Integrated Surface Water and Groundwater Assessment of Large Springs in the Green River Basin (BMU4, Round 2)

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All springs and related karst features used in this study are on private property. Do not visit any of these sites unless you have talked to the landowner and been granted permission for access.

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Conversion Factors

Multiply	by	To obtain
acre	43559.66	ft^2
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
gallon (gal)	3.785	liter (L)
gallon per minute (gpm)	0.06308	liter per second (L/s)
cubic feet per second (ft^3/s)	0.02832	cubic m per second (m^3/s)
$ft^3/s/mi^2$ (cfsm)	10.931	$L/s/km^2$ (lsk)
foot per mile (ft/mi)	0.1894	meter per km (m/km)
square mile (mi^2)	640	acres
mi^2	2.59	km^2
acre (ac)	0.4047	hectare (ha)
ounce (oz)	28.35	gram (g)
pound (lb)	0.454	kilogram (kg)
km	0.621	mi
$L/s/km^2$	0.0915	$ft^3/s/mi^2$
km^2	0.386	mi^2
meter	3.28	feet
m^3/s	35.31	ft^3/s
m/km	5.28	ft/mi
kg	2.2	lb
hectare	2.471	acre

EXECUTIVE SUMMARY

Recent groundwater quality studies in Kentucky's karst regions have integrated the surface water and groundwater quality assessment approaches to better define the relationship between the two flow systems. Surface water and groundwater are conjunctive systems, no more directly so than in karst terranes. Surface water assessments (§305b report) in the well-developed karst areas of Kentucky are limited due to a relative lack of flowing surface streams. Particularly in the sinkhole plain of south-central Kentucky, karst spring basins represent large areas of contribution to the Green River that are un-assessed for water quality. Subsurface streams that drain these basins can only be assessed via their discharges to surface waters at discrete springs or by water pumped from conduit-intercepting wells. Any adequate strategy for assessing these flows must meet the requirements for surface water assessment protocols.

An integrated approach attempts to address the deficiencies of inadequately assessed "stream segments" and provide needed information on spring conditions relative to nonpoint source impacts to both surface water and groundwater in Kentucky. Such assessments have implications relative to listing and delisting springs as water bodies in the 305(b)/303(d) integrated report, TMDLs, watershed planning, and the availability of grant funds (e.g. §319(h)) for watershed projects in these areas. This study focused on ten large springs in the Green River basin applying this holistic watershed approach. Water quality samples (including major ions, nutrients, TOC, TSS, TDS, pH, alkalinity, metals, VOCs, and pesticides) were collected monthly for one year from each spring. Total coliform and *E. coli* bacteria samples were collected monthly from May through October. Of the ten springs assessed in the Green River basin, nine springs were "Not Supporting" for Primary Contact Recreation (PCR), and one spring was "Partially Supporting" for PCR. Five of these springs were "Fully Supporting" for Aquatic Life Use; the other five springs were "Partially Supporting."

Four of the study area springs were assessed for aquatic macroinvertebrates and their relationships to various physical and chemical parameters. This represents a cursory evaluation

of benthic communities found in large springs in Kentucky and a starting point to develop further assessment criteria in this regard.

Comparison of hydrologic maps developed using groundwater tracer data to the USGS 6-, 8-, 10- and 12-digit Hydrologic Unit Code (HUC) boundaries indicates that significant amounts of mapped karst groundwater basins deviate from hydrologic boundaries based on topographic divides. Accurate hydrologic mapping is necessary to calculate water budgets and develop watershed models for TMDLs, for implementing watershed-based solutions to water quality and quantity problems, and for first responders to spills.

INTRODUCTION and BACKGROUND

The Kentucky Division of Water (DOW) has adopted an integrated approach to the management of water resources. The approach, known as the Kentucky Watershed Framework, is ". . . a means for coordinating and integrating the programs, tools and resources of stakeholders to better protect, maintain and restore the ecological composition, structure and function of watersheds and to support the sustainable uses of watersheds for the people of the Commonwealth" (KDOW, 2002a). Under this system, the watersheds of the state are subdivided into five Basin Management Units (BMUs). As part of the data gathering and assessment efforts of the watershed approach, the Division of Water former Groundwater Branch assessed nonpoint source pollution impacts to groundwater within the Green and Tradewater River basins (BMU 4).

Before 1995, ambient groundwater quality data throughout the state were inadequate to assess groundwater quality on a regional, basin-wide or statewide scale. In order to correct this situation, the Division of Water initiated statewide ambient groundwater monitoring in 1995 to begin the long-term, systematic evaluation of groundwater quality throughout the state. In 1998, legislation established the Kentucky Interagency Groundwater Monitoring Network, which formalized groundwater assessment efforts. Oversight for this network is through the Interagency Technical Advisory Committee on Groundwater, which includes the Division of Water.

The Division of Water regularly collects ambient groundwater samples throughout the state. To date, the division has collected more than 5600 samples from approximately 1600 sites. The information from these samples is used for a variety of purposes, including: 1) assessment and characterization of local and regional baseline groundwater quality, 2) documentation of spatial and temporal variations in groundwater quality, 3) support of public water systems, especially through source water characterization and Wellhead Protection, 4) development of Total Maximum Daily Loads (TMDLs) for surface water in areas where groundwater directly influences this resource, 5) support of the state's pesticide management plan, 6) development of groundwater quality standards and aquifer classification and 7) to address compliance and nonpoint source pollution issues. The Division of Water forwards analytical data to the Kentucky Geological Survey (KGS) Groundwater Data Repository where it is available to the public. Data requests can be made via their website (http://kgs.edu/KGS/home.htm), by phone at (859) 257-5500, or by mail at 228 Mining and Minerals Resources Building, University of Kentucky, Lexington, KY 40506.

Project Description

The purpose of this project was to assess the nonpoint source pollution impacts to groundwater in Kentucky's Basin Management Unit 4 (BMU 4-Green River and Tradewater River basins), and to integrate groundwater and surface water quality information, combined with biological data to better define the nexus between the two flow systems. Groundwater and surface water are conjunctive systems, no more directly so than in karst terrane. Surface water assessments (305b report) in the well-developed karst terrane of the central Kentucky sinkhole plain are limited due to a paucity of flowing surface water streams. These karst basins represent large un-assessed areas of contribution to the Green River basin. For example, Gorin Mill Spring drains an area of 150 square miles and contributes approximately 10% of the base flow of the Green River at the point where it discharges to the stream. Subsurface streams drain these basins that discharge to surface waters at discrete springs. This integrated surface water/groundwater assessment will address the deficiency of significant "stream segments" that have been properly assessed, and provide needed information on spring conditions relative to nonpoint source pollution impacts to both the surface water and groundwater programs. Figure 1 shows a map of the study area springs in the northcentral portion of the Green River basin. Basic information about these springs is summarized in Table 1. Springs are listed in descending order according to base flow. The AKGWA Numbers for all springs in the Groundwater Database are preceded by "9000-". This prefix has been dropped for Table 1 and all maps/figures in this report, such that Gorin Mill Spring (AKGWA Number 9000-0793) is simply reported as 0793.

Spring Name	AKGWA	County	Base Flow (ft^3/s)	Basin Area (mi^2)	Geologic Formation
Gorin Mill Spring	0793	Hart	24.0	152.4	Ste. Genevieve LS
Graham Spring	0051	Warren	19.8	122	Ste. Genevieve LS
McCoy Bluehole	0792	Hart	12.7	34.1	Ste. Genevieve LS
Lost River Rise	0054	Warren	12.4	58.8	Ste. Genevieve LS
Skees Karst Window #1	1398	Hardin	6.4	27.5	Ste. Genevieve LS
Nolynn Spring	2673	Larue	4.6	56.4	St. Louis LS
Goodman Springs	0230	Hardin	4.6	14.7	Ste. Genevieve LS
Mill Spring	1193	Grayson	3.0*	7.1	Reelsville LS
Head of Rough River	1011	Hardin	4.0	17.7	Ste. Genevieve LS
Mahurin Spring	0202	Grayson	2.1*	25.3	Ste. Genevieve LS**

Table 1. Study Area Springs Assessed with Integrated Approach
* Based upon limited data. ** Stratigraphic position questionable – complicated by faulting.

