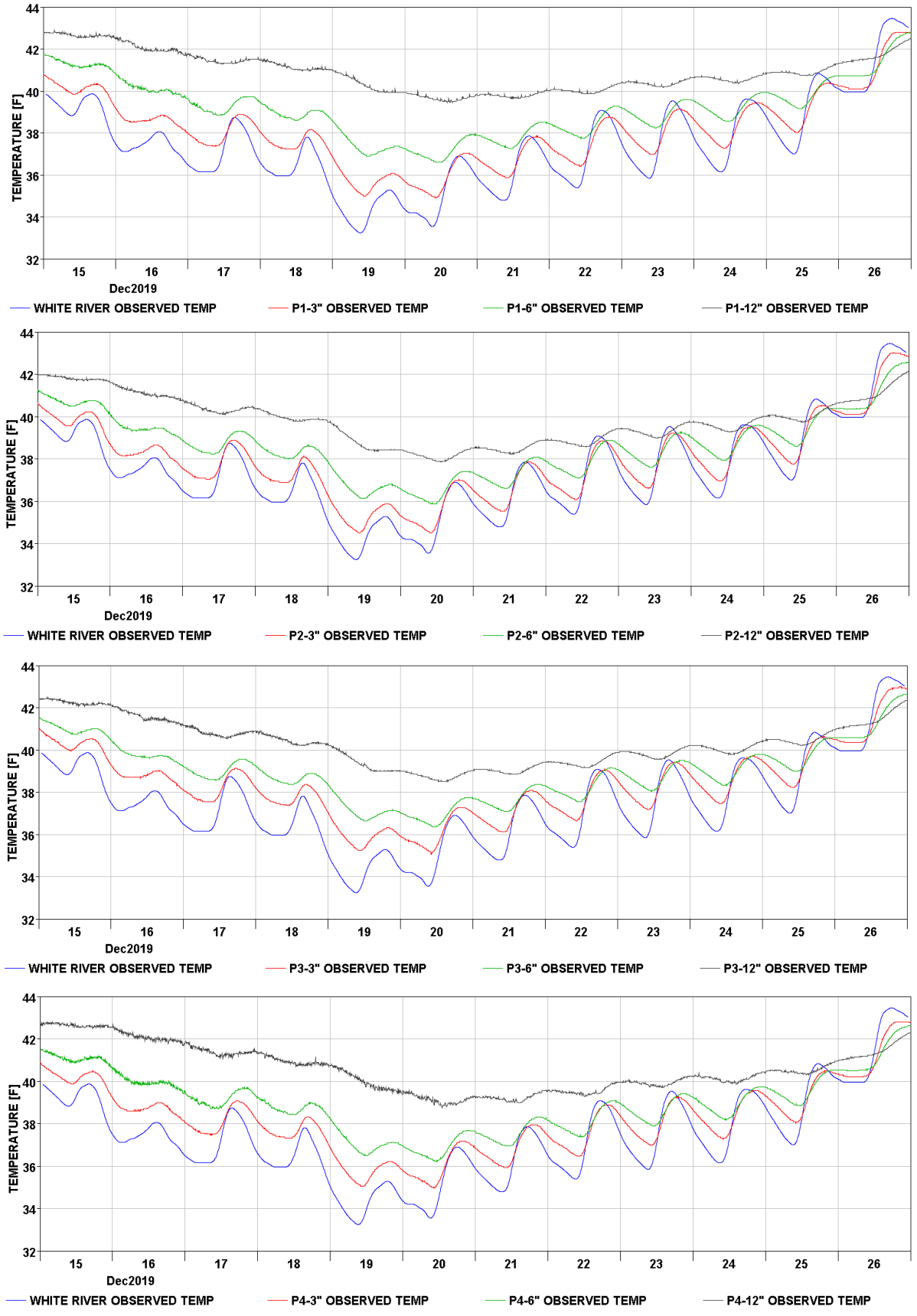


Figure E.7: Temperature observations in piezometers at Carmel Well 30, December 15-26, 2019.

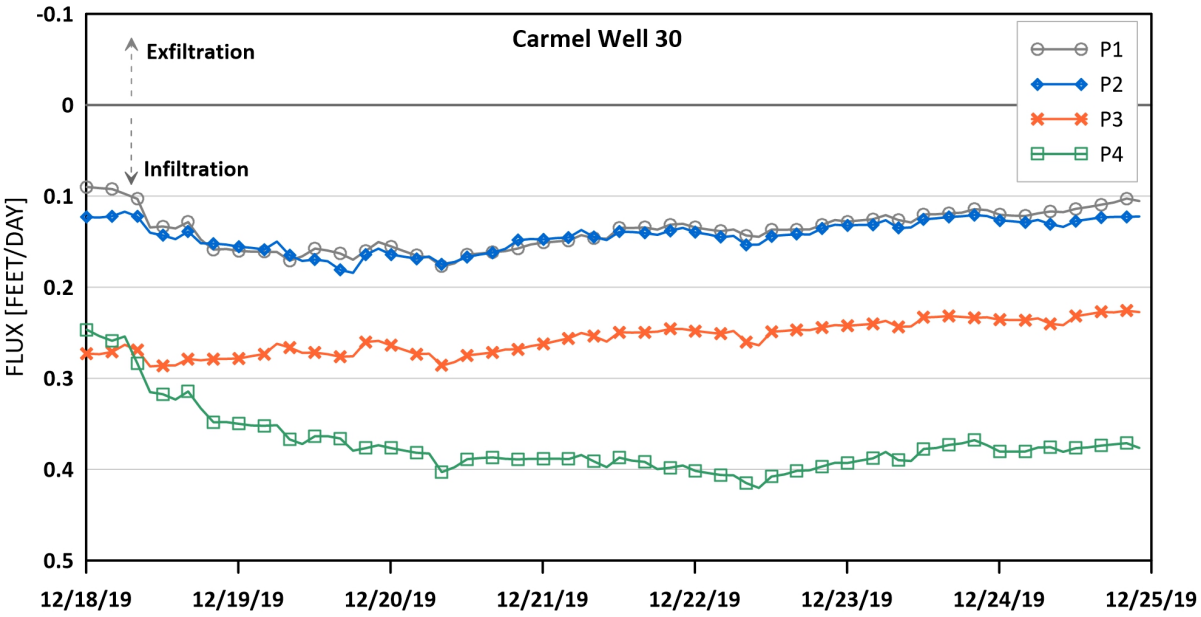


Figure E.8: Estimated flux from piezometers installed in the White River adjacent to Carmel Well 30.

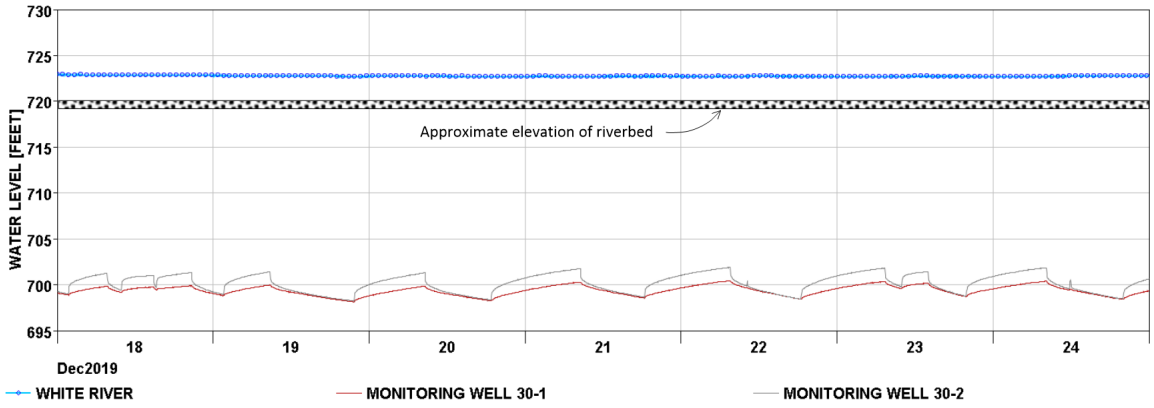


Figure E.9: Water levels recorded at Well 30, including the White River and existing monitoring wells 30-1 and 30-2.

E.6 Carmel Well 27

Carmel's North Beach Well Field is located on the west side of the White River, south of 116th Street (Figure E.10). The well field consists of two production wells, Well 27 and Well 28, which pump from a productive area of the outwash aquifer, consistent with thick sections of sand, gravel, and cobbles (Figure E.11). Test borings at the site show that the unconsolidated deposits are comprised mostly of coarse-grain deposits, with discontinuous clay stringers less than approximately 5 ft appearing in some of the logs (JHE, 2010). Well 27 is approximately 160 ft from the edge of the White River, was installed in 2010, is 78 ft deep, and has a rated capacity of 1,800 GPM.

Four piezometers (P5-P8) were installed in the riverbed adjacent to Well 27 (Figure E.10). The diurnal temperature signals recorded below the riverbed in piezometers were damped with depth (Figure E.7), but were distorted by pumping effects, particularly at P6 (Figure E.12). The signal processing techniques employed here do not perform well when the diurnal signals are weak or poorly formed.

The VFLUX results indicate that infiltration at this site is highest of the four sites. VFLUX was unable to derive fluxes for P6 due to distortions in the signal. However, the results show consistency between the three other piezometers, with infiltration at a rate between approximately 0.25 and 2.0 ft/day (Figure E.13).

Hydraulic measurements in the piezometers confirm downward hydraulic gradients. Figure E.14 show the water level in the piezometers and one existing monitoring in relation to river stage. During the analysis period, only Well 27 was operating. Water levels in the monitoring points rise and fall through time in response to Well 27 cycling and and off. All of the measuring points indicate a downward hydraulic gradient between the river and the shallow sediments, including P6. This indicates that infiltration at P6 is likely similar to the other three piezometers at this site.