Previous Investigations

O'dell and others (2007) conducted a cursory assessment of groundwater quality across the Green River basin. They found that "*ambient groundwater quality in BMU 4 is generally good, with land use the primary determining factor*." O'dell identified definite Nonpoint Source (NPS) impacts to groundwater from herbicides and volatile organic compounds. Additionally, possible NPS impacts were recognized related to nutrients, including nitrate-nitrogen, ammonia-nitrogen, total phosphorus and orthophosphate.

Faust and others (1980) compiled groundwater quality data on a limited number of parameters for the entire state, but did not analyze or summarize the data. The United States Geological Survey has published Hydrologic Atlases (HA-26, HA-27, HA-28, HA-28, HA-29, HA-30, HA-31, HA-32, HA-33, HA-34, HA-35, HA-72, HA-74, HA-91, HA-96, HA-110, and HA-129) and 7.5-minute Geological Quadrangle maps (GQs) for the entire basin.

The Kentucky Geological Survey (1969, 2002) has prepared index maps for the both the Geologic Quadrangle maps and the Hydrologic Atlas series. Geochemical data in the HAs are limited and generally include only common metals and major inorganic ions. However, the atlases usually provide information that is somewhat more detailed for areas showing the Ohio River alluvium. In general, groundwater found in the Ohio River alluvium is hard and may contain high amounts of iron, especially in areas adjacent to valley walls.

Several investigators have mapped karst groundwater basins within BMU 4 and Currens and others (1998, 2002) have compiled the results. Carey and Stickney (2001) have prepared county groundwater resource reports, including general descriptions of groundwater quality. Ray and others (1994) have interpreted groundwater sensitivity to contamination for the entire state.

The *"Hydrology of the Cavernous Limestones of the Mammoth Cave Area, Kentucky"* (Brown, 1966) conceptually describes groundwater flow in the Mammoth Cave area. It also illustrates how nonpoint source pollution can enter the groundwater easily in this highly developed karst area.

Carey and others (1993) examined data from 4,859 samples collected throughout the state for ammonia, nitrate-nitrogen, nitrite-nitrogen, chloride, sulfate, conductivity, alachlor and triazine. They found that: 1) 4.6% of the samples for nitrate-N exceeded the Maximum Contaminant Level (MCL) of 10.0 mg/L, 2) 0.9% exceeded the MCL of 0.002 mg/L for alachlor and 3) 0.3% exceeded the atrazine MCL of 0.003 mg/L. (Note: this study measured total triazines and did not differentiate between various triazine herbicides, such as atrazine, simazine and cyanazine. Additionally, this study applied the MCL for atrazine to the entire triazine group.)

Conrad and others (1999) described the occurrence of nitrate-N and fluoride in the state and Fisher (2002) described the occurrence of arsenic. In their study of nitrate-N, Conrad and others (1999) found that MCL exceedances decreased with well depth and that for fluoride, less than 1% of 2,363 analyses exceeded the MCL of 2.0 mg/L. Fisher (2002) concluded that "arsenic in Kentucky groundwater generally does not exceed the MCL and that there are no widespread occurrences of high arsenic concentrations."

Currens (1979) compiled a bibliography of karst publications for the state. This report includes a large number of publications that describe historical research and water quality in the Mississippian plateau karst area of BMU 4. Although dated, this publication provides direction in locating karst information in the basin.

Currens, Ray, and others (1998, 1998, 1998, 2000, 2003, 2009, Draft) have compiled a Karst Atlas Series of Maps, which show mapped karst groundwater basins in various 30 X 60 minute quadrangles. The quadrangles covering portions of the Green and Tradewater Basins include: Harrodsburg, Bowling Green, Campbellsville, Beaver Dam, Tell City and Hopkinsville (draft). These maps include known groundwater tracer tests, interpreted basin boundaries and geology-inferred limits to karst development. They also include references to the original published and unpublished groundwater tracer data. These are dynamic maps that are updated as information becomes available. Most of the study area springs appear on these maps with tracer data and interpreted groundwater basin boundaries. Tracer tests conducted for this study allowed for the delineation of Nolynn and Mill spring basins and refinement of basin boundaries for Goodmann Springs and Skees KW #1 (Waddell Spring basin).

Kentucky Division of Water (2001) *"Green and Tradewater Basins: Status Report"* compiles and summarizes all known environmental quality data for the Green and Tradewater basins using GIS maps and discussions. The publication also indentifies known problems and data needs to better understand the basin.

Fisher and others (2004) prepared the *"Summary and evaluation of groundwater quality in the Upper Cumberland, Lower Cumberland, Green, Tradewater, Tennessee, and Mississippi River Basins."* For their study, all known water quality data from the BMU 3 and BMU 4 basins were evaluated and statistically analyzed.

Leist, (1986) compiled "*An evaluation of water-quality data from hydrologic accounting unit 051100, Green River Basin, Kentucky,*" which compared the water quality of the Green River before it entered the Western Kentucky Coal Field with water quality of the river at stations located within the coal field. He found that the levels of chloride, sulfate, iron and dissolved solids increased downstream once the river entered the coal field province. The increase of these water quality parameters was attributed to the impacts of specific land uses of both coal mining and oil production.

Reynolds (2001) compiled the "*Strategic Monitoring Plan for the Green and Tradewater River basins.*" The document describes all the activities of the agencies and groups that are working together to collect various types of environmental data in the basin. It covers surface water, groundwater, air quality and biological resources.

PHYSIOGRAPHIC and HYDROGEOLOGIC SETTING

BMU 4 covers more than 11,541 square miles - 454 of which are in Tennessee. It includes the Green and Tradewater River basins, as well as several other direct minor Ohio River tributaries (MORT). The study focused on ten springs in the Green River basin. Figure 1 illustrates the location of study area springs relative to the Green River watershed. The study area includes Hardin, Larue, Grayson, Hart and Warren Counties.

Green River Basin

The Green River rises in Lincoln County and flows generally west-northwest to its confluence with the Ohio River north of the city of Henderson in Henderson County. The Green River is approximately 400 miles long and drains more than 9,100 square miles (ORSANCO, 2002) in Kentucky and Tennessee. In Kentucky alone the Green River drains more than 8,800 square miles - approximately 20% of the state. The Green River watershed drains portions of two major physiographic regions; the Mississippian Plateau and Western Coal Field.

Groundwater flow in the Green River basin varies according to local geology. After initial runoff of precipitation, groundwater provides base flow to surface water streams, thereby sustaining stream flow during periods without rain. Principal tributaries are the Barren River, Nolin River, Rough River and the Pond River. The largest impoundments in BMU 4 are Green River Lake, Barren River Lake, Nolin Lake, Lake Malone, and Rough River Lake; all of which are operated by the Army Corps of Engineers.

Physiographic Regions

Based upon variations in geology, topography and hydrologic regime, groundwater underlying Kentucky's various physiographic regions has varying sensitivity to contamination from activities conducted on the surface. Groundwater sensitivity to potential impacts is based upon three primary hydrologic components: recharge, flow velocity and dispersion. Sensitivity ranges from low (1) to high (5). In general, quicker recharge, faster flow and the potential for more extensive dispersion lead to greater sensitivity. Ray and others (1994) discuss this topic in detail. In BMU 4, groundwater sensitivity ranges from high in the well-developed karst of the Mississippian Plateau to low in the Western Coal Field region.

Most of the land area in BMU 4 occurs in three physiographic regions: the Western Coal Field, the Mississippian Plateau, and the Ohio River Alluvium, but also includes small portions of the Jackson Purchase and the Knobs. Because each region differs in physiography and subsurface flow regime, sensitivity to contamination from nonpoint source pollution also differs. The ten springs chosen for this study all occur in the Mississippian Plateau Region. The information below is summarized from Noger (1988), McDowell (2001), and Ray and others (1994).

The **Mississippian Plateau**, also known as the Pennyroyal or Pennyrile, is characterized by flat-lying Mississippian-age carbonate rocks, primarily limestone with some dolostone. Well-developed karst drainage occurs in this region with an abundance of sinkholes, caves and influent streams. Groundwater flow is primarily through solutionally enlarged conduits, but fracture flow and flow along bedding planes also occurs and can be locally important. In general, yields from wells vary widely according to the size of any enlarged water-filled conduits encountered by the well-bore and can range from less than one gallon per minute (gpm) to more than one hundred gpm. Springs developed on these thick and generally pure carbonate sedimentary rocks tend to have larger discharges than in other areas within the watershed, with base flow discharges measured up to 24 cubic feet per second (cfs). The Mississippian Plateau is very sensitive to contamination from surface activities.