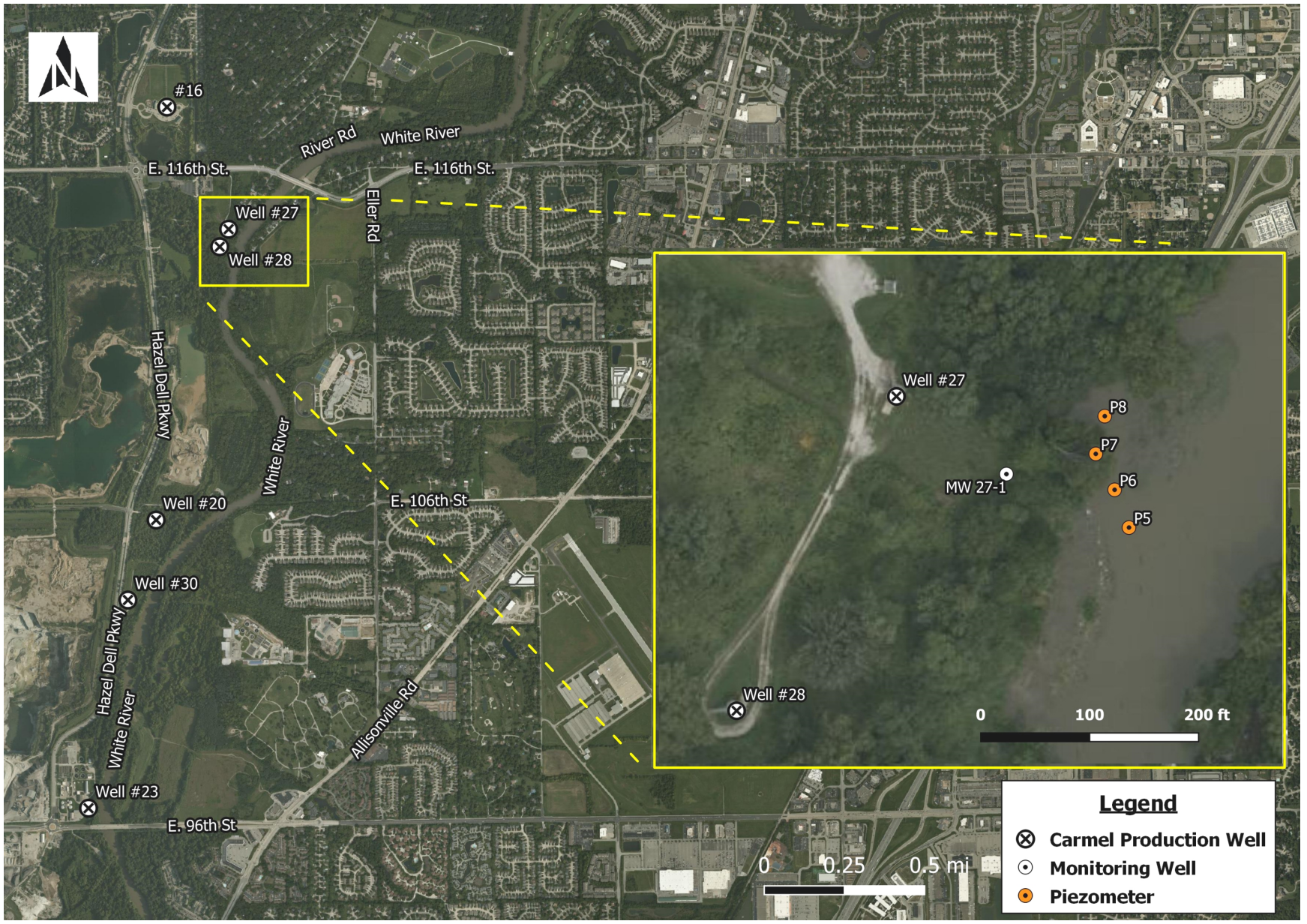


Figure E.10: Carmel Well 27 location and monitoring layout.

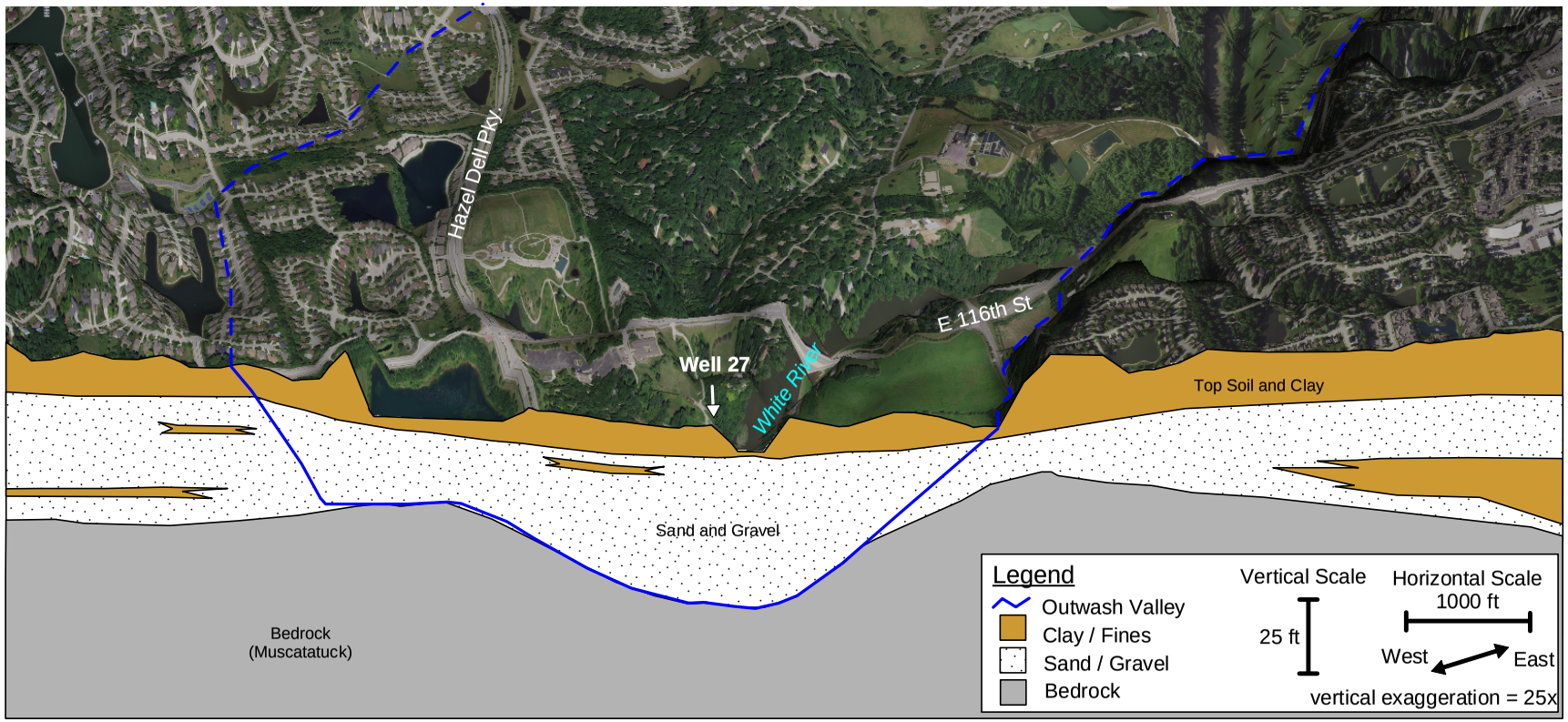


Figure E.11: Geologic cross section at Well 27.

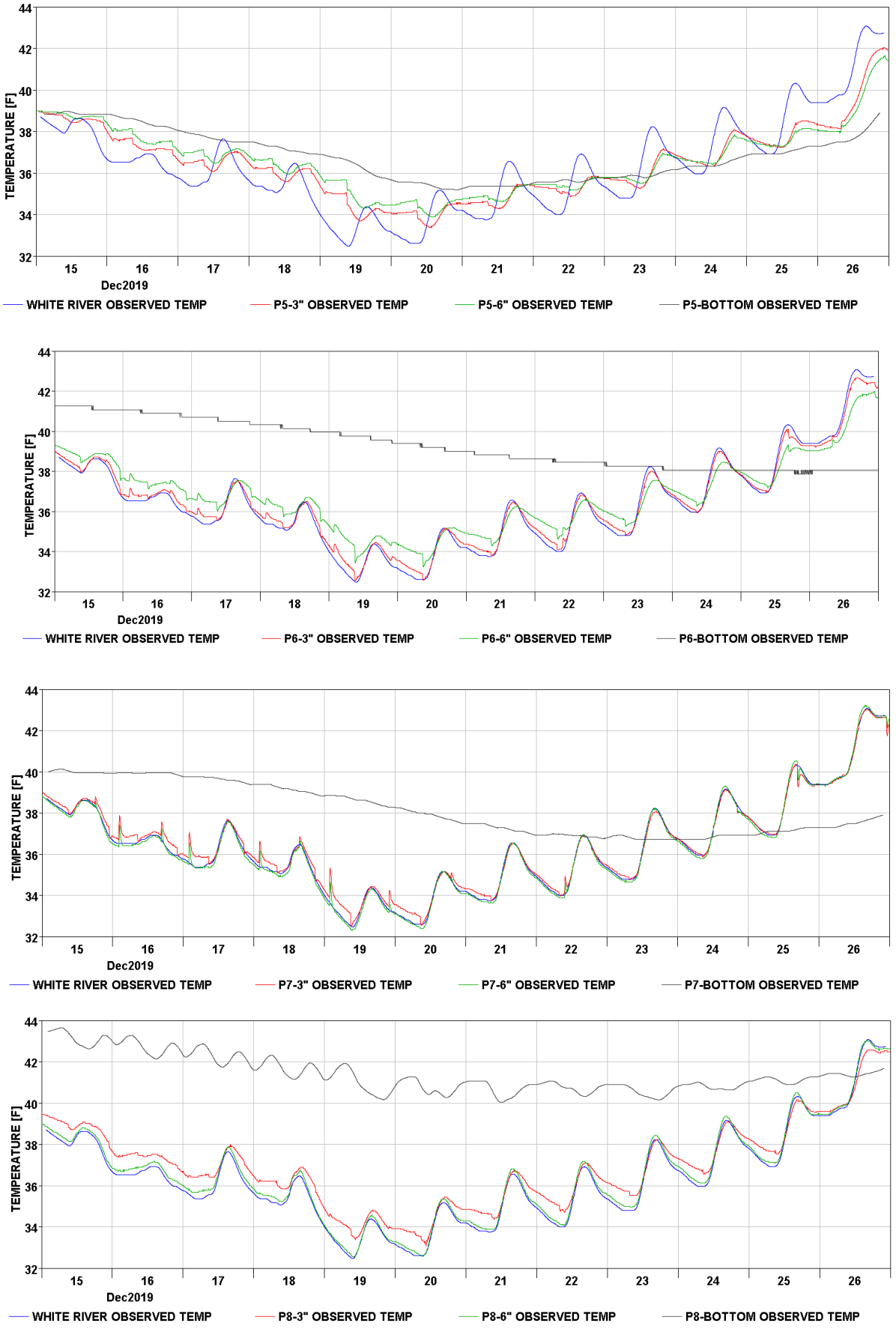


Figure E.12: Temperature observations in piezometers at Carmel Well 27, December 15-26, 2019.

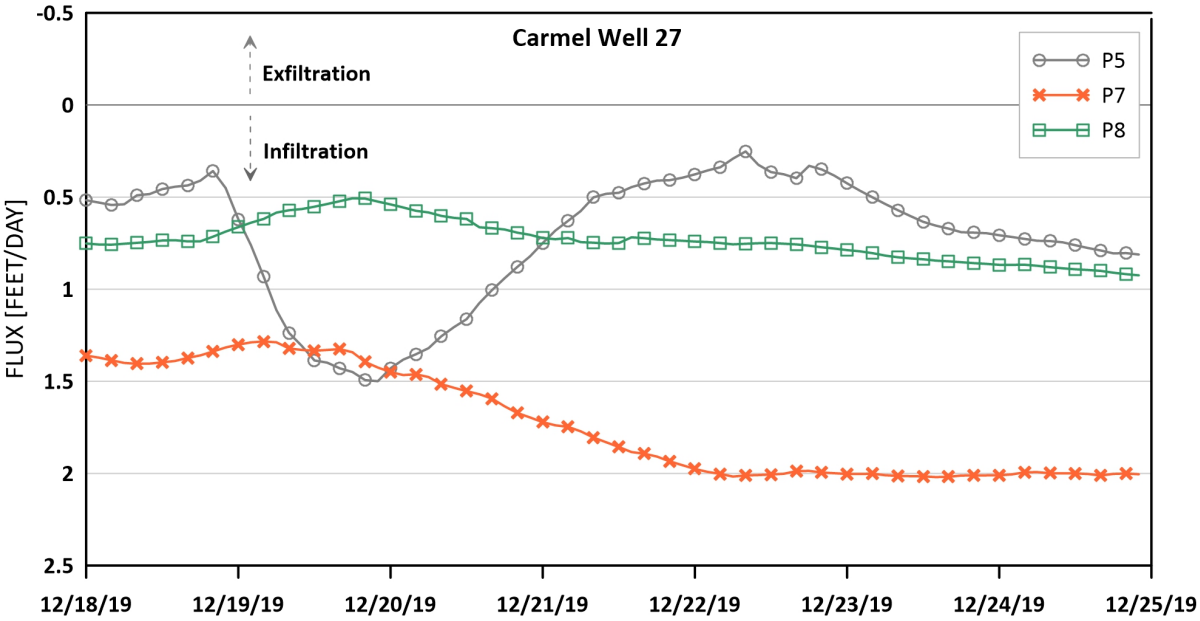


Figure E.13: Estimated flux from piezometers installed in the White River adjacent to Carmel Well 27.

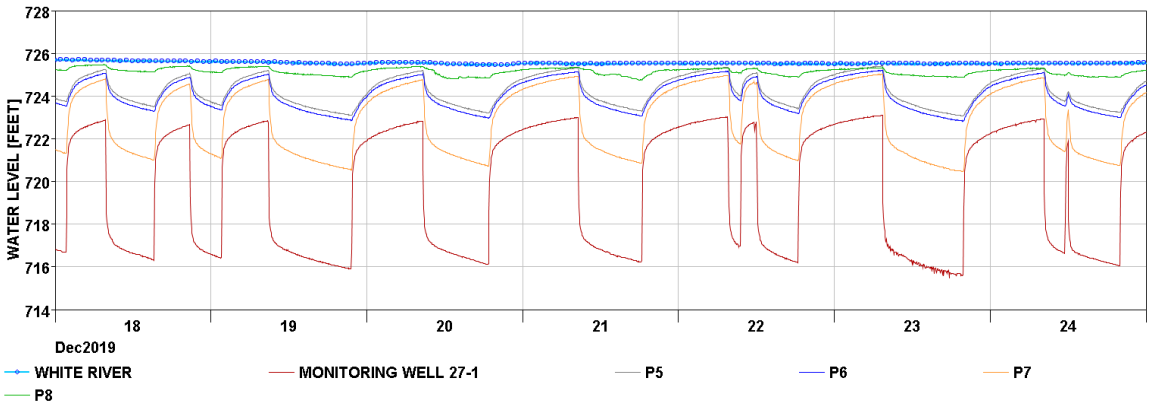


Figure E.14: Water levels recorded at Well 27 site, including the White River, piezometers, and existing monitoring well MW 27-1.

E.7 Indiana American North Well Field

Indiana American's North Well Field is located upstream of Noblesville on the north side of the White River (Figure E.15). The well field consists of five production wells located along a 1,500 ft reach of the White River. Four piezometers (P9-P12) were installed in the riverbed adjacent to Well 1 (P9 and P10) and Well 2 (P11 and P12). The rated capacity of Well 1 and Well 2 is approximately 500 GPM each. Well 1 and Well 2 are both located approximately 100 ft from the edge of the White River at normal flows.

The wells pump from an area where the outwash aquifer consists of permeable sand and gravel deposits overlain by fine materials consisting silt and clay (Figure E.16) (Eagon, 1995). The fine-layered material separating the river and the aquifer zone pumped by the production wells is variable, ranging from thin or absent at the upstream and downstream ends of the well field to an approximate high of 40 ft thick near Well 1 and Well 2 . Eagon (1996) noted these areas as "windows" through the confining layer.

Diurnal temperature signals recorded below the riverbed in piezometers at Well 1 and Well 2 were damped with depth (Figure E.15). The VFLUX results show consistency between the piezometers, with all four piezometers indicating infiltration at rates between approximately 0.5 and 1.1 ft/day (Figure E.18). This is consistent with hydraulic measurements in the piezometers, which indicate downward hydraulic gradients in the shallow river bed sediment (Figure E.19A).

It appears that the confining layer between the riverbed and the production wells inhibits infiltration from the river, but the gradients produced by pumping induces some recharge through leakage of the confining layer and/or induced recharge at discrete "windows" in the confining layer.

The hydraulic gradient in the shallow river bed is not directly affected by pumping. In Figure E.19AB, the water level in the MW 94-1 is rising and falling through time in response to the production wells cycling on and off with no effect in the piezometers. Water levels recorded in an existing monitoring well MW 94-I at the site indicate that water levels in the lower portion of the aquifer are below the bottom of the riverbed, but above the bottom of the confining layer. This is consistent with observations during the original aquifer testing at the well field, where Eagon (1996) noted that water levels in the deeper zone were not affected by river fluctuations and that the repose in the deep zone was indicative of a leaky artesian aquifer model, with leakage coefficients varying between the monitoring points from 0.03 ft/d to 40 ft/day.



Figure E.15: INAWC North Well Field location and monitoring layout.