Figure 2 illustrates surface drainage in a large portion of Kentucky. In particular, the paucity of surface drainage in the Mississippian Plateau region causes it to stand out. This is due to the well-developed karst drainage formed in the Mississippian-aged carbonate rocks underlying the region. Drainage in this corridor is primarily in the subsurface. This is the main area of inadequate surface water assessment and the focus of this study.

Hydrogeologic Setting of Study-Area Springs

Well-developed karst drainage in the study area occurs primarily in the Ste. Genevieve and St. Louis limestones of the Meramecian Series of the Mississippian System. These limestones were deposited mainly in shallow seas. One of the study area springs, Mill Spring, occurs in the Reelsville Limestone of the Chesterian Series of the Mississippian System. However, as noted in the Groundwater Tracing section, an additional, unmapped spring may be inundated and obscured by the Nolin Reservoir south of Mill Spring.

The purity and high solubility of the limestones make the terrane highly susceptible to karst development. Long-term bedrock dissolution of these limestones has strongly influenced the Mississippian Plateau's characteristic flat-lying to undulating topography, which contains numerous shallow sinkholes and caves, losing and sinking streams, dry valleys, intermittent lakes, and large springs.

Reelsville Limestone

The Reelsville Limestone is described as light olive gray to light gray and fine- to medium-grained. It has few fossils, the base is oölitic and it tends to form cliffs and steep slopes of blocky outcrops. Unit thickness is 12 to 45 feet and the lower contact grades into the Sample Sandstone (Moore, 1965).

Ste. Genevieve Limestone

Most of the karst drainage basins investigated in this study are developed within the Ste. Genevieve Limestone. The Ste. Genevieve is composed of thick-bedded, light-colored, medium- to coarse-grained, oölitic and bioclastic calcarenite; light-colored to gray, bioclastic calcirudite; gray calcilutite; and gray, very finely crystalline dolomite. Minor amounts of chert occur as nodules, thin beds and stringers, and siliceous replacements of fossiliferous beds. The Ste. Genevieve typically ranges in thickness from 180 to 240 ft in the study area (Sable & Dever, 1990). The Lost River Chert is a distinctive 3- to 9-feet thick zone of nearly continuous chert that occurs at, or near, the base of the Ste. Genevieve Limestone. This chert is highly fossiliferous with fenestrate bryozoans, brachiopods, and gastropods. It is nearly indistinguishable from surrounding light gray limestone when freshly exposed, but when weathered reveals characteristic porous blocks of chalky white chert stained with red soil. Because of its resistance to corrosion, this chert bed is suspected to perch water bodies such as the Waterworks Spring basin near Bowling Green, Kentucky (Moody and others, 2000), and to decrease sinkhole density where it underlies the surface, such as in the Bristow Plain east of Bowling Green (Quinlan & Ewers, 1981).

St. Louis Limestone

One of the karst drainage basins in this study discharges from the St. Louis Limestone, which underlies the Ste. Genevieve Limestone. The St. Louis consists of a very fine-grained, micritic, cherty, argillaceous, and dolomitic limestone. It is characteristically gray to dark gray, fossiliferous, and thick-bedded to massive (Sable & Dever, 1990). The upper part of the St. Louis Limestone is highly cherty, which helps to locally perch groundwater. Although this unit ranges from 300-475 ft in thickness, most of the karst groundwater circulation relevant to this study occurs in the upper portion.

Karst Hydrology

Because of the characteristics of karst terrane, rates of groundwater recharge, flow velocities, and potential dispersion within the study areas can be extremely high. These groundwater systems can be rapidly recharged by widespread influx of precipitation and snow melt through soil macropores, runoff into sinkholes, and concentrated flow from losing and sinking streams. Groundwater flow velocity through conduits often matches runoff in surface channels, which may travel several miles per day. Likewise, karst groundwater flow can be dispersive, potentially distributing pollutants over broad areas at relatively long distances from the source(s). Three major hydrologic parameters of *recharge*, *flow*, *and dispersion*, were used to assess the groundwater sensitivity to pollution from surface activities in Kentucky (Ray and others, 1994). Hydrogeological sensitivity was rated on a scale of 1 (low) to 5 (high), based on quantitative assessments of these three parameters. Documentation of conduit-flow velocities in karst aquifers by numerous tracer tests was especially useful for rating the important *flow* component in a particular hydrologic setting. In the karst terrane of the Mississippian Plateau, *recharge* porosity can range up to several yards in diameter, which is exemplified by stream insurgence into a cave or vertical shaft. *Flow* velocity within trunk conduits may range from 30 ft/hr at low flow to 2400 ft/hr during flood conditions (Ray & O'dell, 1993). *Dispersion* of contaminants within this karst aquifer is usually linear or bi-directional, but widespread to radial flow patterns do occur. Because of these extreme ranges, the study area is rated as “5”, which is the most sensitive hydrogeologic setting for potential pollution from surface activities and nonpoint sources.

The relatively shallow karst aquifers of Kentucky, formed in dense Paleozoic carbonates, typically contain low to moderate long-term storage of groundwater (White, 1988). Most seasonal groundwater storage is within the soil/regolith cover, the underlying weathered bedrock zone called the *epikarst*, and in bedrock fractures. Long-term storage within the epikarst, commonly in the form of a perched water zone, continually seeps and percolates down fractures and shafts, and collects within the regional conduit drainage network. The karst flow system is typically an interconnected dendritic or branched horizontal network that discharges at large springs (Palmer, 1990). These convergent conduit networks tend to form distinct, contiguous groundwater drainage basins. Hydrologic interconnections between basins are typically localized along basin boundaries. However, inter-basin transfer from one trunk conduit to another may occur locally during overflow (high-water) conditions. Near the basin discharge zone, divergent distributaries are common and are usually overflow networks (Ray, 1997). Perennial-flow distributaries are less common.

One method of classifying springs is by karst basin type – see Ray (2001) and Ray and Blair (2005) for detailed descriptions and a full explanation. Springs used in this study can be divided into two simplified categories: Groundwater Basin Springs and Stream (or Subterranean) Cutoff Springs. Subterranean Cutoff Springs were first defined by Malott (1922). Groundwater basin springs are fed by extensive conduit networks that receive recharge as described above through sinking/losing streams, sinkholes and epikarst seepage. Stream cutoff springs are recharged primarily through an intra-valley subsurface diversion of a surface stream. These springs are fed by minimal conduit networks and water chemistry does not vary greatly from that of the surface stream that has been diverted. Nolynn Spring is an example of a composite of stream cutoff and groundwater basin drainage.

Land Use

Land use is an important consideration regarding potential impacts to groundwater quality. Approximately 1.9% of the surface area in BMU 4 is urban, 47% is agricultural (row crop or pasture) and 49% is forest. Forest usage is combined with the area covered by wetlands, lakes and reservoirs and reclaimed strip mines because these individual areas are so minor (2.17 %). According to the Kentucky Department of Mines and Minerals (2002), approximately one-third of all the coal mined in the state (27, 224, 316 tons in 2002) has come from counties which are all or partly in BMU 4. The five primary coal-producing counties in BMU 4 are Webster, Union, Muhlenberg, Hopkins, and Henderson Counties. Both surface and underground mines are active in this area. Table 2 illustrates potential nonpoint source impacts to groundwater from varying land use. Table 3 displays the percentages of major land cover categories within each study area spring basin along with the spring basin areas. The predominant land cover category in each spring basin is highlighted. Agriculture dominates the majority of the land drained by study area springs.