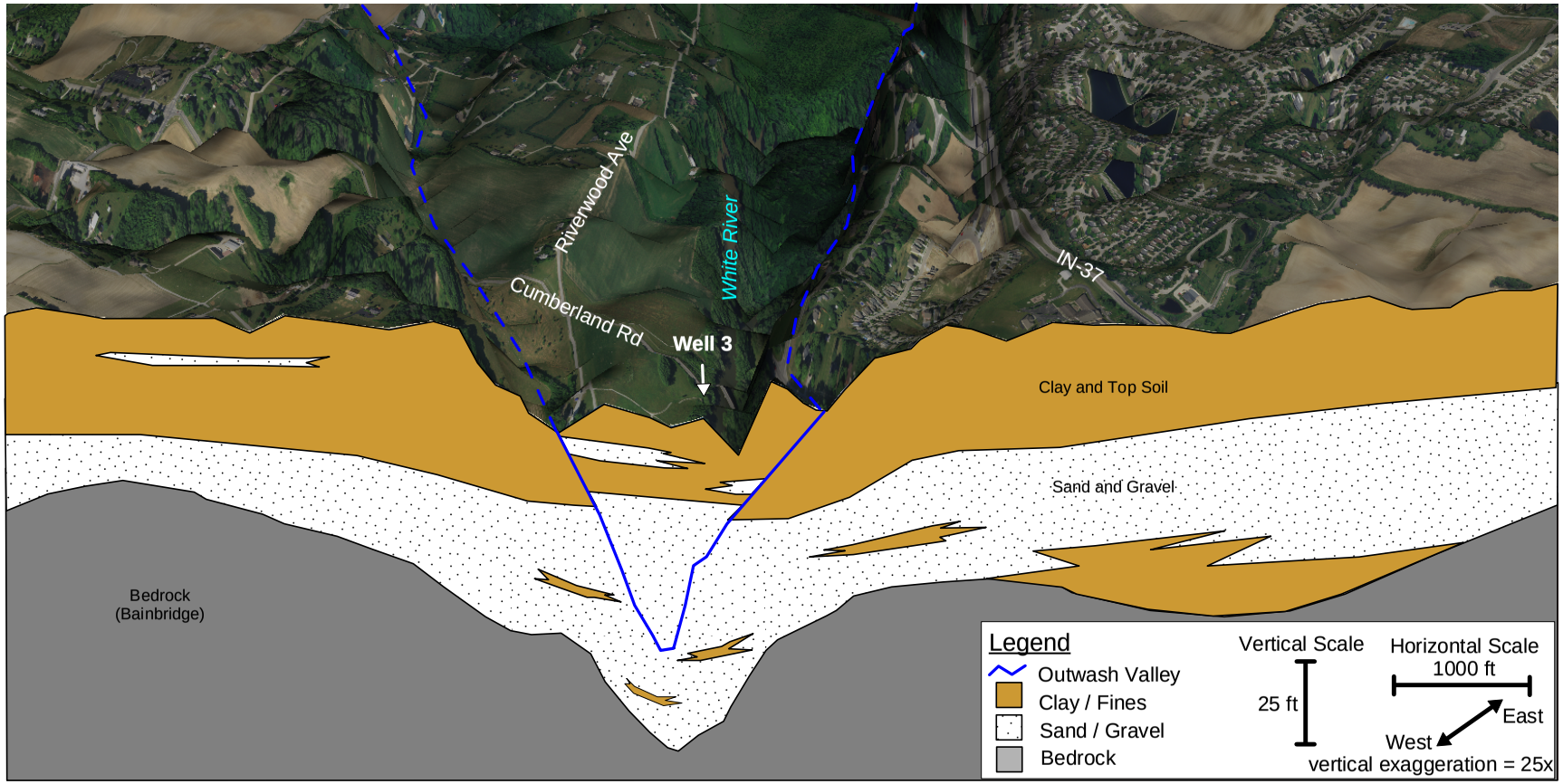


Figure E.16: Geologic cross section at Well 27

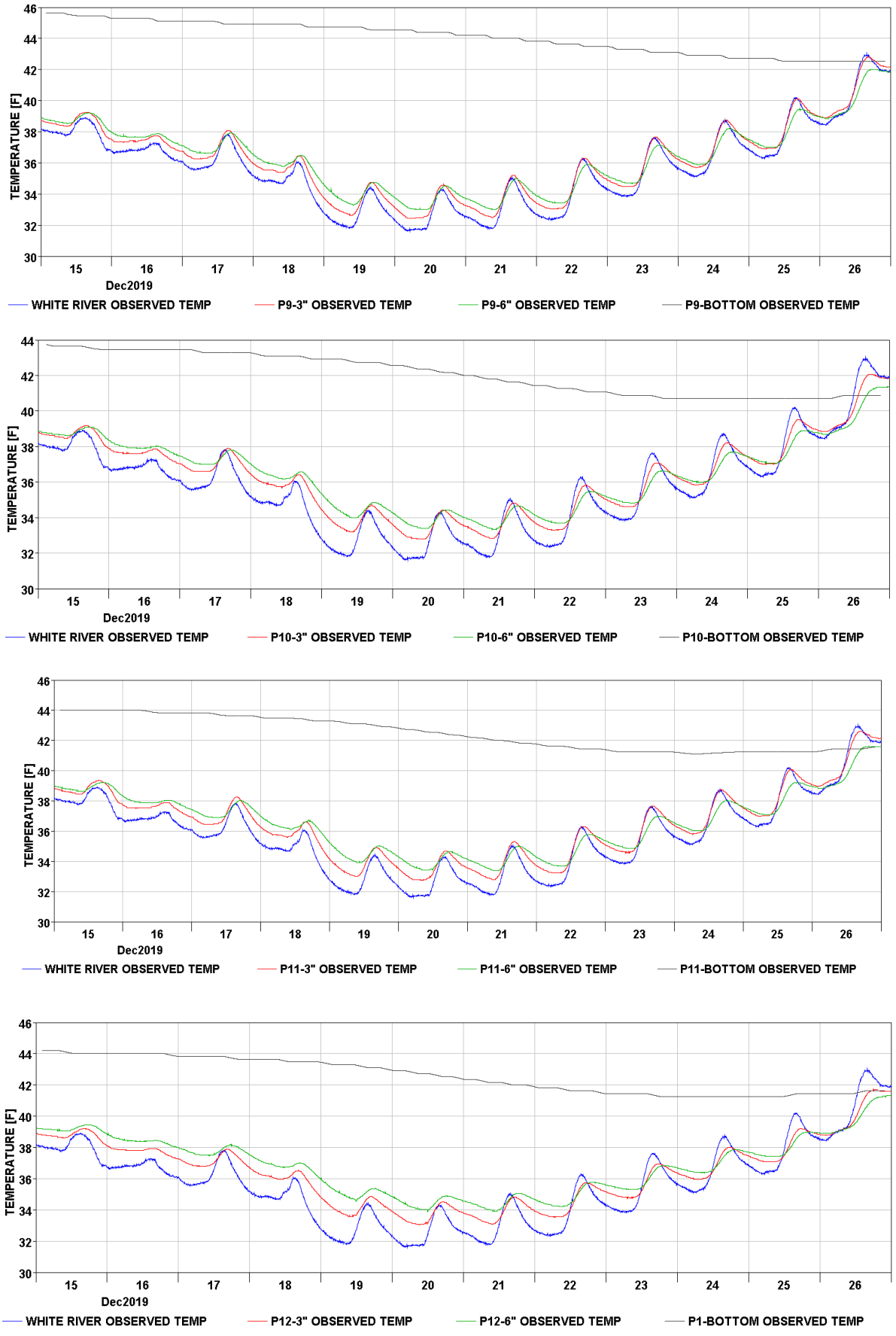


Figure E.17: Temperature observations in piezometers at INAWC North Well Field, December 15-26, 2019.

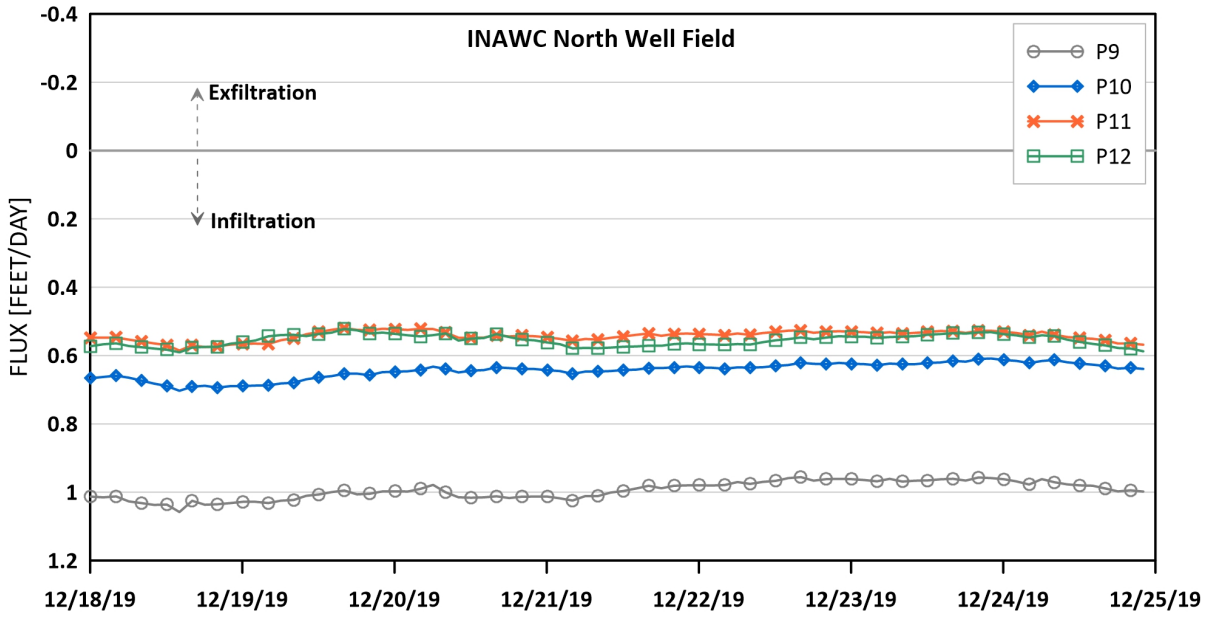


Figure E.18: Estimated flux from piezometers installed in the White River adjacent to Indiana American's North Well Field.

E.8 Greenfield Riley Park Well Field

Greenfield's Riley Park Well Field is located along Brandywine Creek, north of State Road 40 (Figure E.20). Well 2 is the closest well to the creek at approximately 160 ft from the bank of Brandywine Creek. Four piezometers (P13-P16) were installed in the riverbed adjacent to Well 1. The production wells at the well field pump from a section of coarse outwash deposited along the present course of Brandywine Creek (Figure E.16). The wells are approximately 120 ft deep, with rated capacities of 1,000 GPM. An intervening clay layer that appears to be continuous lies between the riverbed and a lower permeable zone that the production wells pump from.

Diurnal temperature signals recorded below the riverbed in piezometers were generally more damped with depth and noisier than the other three sites (Figure E.22). The noise could be due to an outfall located near P-16, which was periodically flowing when we were onsite. The VFLUX results between the piezometers were less consistent than the other three sites (Figure E.23).

The range of results at this site suggest the creek is connected to a shallow, discontinuous permeable zone and is disconnected from the deep permeable zone pumped by the wells. One the piezometers indicated exfiltration for the entire analysis period, one piezometer indicated infiltration, and two piezometers switched between infiltration and exfiltration. The hydraulic measurements suggest a setting where the gradients are very small and switch between positive and negative depending on the stage in the creek and the water level of the shallow sediment. Hydraulic measurements in the piezometers indicate small downward hydraulic gradients that are a sometimes positive (Figure E.24). The water levels respond to pumping with very small

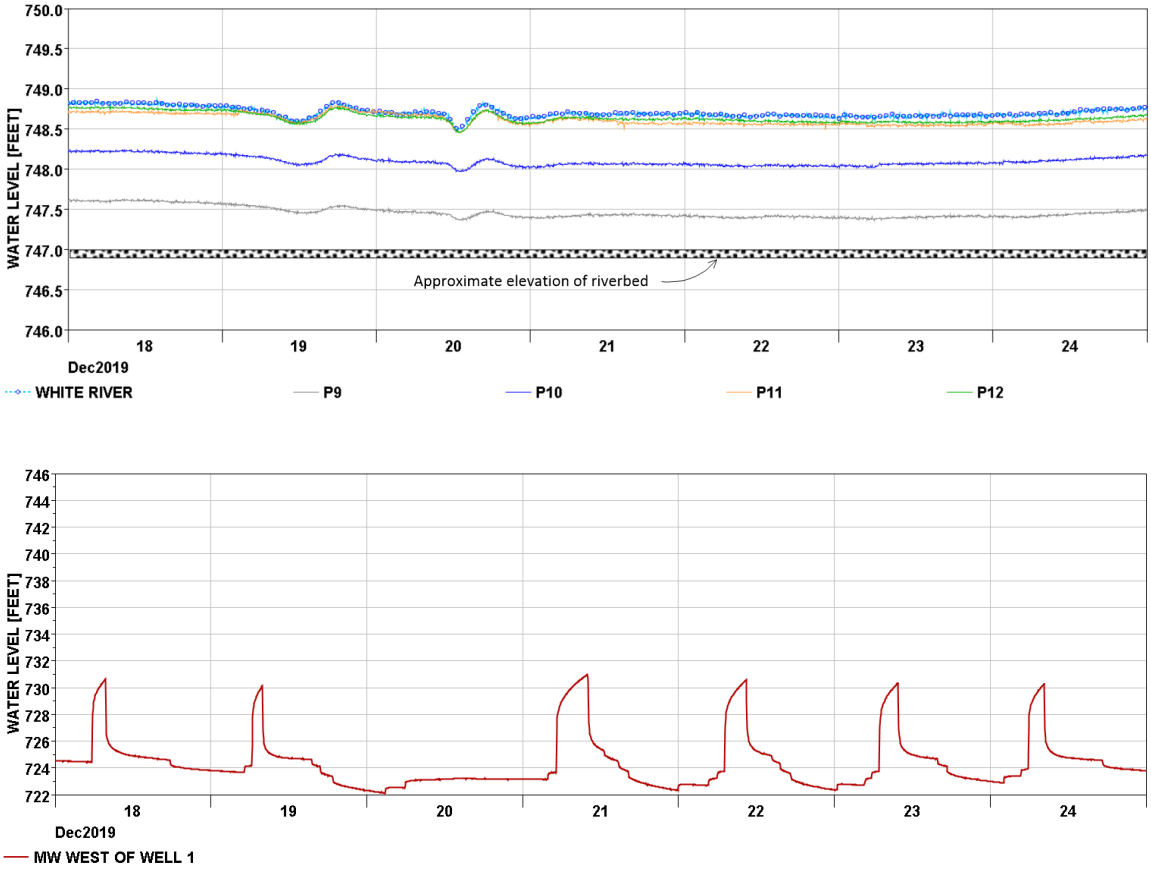


Figure E.19: Water levels recorded at INAWC North Well Field, including the White River and piezometers (*top*), and existing monitoring well MW 94-1 (*bottom*).

fluctuations. This suggest that the lower permeable unit pumped by the production wells is isolated from the creek.