Land Use	**% in BMU 4**	**Potential Contaminants**
Agriculture, including row crop production, livestock grazing, fuel/pesticide storage	47	Pesticides, nutrients (esp. nitrate-n), salts/chloride, volatile organics, bacteria
Urban	1.9	Pesticides, volatile organics, chlorides
Forested, including mining, logging, silviculture	49	Metals, pesticides, nutrients, sediment, pH

Table 2. Land Use and Potential NPS Contaminants within BMU 4

Spring Name	**Major Land Cover Categories**			**Total Groundwater Basin Area (mi^2)**
	% Urban/Residential	**% Agriculture**	**% Forest**	
Gorin Mill Spring	7.5	71.1	21.4	152.4
Graham Spring	8.4	74.9	16.7	122.0
McCoy Bluehole	3.4	14.3	82.3	34.1
Lost River Rise	25.3	67.1	7.5	58.8
Skees KW #1	5.3	75.5	19.2	27.5
Nolynn Spring	6.1	61.5	32.4	56.4
Goodmann Springs	3	53.2	43.8	14.7
Mill Spring	2.5	18.5	79.1	7.1
Head of Rough River	3.3	63.2	33.5	17.7
Mahurin Spring	3.9	31.8	64.3	25.3

Table 3. Land Use Percentages within Karst Groundwater Basins monitored for study

Groundwater Use

Groundwater is an important resource in BMU 4, providing private and public drinking water, as well as water for industrial and agricultural purposes. Additionally, groundwater discharge from springs maintains base flow to surface water streams after runoff from precipitation events.

Groundwater usage from wells and springs was calculated from County Water Plan data for Counties that are entirely in the study area. Based on these data, more than 39,310 people in the Green and Tradewater Basins use self-supplied groundwater as a source of drinking water (KWRIS, 1999). Figures were not available for the agricultural use of groundwater, which does not require a permit. This use includes irrigation, livestock watering and general farm use. Although no figures are available, field observations indicate that such use is significant, especially for irrigation during the growing season.

Currently, none of the ten springs monitored for this study are used as a primary groundwater source for any purpose. Nolynn Spring is a former public water supply spring and the Head of Rough River Spring has been developed as a back-up water supply for human consumption. None of the remaining springs in the study have been developed as drinking water supplies.

MATERIALS and METHODS

Introduction

This groundwater study represents a new approach for assessing groundwater resources in the karst regions of Kentucky. Historical Nonpoint Source (NPS) groundwater assessments conducted by the Division of Water generally took one of two forms: 1) Thirty monitoring sites (wells and springs) spread throughout a major river basin, sampled quarterly over the course of one year, or 2) Fewer monitoring sites in a sub-watershed sampled at a greater frequency - 6 to 8 times - over the course of one year with the intent of creating a more statistically valid dataset. Samples were analyzed for a broad range of parameters including Bulk Parameters, Major Inorganic Ions, Nutrients, Metals, Pesticides, Volatile Organic Compounds and occasionally Bacteria. Both of these approaches served to increase knowledge of ambient groundwater conditions and impacts from NPS pollution. However, due to aspects such as sampling frequency and parameters analyzed, the data were not directly comparable to surface water data in the same watersheds.

As previously noted, groundwater and surface water are interconnected systems. These connections are especially pronounced in regions of well-developed karst drainage. Thus, a new approach for groundwater assessment in karst areas was desired. This project was intended to address discrepancies between surface water and groundwater data sets by integrating surface water assessment protocols into a groundwater study. The ultimate goal was to have these ten springs assessed and reported in the *2008 Integrated Report to Congress on Water Quality in Kentucky*.

Groundwater quality sample results were compared to the Surface Water Standards found in 401 KAR 10:031 for Warm Water Aquatic Habitat and Primary Contact Recreation (LRC, 2007). The parameters assessed are shown in Figure 3, which is a simplified checklist created for this project. Ten analytes are listed as "NO DATA" in the *Impairment Level* column. These analytes were not requested for analysis due to an oversight by the lead author. However, their omission did not preclude assessment. Physicochemical samples were collected monthly from each of the ten springs for twelve consecutive months beginning in April 2006 and ending in March of 2007. Bacteria samples were collected monthly from each spring during the months of May through October 2006.

Sample Collection Methods

Consistent with the Division of Water's other ambient groundwater monitoring efforts, samples of fresh, untreated groundwater were collected at each spring or well and analyzed for major inorganic ions; nutrients; volatile organic compounds; total organic carbon; pesticides, including the most commonly used herbicides, insecticides and fungicides; and dissolved and total recoverable metals. The analytical methods, containers, volumes collected, preservation and sample transport are consistent with the Division of Water's Kentucky Ambient/Watershed Water Quality Monitoring Standard Operating Procedure Manual, prepared by the Water Quality Branch (2002c). Parameters to be measured, volume required for analysis, container type and preservative are shown on the attached Chain-of-Custody Form (Appendix B).

Major inorganic ions are used to establish background groundwater chemistry and also to measure impacts from nonpoint source pollutants such as abandoned mine lands and abandoned hydrocarbon production operations by measuring pH, alkalinity, chloride, sulfate and fluoride. Nutrients and total organic carbon are used to measure impacts from agricultural operations (ammonia-N, nitrate-N, nitrite-N, total phosphorous and orthophosphate) and/or improper sewage disposal (nitrates, ammonia). Pesticides are measured to determine both rural agriculture and urban domestic-use and commercial-use impacts on groundwater. Metals are useful to establish rock-groundwater chemistry, local and regional background levels and to determine nonpoint source impacts from active or abandoned coal mining operations. Volatile organic compounds determine impacts from urban run-off, oil and gas production, and other point and nonpoint source impacts to groundwater.

Pathogen samples were collected and preserved in accordance with the procedures outlined by the WATERS Laboratory at Western Kentucky University. These samples were analyzed for Total Coliform and *E. Coli* bacteria. Bacteria determine impacts from agricultural operations and failing septic and sewer systems. Bacteria sources could not be differentiated based on the analyses conducted. Parameters to be measured, volume required for analysis, container type and preservative are shown on the attached Chain-of-Custody Form (Appendix B).

All samples collected to meet grant commitments were analyzed by the Environmental Services Branch (ESB) and WKU WATERS laboratories according to appropriate U.S.EPA methods.

Graphical Methods

Maps created to display assessment results utilize graduated color points based on each spring's use support level. These are overlain on a simplified land use map with county boundaries, major surface streams, topographic watershed boundaries and karst groundwater basin boundaries.

Maps used to show results of tracer tests conform to the standards used in the Kentucky Karst Atlas map series published by the Kentucky Geological Survey with the Kentucky Division of Water. This dye trace map legend is shown in Figure 4. The one exception to this legend is that inferred groundwater flow routes derived from traces conducted for this study will be displayed in orange so that they can be distinguished from previous investigations. Tracer data and stream coverage are displayed in color overlain on black and white 7.5 minute, 30 x 60 minute or 1 x 2 degree topographic quadrangles. All maps were created with ArcGIS 9.2 software using data obtained from the Kentucky Geography Network, Kentucky Division of Water and data files created by the authors specifically for this project. In electronic versions of this report, all figures are accessible by clicking the blue reference "hyperlink". In paper reports these same figures are available in an addendum.

Site Selection

The Groundwater Section selected sites based on numerous criteria. Preference was given to springs draining the corridor of Mississippian-aged limestone, which has a relative lack of surface drainage. Springs were selected for monitoring using base flow discharge measurements, where springs with larger base flows were preferred. A spring's base flow *typically* correlates directly to groundwater basin size; thus springs with larger base flows allow for assessing greater areas. All of these springs had been identified by previous investigators and four had been classified according to discharge and basin character by Ray and Blair (2005).

Because this study was designed to assess ambient groundwater conditions, those areas with known point source discharges were eliminated from consideration. For example, sites affected by leaking underground storage tanks or landfills were not sampled as part of this study. Finally, other important considerations included accessibility of the site and landowner permission to access sites located on private property.

A unique eight-digit identification number, called an AKGWA number, catalogs springs maintained in DEP's databases. All springs used in this study had been previously identified and inventoried. The spring inventory form notes details of the site, including owner's name and address, location, spring development, yield and topographic map location. The data are then entered into DEP's electronic database and forwarded to the Groundwater Data Repository at the Kentucky Geological Survey. The spring forms are scanned and stored in a database as an indexed electronic image.

Tracer Test Methods

Qualitative groundwater tracer tests, as described by Quinlan (1986) and Aley (2002), were conducted using four non-toxic fluorescent dyes. The names of dyes used in this study are shown in bold in Table 4:

Dyes Used	Trade Name	Color Index	Number of Injections
SRB (Sulforhodamine B)	Ricoamide Red XB	Acid Red 52	6
Eosine	15189 Eosine OJ	Acid Red 87	5
Uranine (Fluorescein)	Uranine Conc (Disodium Fluorescein)	Acid Yellow 73	7
RWT (Rhodamine WT)	Keyacid Rhodamine WT	Acid Red 388	1

Table 4. Fluorescent Tracer Dyes Used and Number of Injections for each

As indicated by Schindel and others (1994) and Field and others (1995), these fluorescent dyes are optimal for use in groundwater basin delineation because of non-toxicity, availability, analytical detectability, moderate cost, and ease of use. The quantity of fluorescent dye used for these tests was determined empirically over several years of field experience. Prior to fieldwork, powdered dye was dissolved in water at a concentration of eight oz (226 g) per gallon (3.78 L). For uranine and eosine, the liquid-dye mixtures were injected into active stream swallet sites at a rate of about 2-3 pints (1-1.5 L) per mile (1.6 km) of expected flow distance (equivalent to about 2-3 ounces (60-85 g) of powdered dye per mile). Depending on conditions, up to twice as much SRB and RWT dye was used for equivalent flow distances. Greater quantities of dye were used at dry sinkhole sites flushed with hauled water or during high-flow conditions.

During movement of tracers through monitored sites, fluorescent dyes were adsorbed and accumulated onto activated carbon samplers. In some cases, when the dye receptor was missing, dye presence was determined by collecting a water sample for laboratory analysis. The carbon dye receptors were deployed in flowing water of springs, streams, and caves and anchored with either a modified "gumdrop" anchor (Quinlan, 1986), or a brick fitted with a vinyl-clad copper wire. The receptors were secured to the anchor with a commercially available "trot line clip" (Figure 5).

Background dye receptors were usually deployed, exchanged, and analyzed prior to dye injection in the study area. These background dye receptors served as controls for comparison with subsequently recovered receptors. In a few cases prior background assessment was omitted in order to take advantage of unusual field opportunities to inject dye. In those cases, background water samples were carefully collected on the same day as the expedited dye injection in lieu of the background assessment. Dye receptors were typically exchanged weekly.

For analytical processing, samples of the retrieved carbon dye receptors were rinsed with tap water and eluted at room temperature for at least 15 minutes in a solution of 50% 1-propanol, 30% de-ionized water, and 20% ammonium hydroxide (NH_4OH). The eluted samples from this study were processed at the DOW Groundwater Laboratory and analyzed for absence or presence and relative intensity of tracer dye using a scanning spectrofluorophotometer. The DOW's Shimadzu RF-5301 PC instrument was purchased in 1998 and a computer sequence for analyzing dye samples was programmed by Peter Idstein, then PhD candidate at Eastern Kentucky University. A macro to aid setup of the page printout, including site identification data, dye wavelength analyses, and scan specifications was designed by Jack R. Moody. All printouts of dye analyses are archived in the Groundwater Branch Laboratory. Figure 6 shows a typical dye curve analyzed on the spectrofluorophotometer. The horizontal position of a dye peak indicates the fluorescence wavelength, which identifies the type of dye. The vertical height of the curve indicates the relative fluorescence intensity of the recovered dye and thus the qualitative confidence level of the positive dye recovery.

Positive dye recovery was determined when fluorescence intensity exceeded background by four times (4X), although fluorescence of positives typically exceeded background by more than 10X. Dye trace results were recorded on DOW Dye Trace Record Forms. These documents include dye injection site information and a detailed record of each dye receptor recovered during the study and are available upon request.

Documentation of Tracer Tests

During this project, 19 reconnaissance groundwater tracer tests were conducted for the purpose of basin delineation and verification or modification of HUC boundaries. The results of these investigations are discussed individually for each basin, and are listed under abbreviated dye trace ID numbers such as 99-20 (Year-sequence of dye injection; the senior author was the principal investigator for 6 of 19 tests). Analyzed dye-intensity level from recovered dye receptors is indicated by the following symbols, which represent the qualitative confidence level of a dye recovery and hydrologic connection:

– Negative result
? Inconclusive (< 4X background)
+ Positive (> 4X background; < 1000 intensity units)
++ Very Positive (1000-10,000 intensity units)
+++ Extremely Positive (> 10,000 intensity units)

An inconclusive result indicates that dye was apparently recovered at less than the standard criterion of 4X the background level. Two or more successive dye detections at less than the criterion of 4X the background level may be judged to be a positive recovery in certain situations. The desire to use minimal quantities of tracer dye sometimes resulted in lower than desired levels of dye detection. In some cases water samples were assessed to compare with carbon samples or when a carbon sample was missing at the monitoring site.

New tracer data for eight partially mapped basins (Nolynn, Heady Big, Pretty, Mill, Goodman, Waddell, Hawkins Bluehole and Copelin springs) are described below. A map of each karst watershed shows the final results of flow-path interpretation and delineation of the approximate basin boundary. Diagrams are presented on US Geologic Survey 30 x 60 Minute Metric Topographic Quadrangle base maps, or 1 x 2 Degree Topographic Quadrangle base-maps, depending on the land area presented in the image. Topographic contours and cultural features are displayed in gray tone for improved discrimination of the color-coded tracer data.

Inferred groundwater flow routes are illustrated as minimum straight-line to curvilinear distances, which are shorter than actual conduit pathways. Some basin boundary segments are delineated based on topographic divides when tracer data are lacking. The dashed boundary line indicates the imprecise nature of karst groundwater divides (Ray, 2001). Groundwater recharge within about 300 m (1000 ft) on each side of a mapped divide should be assumed to potentially drain to both associated basins.

WATER QUALITY ASSESSMENTS

Introduction

All chemical and biological data assessed were collected by DOW. These water quality data were compared to criteria set forth by the Kentucky Water Quality Regulations (401 KAR 10:031). As previously mentioned some parameters were inadvertently omitted. Where applicable, surrogate indicators were used as much as possible. For instance, nutrient data were used to supplement absent dissolved oxygen data. In other instances supplemental indicators were not available and these analytes simply could not be assessed. Ultimately, data were adequate to draw meaningful conclusions relative to use support levels for Warm-water Aquatic Habitat (WAH) and Primary Contact Recreation (PCR) at each of the ten springs. The maps in Figure 7 and Figure 8 show the support levels determined for each spring for PCR and WAH, respectively.

Goodman Springs is located in Hardin County in the northeast corner of the Millerstown 7.5-minute Quadrangle, but is not mapped on the USGS 1:24,000 topographic or geologic maps. Goodman Spring is a perennial distributary. Spring water issues from multiple orifices in an outcrop of the Beaver Bend and Paoli Limestone, although the majority of this groundwater basin is formed in the Ste. Genevieve Limestone. The discharges occur across a single bedding plane horizon spanning approximately 150 feet. Numerous overflow features occur on each end of this spring horizon, with the perennial discharge points in the middle. The springs each have short runs that join and then flow down to the Nolin River near Spurrier, KY. Tracer data show that Goodman Springs drains an area of 14.7 mi^2 (Quinlan and Ray, 1983). The base flow for this spring has been measured at 4.6 ft^3/s. Figure 9 is a photograph of the center-most discharge points of Goodman Springs. Figure 10 is a map showing the spring location and tracer data. Tracer data from this study and previous research will be discussed in the Tracer Test Results section of this report.

Goodman Springs was found to be non-supporting for PCR. Each of the six *E. Coli* samples collected and analyzed had concentrations over the allowable limit of 240 colony-forming units/100 mL (CFU/100 mL). However, Goodman Springs was found to be fully supporting for WAH. The checklist in Figure 11 shows impairment for only one physicochemical parameter, Selenium. Selenium was detected over the allowable limits in eight out of twelve samples.