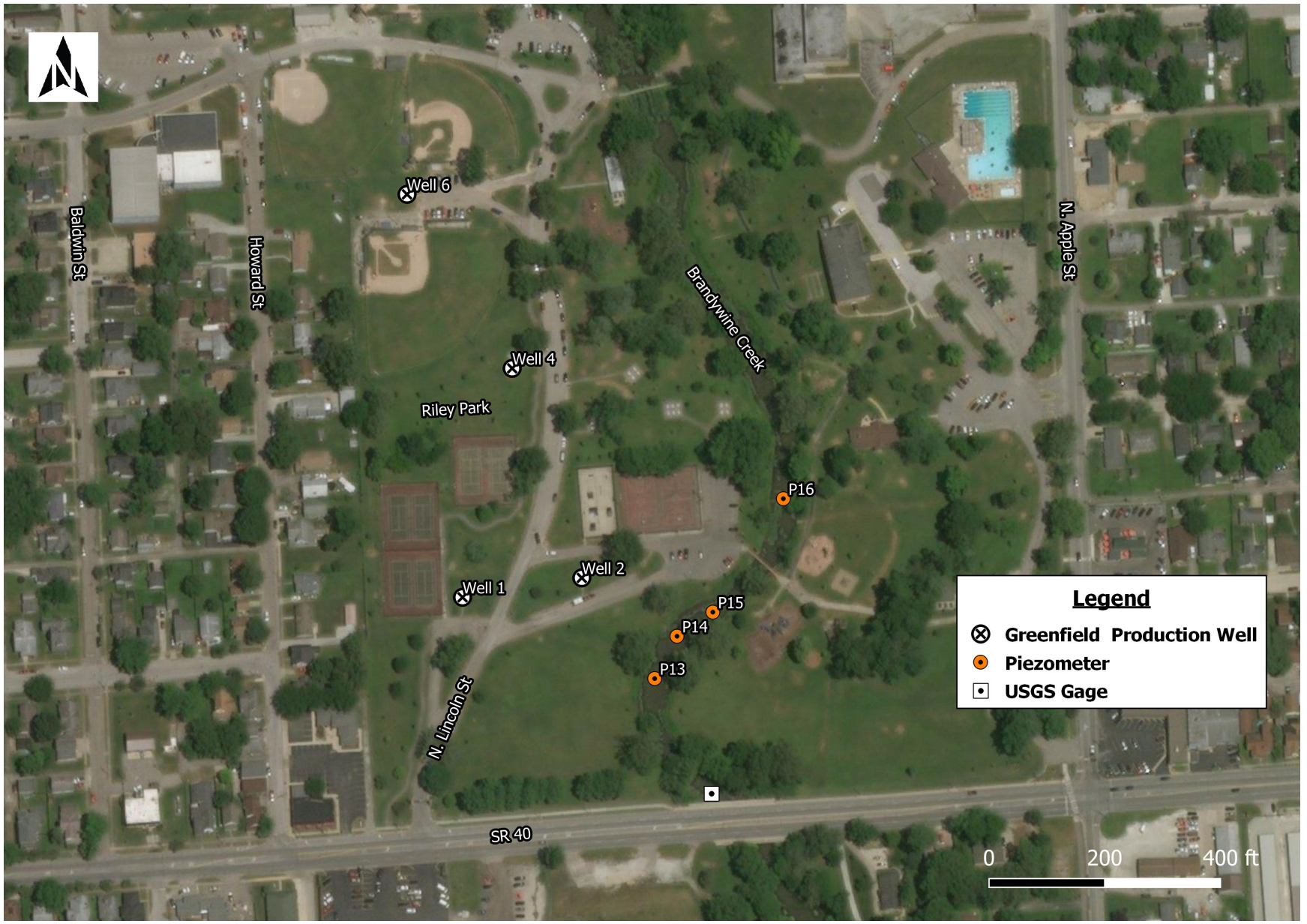


Figure E.20: Greenfield Riley Park Well Field location and monitoring layout

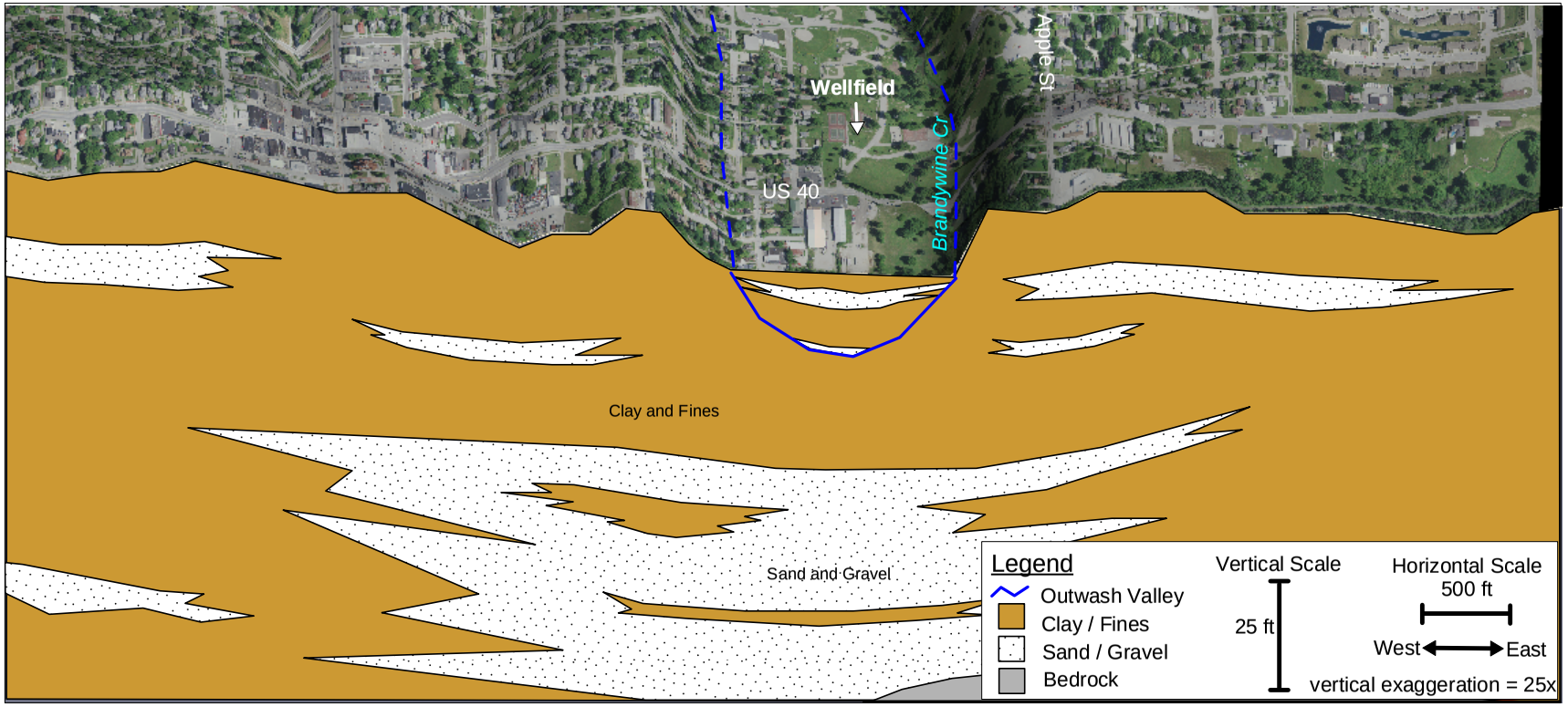


Figure E.21: Geologic cross section at Greenfield's Riley Park Well Field.

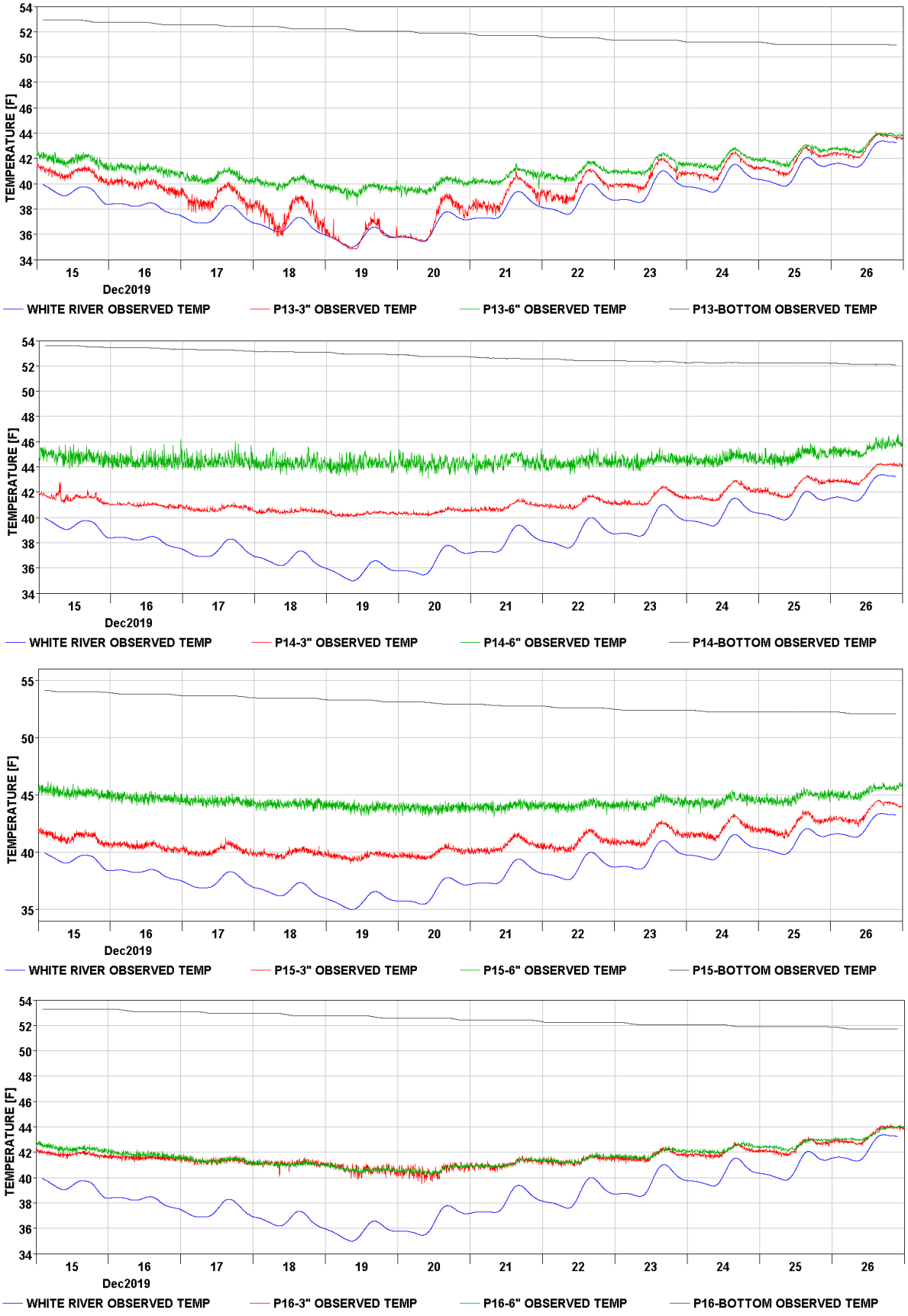


Figure E.22: Temperature observations in piezometers at Greenfield's Riley Park Well Field, December 15-26, 2019.

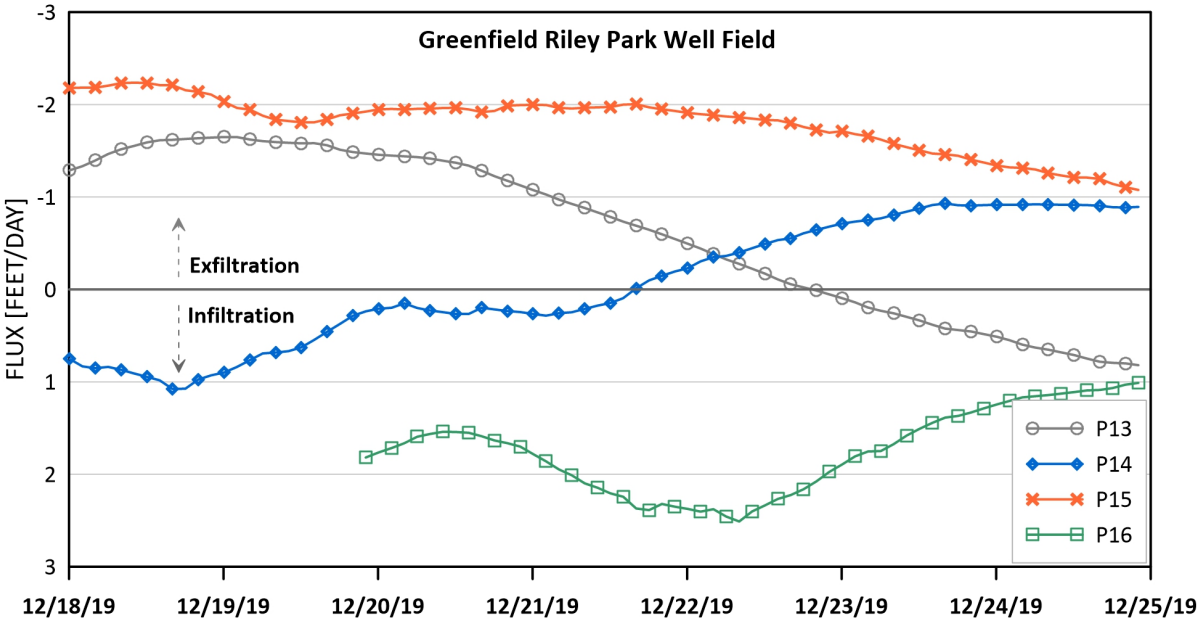


Figure E.23: Estimated flux from piezometers installed in the White River adjacent to Greenfield's Riley Park Well Field.

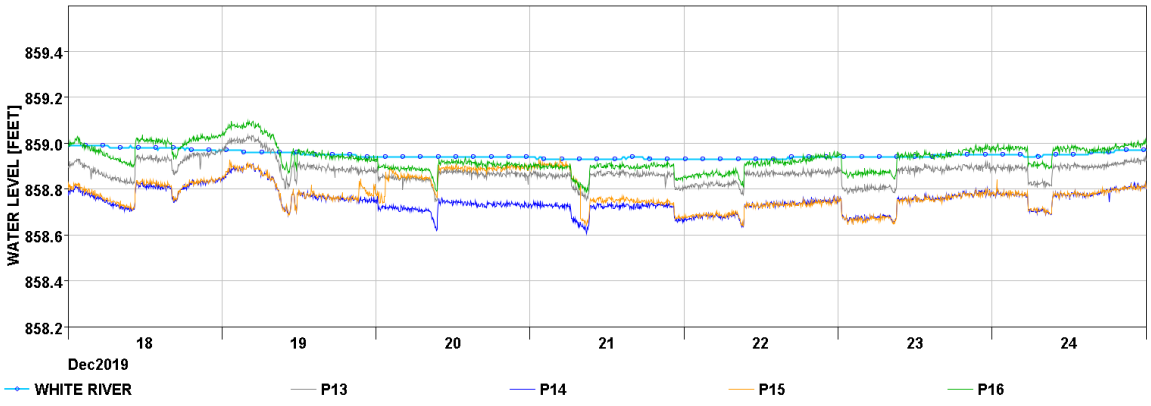


Figure E.24: Water levels recorded at Riley Park Well Field, including Brandywine Creek and piezometers.

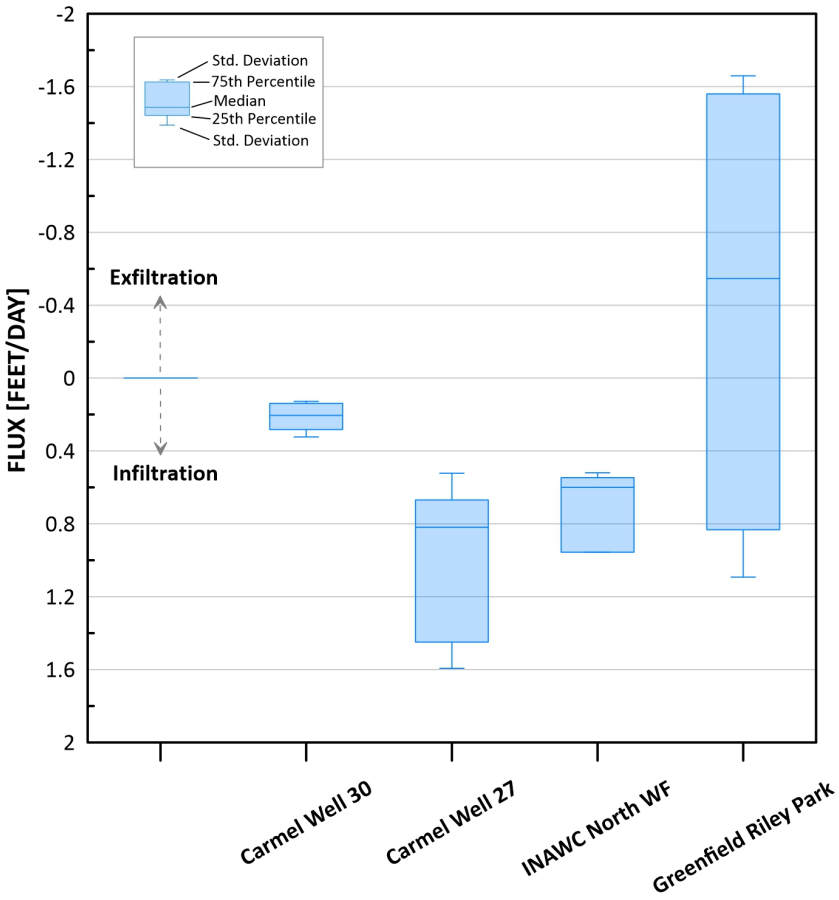


Figure E.25: Distribution of fluxes at each well field site.

E.9 Comparison and Discussion

The distribution of predicted fluxes are summarized by well field in Figure E.25. The highest infiltration rates are predicted at Carmel Well 27, followed by the INAWC North Well Field. The largest range of results were predicted at Greenfield Riley Park and the smallest range was predicted at Carmel Well 30. Note that the predicted fluxes were derived from a limited number of point measurements, and may not fully characterize the heterogeneous conditions at some sites. Of the parameters assumed in the VFLUX analysis, the predicted flux is most sensitive to total porosity, the volume of the pore spaces divided by the total volume. Sites where porosity is lower than assumed will have a lower flux rate and vice versa. Also note that fluxes are temperature dependent. Fluxes at the streambed are proportional to the vertical hydraulic conductivity of the streambed sediments. The vertical hydraulic conductivity is proportional to the water density and inversely proportional to the viscosity, both of which are temperature dependent. Assuming a maximum surface water temperature of at least 45^oF warmer than observed during the analysis period, the predicted absolute fluxes would be approximately twice the values predicted here.

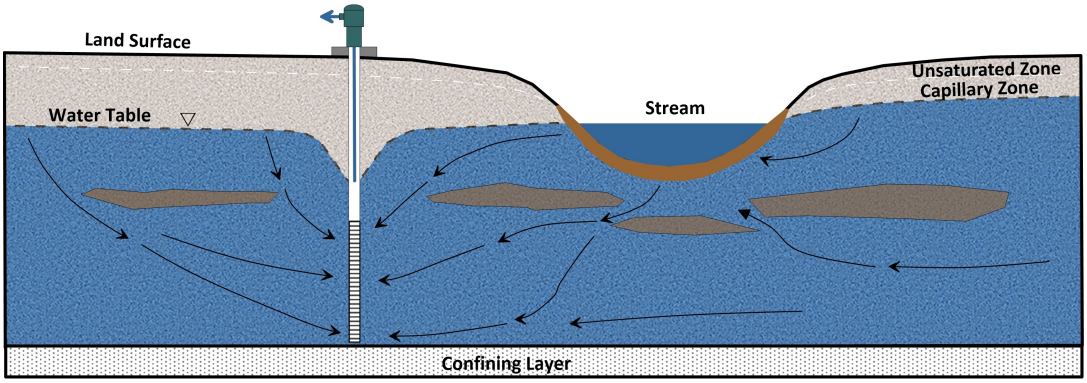


Figure E.26: Schematic showing production well pumping adjacent to a connected stream with discontinuous intervening clay layer.