Gorin Mill Spring is located in Hart County in the southeastern portion of the Munfordville 7.5 Minute Quadrangle, but is not mapped on the USGS topographic or geologic maps. This spring discharges from the Ste. Genevieve Limestone as a moderate-sized bluehole with a spring run that flows approximately 50 feet to the Green River. Tracer data show that this spring has a groundwater basin area of 152.4 mi^2 and high-flow connections to numerous overflow springs along the Green River (Quinlan and Ray, 1981 and Ray and Currens, 1998). Ray and Currens (1998) reference numerous published and unpublished tracer studies and cave surveys that aided in this groundwater basin delineation. These include: Ahlers and others, 1986; Quinlan and Rowe, 1977; Crawford, 1994 and Ray, 1994a. Gorin Mill has the largest base flow of any known spring in Kentucky at 24.0 ft^3/s. Figure 12 shows photographs of Gorin Mill Spring from various view points, a few months after a tornado had occurred in the area. The map in Figure 13 shows the spring's location and tracer data.

Gorin Mill Spring was found to be non-supporting for PCR. Five out of six samples collected and analyzed for *E. Coli* were over the allowable limit of 240 CFU/100 mL. Gorin Mill Spring was listed as partially supporting for WAH. Partial impairment was noted for iron because two out of twelve (17 %)

sample results were over the chronic standard (Figure 14). Additionally, nutrients were found to be problematic by data reviewers in DOW's Water Quality Branch (WQB). In particular, levels of nitrate (as N) in all twelve samples and total organic carbon in six of twelve samples were above allowable limits (KDOW, 2008).

Graham Spring Karst Window (KW), located in Warren County, is part of a large karst distributary that has traditionally been called the Graham Springs system (Ray and Currens, 1998). Graham Spring KW is in the southeastern portion of the Bowling Green North 7.5-minute Quadrangle, but is not mapped on the USGS topographic or geologic maps. It was chosen as the monitoring point for this karst groundwater basin due to ease of access. Groundwater rises from the Ste. Genevieve Limestone to form a large bluehole at Graham Spring KW and is then discharged into a cave that feeds Wilkins Bluehole, approximately 750 feet to the west. During excessively wet periods, Graham Spring KW will overflow to a surface channel it shares with the adjacent Tooley Overflow Spring. Three smaller overflow springs connected to this system are located on the banks of the Barren River and the spring run. In base flow conditions, water is discharged to the surface solely via Wilkins Bluehole, forming a spring run approximately 1000 feet long down to the Barren River. Base flow at Wilkins Bluehole has been measured at 19.8 ft^3/s and tracer data show that it drains an area of 122 mi^2. Figure 15 is a photograph of Graham Spring KW showing the rise and subsequent discharge into the cave which feeds Wilkins Bluehole. The map in Figure 16 shows the spring's location and associated tracer data.

Graham Spring KW was found to be partially supporting for PCR. Only two of the six samples collected and analyzed for *E. Coli* were over the allowable limit of 240 CFU/100 mL. Graham Spring KW was listed as partially supporting for WAH as well. Partial impairment was found for iron becasue two out of twelve (17 %) sample results were over the chronic standard (Figure 17). In addition, nutrient concentrations were found to be degrading water quality. Nitrate (as N) concentrations were over the allowable limit in all twelve samples. Total organic carbon levels were found over the allowable limit in eight of twelve samples (KDOW, 2008).

Head of Rough River Spring is located in Hardin County in the northwestern portion of the Howe Valley 7.5-minute Quadrangle and appears on the USGS topographic and geologic maps. The spring discharges from the Ste. Genevieve Limestone through talus located near the head of a pocket valley. An overflow spring discharges from a low cave approximately 50 feet to the north of the main spring at the head of the same pocket valley. As indicated by its name, this spring forms the head of the Rough River. Base flow at this spring has been measured at 4.0 ft^3/s. Tracer data show that this spring has a groundwater basin area of 17.7 mi^2 (Mull and others, 1990 and Crawford, 1998). Figure 18 contains photographs of both springs. Figure 19 is a map showing the spring location and tracer data.

Head of Rough River Spring was found to be non-supporting for PCR. Five out of six samples collected and analyzed for *E. Coli* were over the allowable limit of 240 CFU/100 mL. This spring was listed as partially supporting for WAH. Partial impairment was found for iron because two out of twelve (17 %) sample results were over the chronic standard (Figure 20). Further water quality degradation was noted from nutrients. All twelve samples analyzed for nitrate (as N) were found to have concentrations over the allowable limit. Additionally, total organic carbon levels in three of the twelve samples were over the allowable limit. One sample of twelve for total nitrogen was too high (KDOW, 2008).

Lost River Rise is located in Warren County in the northwestern portion of the Bowling Green South 7.5-minute Quadrangle, but is not mapped on the USGS topographic or geologic maps. This spring discharges from an opening approximately 20 feet wide, beneath a low bluff formed in the Ste. Genevieve Limestone. It is the ultimate resurgence of the Lost River Cave Valley karst system that begins several miles south of Bowling Green, KY and flows underneath a portion of the city. The Lost River Bluehole emerges within the city and flows into Lost River Cave, where visitors can purchase a boat ride through a section of the cave (this is a privately-owned attraction). The spring run for Lost River Rise flows about 750 feet to its confluence with Jennings Creek. Tracer data show that Lost River Rise drains an area of 58.8 mi^2 and discharge measurements indicate a base flow of 12.4 ft^3/s (Ray and Currens, 2000). Ray and Currens (2000) cite numerous published and unpublished works contributing to mapping of the Lost

River karst system, which include: George, 1973; Arruda, 1985; Groves, 1985; Bearden, 1993; and Crawford, 1985, 1997, 1997a and 1999. Figure 21 is a photograph of this spring. A map showing the spring's location and tracer data can be found in Figure 22.

Lost River Rise was determined to be non-supporting for PCR. Five out of six samples collected and analyzed for *E. Coli* were over the allowable limit of 240 CFU/100 mL. However, this spring was found to be fully supporting for WAH. Figure 23 is the water quality assessment checklist for this spring.

Mahurin Spring is located in Grayson County in the south-central portion of the Falls of Rough 7.5-minute Quadrangle, but is not mapped on the USGS topographic or geologic maps. Mahurin Spring issues from an opening approximately 25 feet wide by a few feet high located beneath a limestone bluff. Although we have listed the geologic formation as the Ste. Genevieve Limestone, this determination is approximate as the setting is complicated by the Rough Creek Fault System and numerous geologic formations are present. The spring run flows 300 feet to its confluence with Spring Fork. Base flow at Mahurin Spring is 2.1 ft^3/s, but this figure is based on a limited number of measurements. Tracer data show that this spring drains an area of 25.3 mi^2 (Quinlan, 1986a). Figure 24 shows a photograph of Mahurin Spring. The spring's location and tracer data are presented on the map in Figure 25.

Mahurin Spring was found to be non-supporting for PCR. Three out of six samples collected and analyzed for *E. Coli* were over the allowable limit of 240 CFU/100 mL. This spring was found to be fully supporting for WAH (Figure 26).

McCoy Bluehole is located in Hart County in the northeastern corner of the Mammoth Cave 7.5-minute Quadrangle, but is not mapped on the USGS topographic or geologic maps. McCoy Bluehole discharges from a near-vertical conduit in the Ste. Genevieve Limestone, forming a large pool at the base of a cliff. The spring flows a short distance to the Green River. Base flow at McCoy Bluehole has been measured at 12.7 ft^3/s and tracer data show that its groundwater basin is 34.1 mi^2 (Quinlan and Rowe, 1977). A photograph of the spring is shown in Figure 27. The spring's location and tracer data are shown on the map in Figure 28.

McCoy Bluehole was determined to be non-supporting for PCR. This was because three of six samples collected and analyzed for *E. Coli* were over the allowable limit of 240 CFU/100 mL. This spring was found to be fully supporting for WAH (Figure 29).

Mill Spring is located in Grayson County in the south-central portion of the Millerstown 7.5-minute Quadrangle and is mapped on the USGS topographic and geologic maps. This spring discharges from a large conduit in the Reelsville Limestone at the base of a bluff located at the head of a small pocket valley. The spring flows into the Nolin River where it has been impounded by the Nolin Reservoir. A limited number of measurements place this spring's base flow at about 3.0 ft^3/s. Tracer data, derived by this study, show that this spring has a groundwater basin area of approximately 7.1 mi^2. Figure 30 shows a photograph of this spring. Figure 31 shows the spring's location and associated tracer data.

Mill spring was found to be non-supporting for PCR. This was because three of six samples collected and analyzed for *E. Coli* were over the allowable limit of 240 CFU/100 mL. This spring was determined to be fully supporting for WAH. Figure 32 shows the water quality assessment checklist for Mill Spring.

Nolynn Spring is located in Larue County in the east-central portion of the Tonieville 7.5-minute Quadrangle, but is not mapped on the USGS topographic or geologic maps. The main discharge from Nolynn Spring issues from a conduit formed in the St. Louis Limestone, but there is also a small bluehole discharge approximately 75 feet down the spring run. A photograph of this spring is shown in Figure 33. This spring discharges almost directly into the North Fork of the Nolin River. Tracer data from this study (Figure 34) show that just over half of the spring's base flow is derived from a subterranean cutoff of the North Fork of the Nolin River about 3 miles upstream of the spring. This spring has a groundwater basin area of 56.4 mi^2 and its base flow is 4.6 ft^3/s. Nolynn Spring is the former water supply for Hodgenville, but its use was reportedly abandoned due to contamination from a sewage treatment plant upstream of the sink point in the North Fork.

Nolynn Spring was determined to be non-supporting for PCR. Five of six samples collected and analyzed for *E. Coli* were over the allowable limit of 240 CFU/100 mL. This spring was found to be partially supporting for WAH (Figure 35). Impairments to water quality were due to nutrients. In particular, nitrate (as N) was found above the allowable limit in all twelve samples. Additionally, total organic carbon was over the allowable limit in three of twelve samples (KDOW, 2008).

Skees Karst Window (KW) #1 is located in Hardin County in the westcentral portion of the Sonora 7.5-minute Quadrangle and appears on the USGS topographic and geologic maps. Photographs of Skees KW #1 are presented in Figure 36. Tracer tests (Figure 37) confirmed that Skees KW #1 drains to Waddell Spring approximately 2700 feet to the west (Crawford and Dotson, 1989). This spring is called *St. Ignatius Spring* on the USGS 7.5-minute Summit Topographic Quadrangle and is labeled simply as *Spring* on the USGS 7.5 Minute Summit Geologic Quadrangle (Moore, 1964). Skees KW #1 was chosen as the monitoring point for this groundwater basin due to access permission and owner participation. Please note that the spring labeled as "Skees Spring" on the USGS maps in Figure 37 is not this site and, in fact, no spring actually exists at that location. The two unnamed springs mapped by the USGS just to the east of State Road 1823 are Skees KW #1 (eastern) and Skees KW #2 (western). Skees KW #1 discharges from a large conduit beneath an outcrop of the Ste. Genevieve Limestone in a large depression. Water flows across the bottom of the depression approximately 150 feet to the swallet at the far end. The ultimate resurgence of this karst system at Waddell Spring drains to the Nolin River. Waddell Spring has a groundwater basin of 27.5 mi^2 and its base flow is 6.4 ft^3/s.

Skees KW #1 was determined to be non-supporting for PCR. Five of six samples collected and analyzed for *E. Coli* were over the allowable limit of 240 CFU/100 mL. This spring was found to be partially supporting for WAH (Figure 38). Impairment to water quality was due to nutrients. Nitrate (as

N) was found over the allowable limit in all twelve samples. Total organic carbon was over the allowable limit in three of twelve samples (KDOW, 2008).

MACROINVERTIBRATE COMMUNITY EVALUATION

Introduction

Karst springs constitute unique freshwater ecosystems providing an interface between hypogean (surface water) and epigean (subterranean) habitats (Smith and others, 2003). As previously noted, surface water and groundwater in these areas are conjunctive systems where surface water runoff acts to recharge karst aquifers and springs maintain stream base flow. In karst regions extensive, well-developed subsurface drainage and the associated lack of surface drainage prohibit assessment with current surface water methodology. New methodologies integrating surface water monitoring protocols into groundwater monitoring programs must be developed.

Macroinvertebrates are an important biological assemblage utilized for surface water monitoring, and are studied in order to document distinct changes in community structure in response to both macro- and micro-scale environmental perturbations (Pond and others, 2003). Springs are known to contain macroinvertebrate assemblages that exhibit much of the structural and functional properties present in neighboring surface waters (Smith and others, 2003); thus development of a methodology for assessing these communities is practical. However, karst spring macroinvertebrate communities are known to differ with regard to taxa, diversity and abundance. Therefore, preliminary study of these springs is important to elucidate potential patterns of community assembly so as to design future large-scale studies, and ultimately develop methodology and macroinvertebrate indices for groundwater quality assessment in karst areas.

In summer 2006, a pilot study involving four of the study area springs was conducted to evaluate the feasibility of using aquatic macroinvertebrates for bioassessment. In particular, samples were collected from Goodman Springs, Nolynn Spring, Mill Spring and Skees KW #1; all four springs drain to the Nolin River (Figure 39), a tributary of Green River. This was part of an assessment aimed at integrating surface water monitoring protocols into groundwater monitoring programs. The goals of this pilot study were to: 1) determine patterns of macroinvertebrate community structure at differing spring locations; 2) detect differences in spring physiochemical parameters; and 3) explore potential relationships between macroinvertebrate community structure and measured physiochemical parameters to identify potential classification schemes and stressor gradients for future study design.

Methods

Macroinvertebrate Communities

Macroinvertebrates were collected using three Hester-Dendy samplers secured to concrete blocks and deployed at each spring for approximately six weeks (8 June through 21 July 2006). The Hester-Dendy samplers were retrieved and their contents were stored in 95% ethanol. Upon return to the laboratory, samples were replenished with a 70% ethanol solution for storage. Macroinvertebrates were identified to the lowest practical taxonomic unit, such as genus/species when possible (following sources of Merritt and Cummins 1996, Taylor and Schuster 2004, Needham and others 2006, Thorp and Covich 2001, Epler 2001, Brigham and others 1982, Stewart and Stark 1993 and others), and enumerated. Community metrics - i.e., abundance, modified %Ephemeroptera, Plecoptera and Trichoptera (m%EPT), %Chironomids, %Ephemeroptera, and the Hilsenhoff Biotic Index (HBI) - commonly used for surface water assessments - were calculated to characterize communities.

Physiochemical and Water Chemistry Parameters

Physicochemical parameters (temperature, conductivity, and pH) were collected using a multiparameter probe when Hester-Dendy samplers were deployed (8 June) and when they were retrieved (21 July) (KDOW 2009a). Water chemistry (i.e. nutrients, metals, pesticides, bulk parameters and alkalinity/acidity) was assessed once per month for the year by collecting grab samples to quantify analyte concentration (KDOW 2009b).

Data Analysis

Macroinvertebrate community metrics, physicochemical and water chemistry parameters were analyzed using a one-factorial ANOVA (SYSTAT 12, Systat Incorporated, Chicago, IL) to determine differences between means. Results are reported as significant at $P < 0.10$ due to the limited number of sample sites and replicates. All data were tested for normality using Shapiro-Wilk test of normality and non-normal data were log-transformed (ln). All figures show data as raw values, though p-values are based on log-transformations if required. Tukey's Honestly Significant Difference (HSD) was used for select pairwise comparisons of springs

Detrended Correspondence Analysis (DCA) (MVSP, Kovach Computing Services, UK) was used to assess potential differences in macroinvertebrate community structure. Spring community groupings were assessed to determine whether spring macroinvertebrate communities clustered independently of one another in space.

Correlation analysis (Proc CORR, SAS 9.1, SAS Institute, Cary, NC, USA) was used to determine potential relationships between biotic and abiotic variables. Redundant variables were eliminated to reduce the number of variables entered into multiple regression models. Multiple regression analysis (Proc REG-Stepwise, SAS 9.1) was used solely as a means to explore potential relationships between physicochemical and water chemistry parameters and macroinvertebrate community metrics. Predictor variables allowed to enter the models were significant at $P \leq 0.05$. Relationships identified in the multiple regression analyses as significant and accounting for the majority of variation explaining a metric were further analyzed using ordinary least squares (OLS) and robust regression (SYSTAT 12, Systat Incorporated, Chicago, IL). Good relationships identified using OLS and robust regression were considered significant at $P \leq 0.10$.