The manifestation and rate of induced recharge depends on several site-specific factors, including the pumping rate of the well, the distance from the river, the location of the water table relative to the bottom of the river, and aquifer properties, including the hydraulic connection between the river and the aquifer. It is common in the Study Area for fine-grained sediments in the riverbed or layered in the aquifer between the riverbed and the well screen to limit or prohibit the possibility of induced infiltration. At Carmel Well 27, where the intervening clay is thin and discontinuous, resulting infiltration is the highest of the four sites (Figure E.26). At INAWC North Well Field and Greenfield Riley Park, intervening clay layers inhibit exchange with the deeper permeable units used for public supply (Figure E.27).

Fluxes at Carmel Well 30 are constrained due to the disconnected water table. When a stream is disconnected, infiltration can still occur, but the rate is limited as water percolates through the capillary zone (Figure E.28). Once disconnection occurs at a certain point in the stream, the flux will not be affected by further lowering of the water table or an increase in river stage. Not all streams can become disconnected. Factors that lead to disconnection include a clogging layer with a significantly lower hydraulic conductivity than the underlying aquifer, or a low water table due to pumping or to naturally dry conditions such as in arid climates. At Well 30, disconnection may be due to over pumping related to public water supply and mine dewatering, and compounded by a clogging layer in the White River, possibly due to long-term deposition of fine material resulting from mining wash discharge.

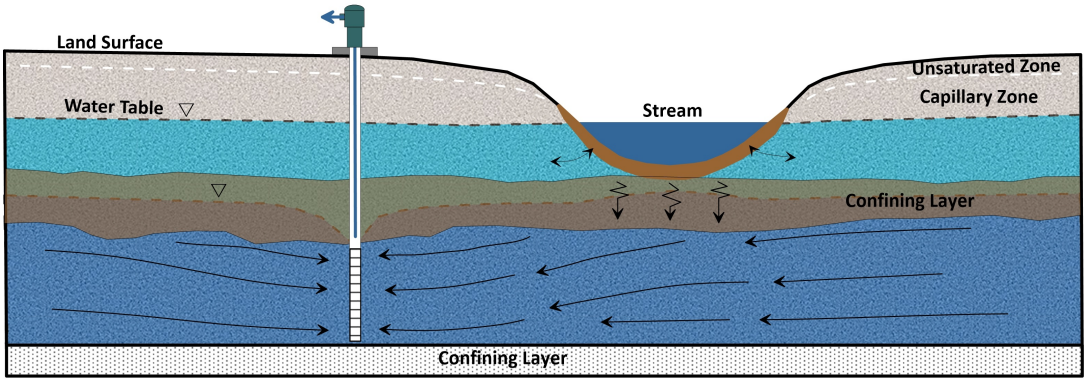


Figure E.27: Schematic showing production well pumping adjacent to a connected stream with continuous intervening clay layer.

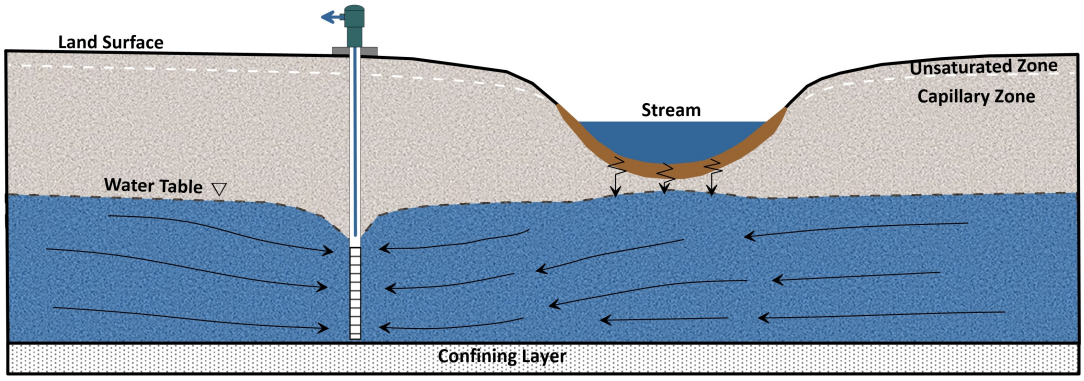


Figure E.28: Schematic showing production well pumping adjacent to a stream where the water table is disconnected.

E.10 Piezometer Construction Logs

Logs showing construction and instrumentation characteristics for the piezometers are presented below for Carmel Well 27 (Figure E.29), Carmel Well 30 (Figure E.30), INAWC North Well Field (Figure E.31), and Greenfield Riley Park (Figure E.32).

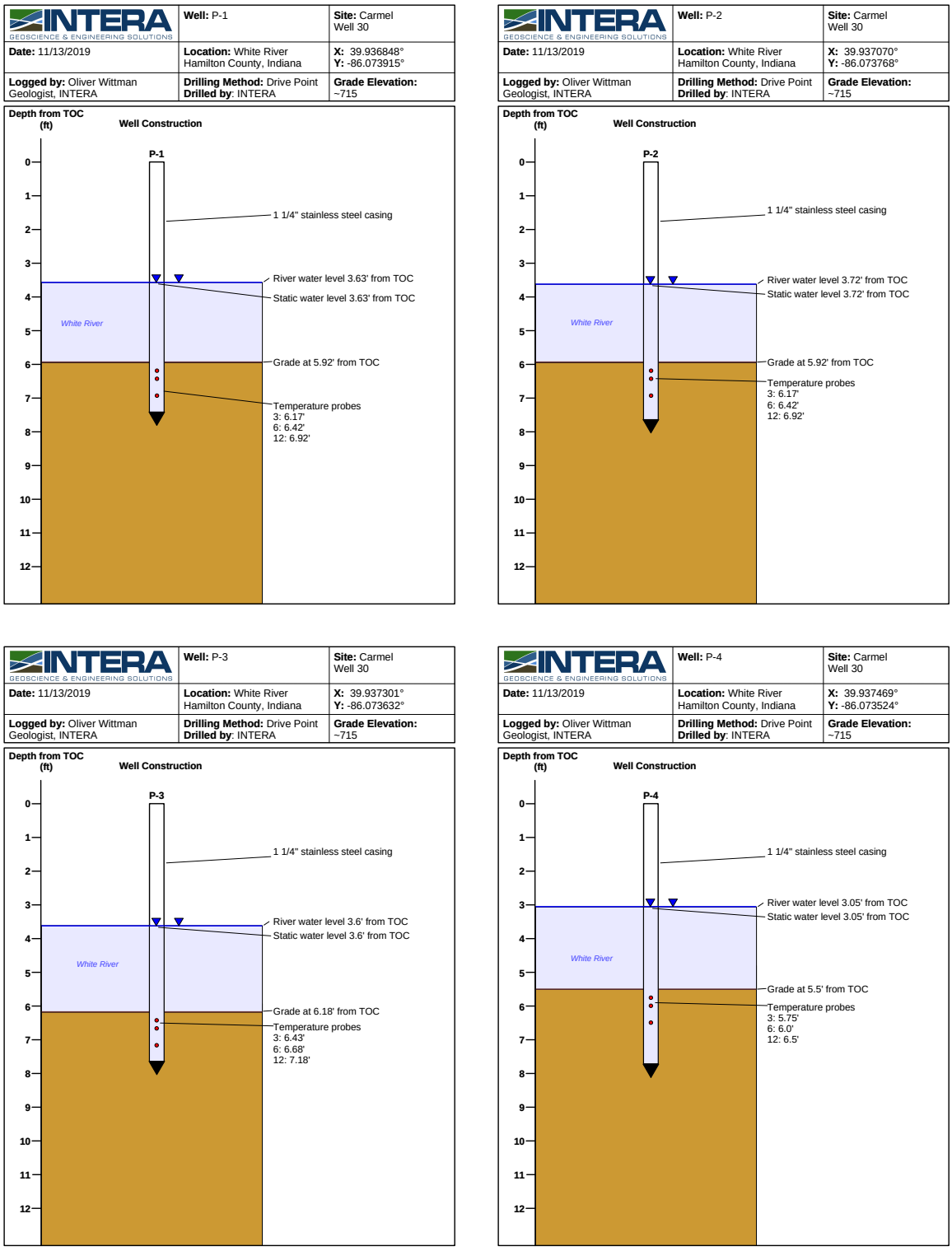


Figure E.29: Construction and instrumentation logs for piezoemeters P-1 (*top left*), P-2 (*top right*), P-3 (*bottom left*), and P-4 (*bottom right*) installed at Carmel Well 30.

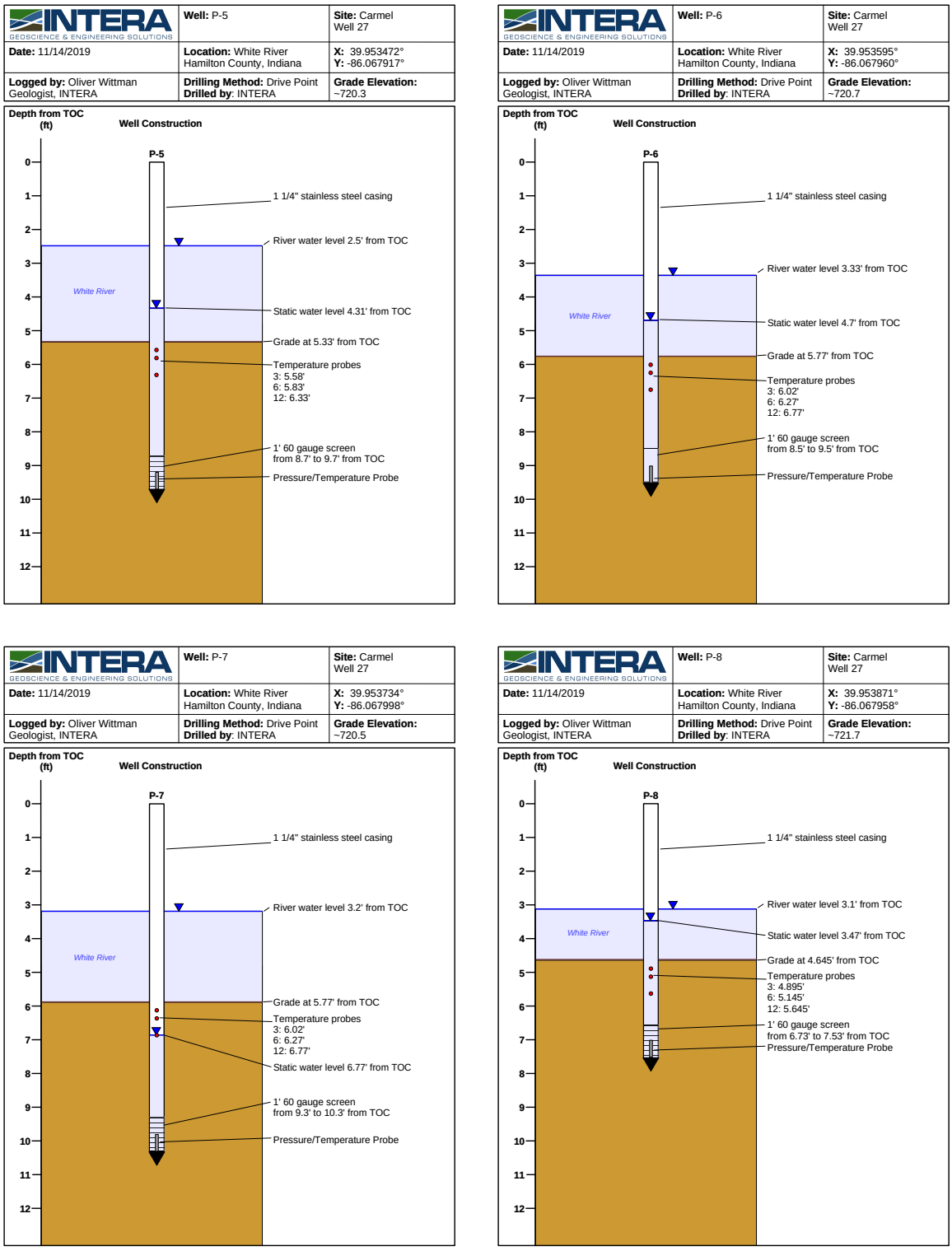


Figure E.30: Construction and instrumentation logs for piezoemeters P-5 (*top left*), P-6 (*top right*), P-7 (*bottom left*), and P-8 (*bottom right*) installed at Carmel Well 27.

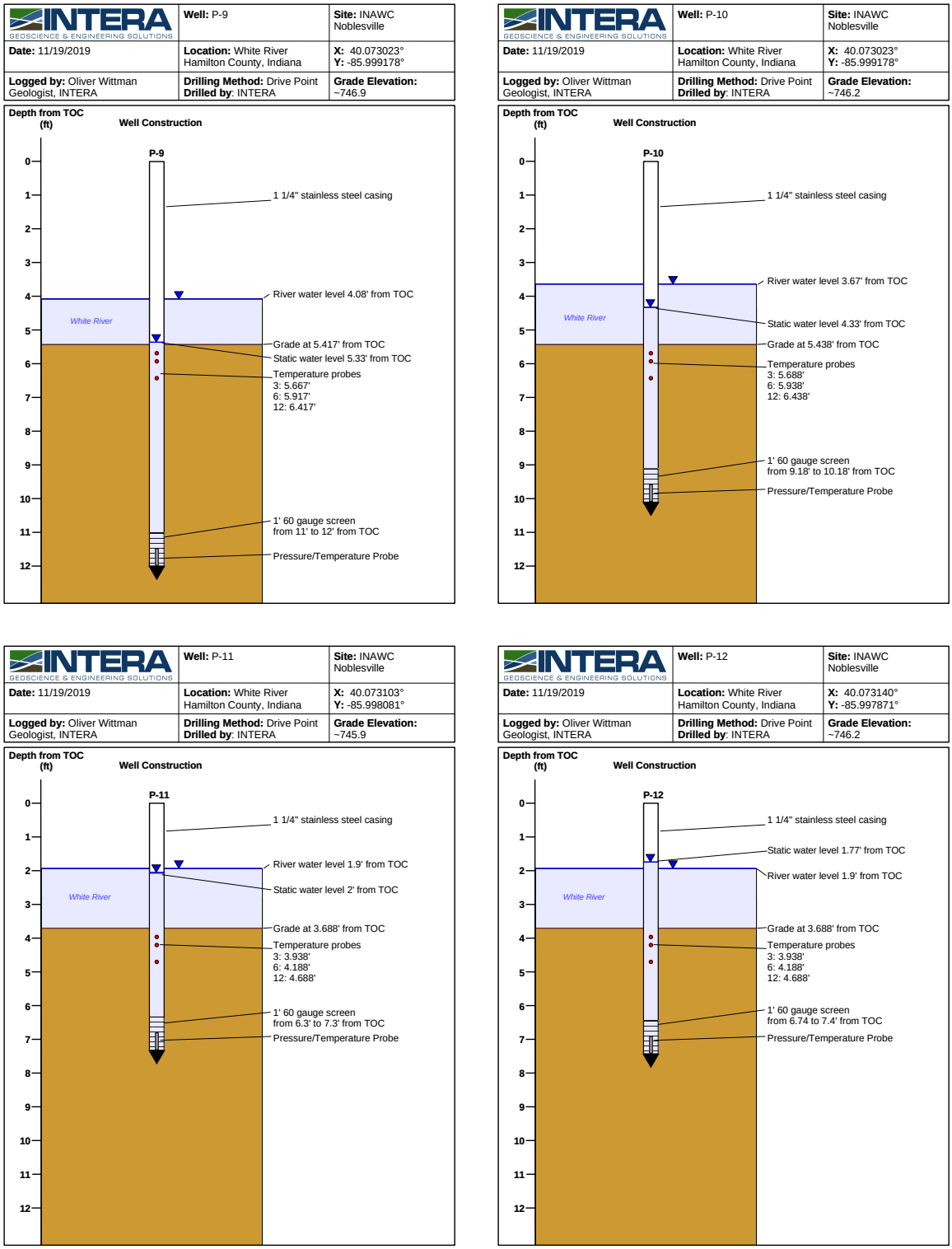


Figure E.31: Construction and instrumentation logs for piezoemeters P-9 (*top left*), P-10 (*top right*), P-11 (*bottom left*), and P-12 (*bottom right*) installed at INAWC North Well Field.

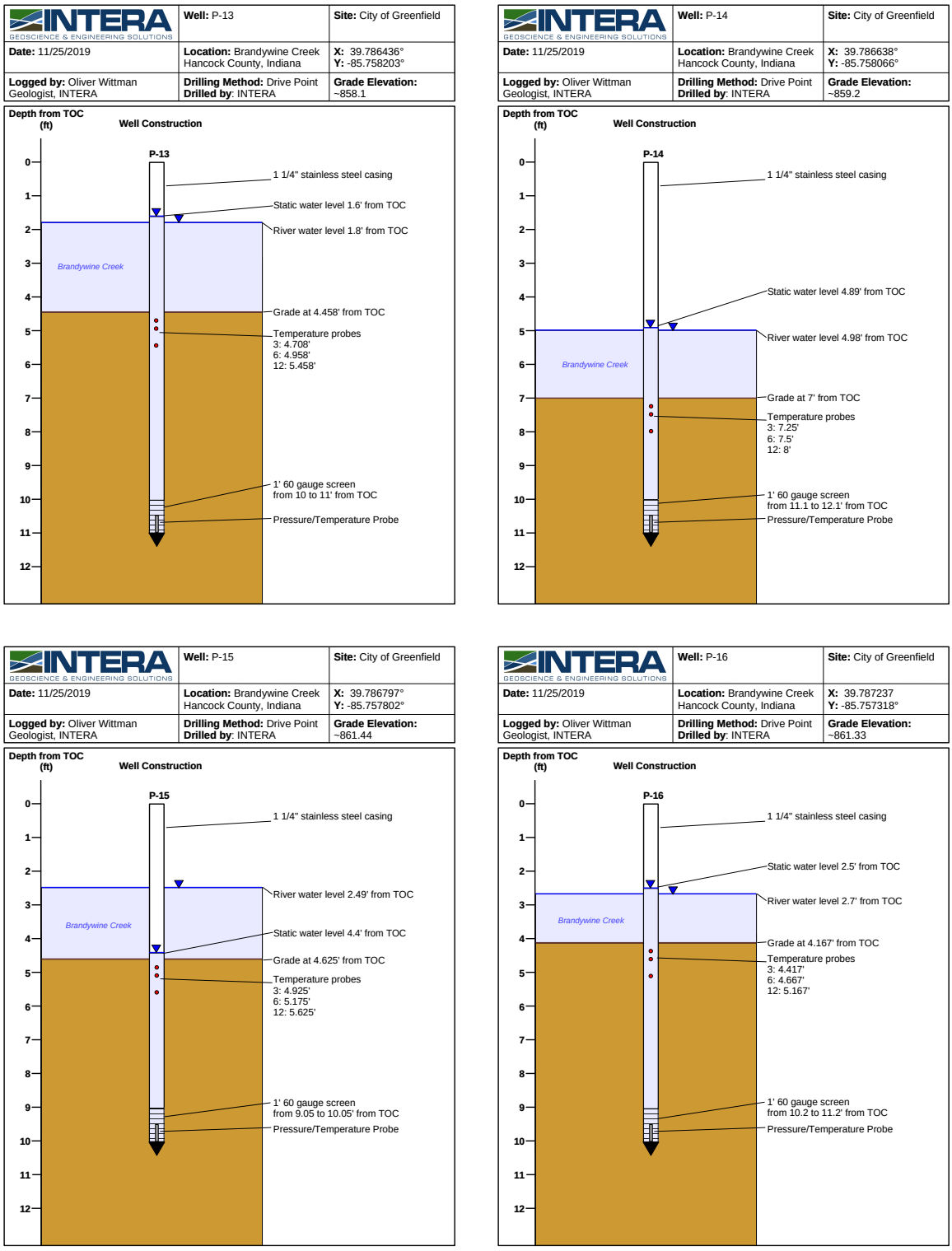


Figure E.32: Construction and instrumentation logs for piezoemeters P-13 (*top left*), P-14 (*top right*), P-15 (*bottom left*), and P-16 (*bottom right*) installed at Greenfield Riley Park Well Field.