Results

Macroinvertebrate Community Analysis

A total of 1,348 aquatic macroinvertebrates from 30 genus/species level taxa were collected from these four springs during summer 2006; 78 from Goodman Springs, 175 from Mill Spring, 225 from Nolynn Spring and 870 from Skees KW #1. These are summarized as the mean number of individuals per plate, percent relative abundance and coefficient of variation in the table presented in Figure 40. Goodman, Mill and Nolynn springs and Skees KW #1 contained 15, 15, 18 and 6 taxa, respectively.

Both a Sørenson Similarity Index (Figure 41) and DCA (Figure 42) showed potential macroinvertebrate communities at each spring with variation in community structure attributed to differences in various macroinvertebrate metrics. Several important community metrics were significantly different ($p < 0.10$) or showed distinctive patterns of difference, as shown in Figures 43 through 47. Skees KW #1 had significantly greater macroinvertebrate abundance than each Goodman, Mill and Nolynn springs (d.f. 3,8; F= 42; P=0.000) (Figure 43). In contrast, though not significant, the other three springs had a pattern of higher taxa richness than Skees KW #1 (d.f. 3,8; F= 1.9; P=0.204) (Figure 44). Both %EPT (d.f. 3,8; F= 3.7; P=0.061) (Figure 45) and %Ephemeroptera (d.f. 3,8; F= 4.03; P=0.051) (Figure 46) were significantly higher at Nolynn Spring than Mill Spring. Patterns of Nolynn Spring had greater percentages for both metrics than all other springs. Lastly, %Chironomids was significantly different, where Goodman > Mill > Nolynn > Skees (d.f. 3,8; F= 3.7; P=0.085) (Figure 47).

Physicochemical Parameter Analysis

A number of physicochemical variables measured at the spring locations showed quantitative patterns of interest (Table 5). Average temperature (°C) at the springs was 13.5°C, with less than 2°C variation at Skees KW #1, less than 6°C variation at Goodman and Mill springs and greater than 10°C variation at Nolynn Spring.

Spring Name	**Base flow (ft^3/s)**	**Basin Area (mi^2)**	**Temperature (°C)**		
			Mean	**Maximum**	**Minimum**
Goodman Springs	4.6	14.7	13.89	16.20	11.40
Nolynn Spring	4.6	56.4	14.00	18.70	8.20
Mill Spring	3.0	7.1	13.11	15.90	9.20
Skees KW #1	6.4	27.5	13.73	14.30	12.70

Table 5. Base Flow, Basin Area and Mean, Maximum and Minimum Water Temperatures at Evaluated Springs.

Water chemistry parameters assessed at the springs show differences that may characterize the springs' baseline concentrations or indicate anthropogenic inputs. Alkalinity differed significantly at all springs, with Goodman>Skees>Mill> Nolynn. Both total dissolved solids (TDS) and total suspended solids (TSS) showed significant differences, with TDS higher at Goodman Springs than at Nolynn and Mill springs. TSS was higher at Nolynn Spring than Mill Spring (Table 6). Two distinct gradients were apparent with regard to nitrate (as N) (mg/L) and total phosphorous (mg/L). Nitrate (as N) concentration differed statistically between all springs, with Skees>Nolynn>Goodman>Mill (Table 6). Total phosphorous did not differ significantly in this study; however, a gradient was apparent across springs.

Spring Name	Alkalinity	Nitrate (as N)	Total Phosphorus	TDS	TSS	TKN
Goodman Springs	216.92	1.95	0.0784	272.83	12.08	0.4399
Nolynn Spring	158.58	3.02	0.0737	215.00	18.54	0.4625
Mill Spring	117.22	0.66	0.0589	218.83	7.54	0.4728
Skees KW #1	192.00	3.62	0.0850	254.67	8.75	0.5143

Table 6. Mean water chemistry concentrations (mg/L) for evaluated springs.

Regression Analysis

Several relationships were apparent between physicochemical and chemical parameters, and macroinvertebrate community metrics. Although some relationships were not significant at the $p \leq 0.10$, they are presented here as patterns of interest.

Base flow had a significant relationship with each macroinvertebrate abundance ($p \leq 0.071$, R^2=0.89) (Figure 48), taxa richness ($p \leq 0.057$, R^2=-0.93) (Figure 49) and %Chironomids ($p \leq 0.081$, R^2=-0.90) (Figure 50). Base flow had negative relationships with both taxa richness and %Chironomids, but had a positive relationship with macroinvertebrate abundance.

Relationships were also apparent between nitrogen parameters and macroinvertebrate abundance, taxa richness and %Chironomids. Total kjeldahl nitrogen (TKN) was a positive predictor of macroinvertebrate abundance ($p \leq 0.056$, R^2=0.93) (Figure 51), while both taxa richness ($p \leq 0.011$, R^2=-0.89) (Figure 52) and %Chironomids ($p \leq 0.134$, R^2=-0.69) (Figure 53) had negative relationships with nitrate (as N) concentration. Total Phosphorous concentration had strong predictive relationships with taxa richness, %Chironomids and Hilsenhoff Biotic Index (HBI) scores. These relationships were negative with regards to taxa richness ($p \leq 0.185$, R^2=-0.69) (Figure 54) and %Chironomids ($p \leq 0.307$, R^2=-0.68) (Figure 55), and positive concerning Hilsenhoff Biotic Index (HBI) scores ($p \leq 0.201$, R^2=0.86) (Figure 56).

Discussion of Macroinvertebrate Community Evaluation

Approximately 50% of Kentucky is underlain by rocks with some degree of karst development. The influence of karst drainage can lead to large areas lacking significant surface streams and groundwater flow that deviates from topographic hydrologic boundaries. This geologic characteristic adds complexity for water quality investigations since pollutants may originate over broad areas and in multiple watersheds, yet manifest in a single receiving watershed. Conversely, pollutants may originate over broad areas in one watershed and be delivered to multiple watersheds. Therefore it is important for water quality managers to identify the recharge areas and discharge points of karst systems and to monitor water quality in these areas. However, methodology for biological assessment in springs is lacking and must be developed due to contrasts between spring habitats and associated surface water habitats for which protocols have been developed.

In this study, KDOW addressed the potential efficacy of utilizing aquatic macroinvertebrates for bioassessment purposes by sampling physicochemical and macroinvertebrate community parameters at four large springs in the Green River basin. Results indicate that future expanded studies examining macroinvertebrate communities may yield data reliable for the biological assessment of karst spring use support.

The composition of macroinvertebrate communities in karst springs is known to be shaped by state factors such as topography, geology, abiotic and biotic factors and climate (Mori and Brancelj, 2006; Smith and others, 2003; Gaskin and Bass, 2000). In addition, these communities can be directly and indirectly influenced by anthropogenic disturbances resulting from point and nonpoint source pollution. Each factor contributes to the potential for significant variation of macroinvertebrate community structure displayed by differences in community demographics. KDOW found unique macroinvertebrate communities at each of the four springs sampled in this study. This is illustrated by distinct separation of communities in the detrended correspondence analysis (Figure 42) and low percent community similarity (Figure 41). This was supported by significant differences in individual macroinvertebrate community metrics (Figures 43, 44, 45, 46 and 47) that compose Kentucky's Macroinvertebrate Biotic Index (MBI).

One explanation for macroinvertebrate community differences at the springs is that all spring communities differ naturally due to variations in chemical and physical heterogeneity, availability of colonization sources and past geologic events. Idiosyncratic community assemblage would make development of biotic indices for water quality assessment difficult, if not impossible, if comparison of spring communities spanning a disturbance gradient were not attainable. Although distributional and community structure anomalies do occur, most ecosystems are governed by state factors (e.g. geology, climate, topography) providing resources conducive to distinct patterns of community assembly. The main issues deterring acceptance of this explanation is the small sample size collected for representation of Kentucky's karst springs and the lack of other pertinent variables (e.g. habitat) not measured in this study. Lack of relevant data prohibits conclusive inferences until future sampling occurs where a logical sample design is established that accounts for potential classification schemes (e.g. subecoregion, flow permanence, habitat) and increases the sample size for a more robust and reliable analysis.

A second explanation for the community differences is that the springs sampled were representative of a suite of stratifying factors shaping macroinvertebrate communities in the sample area. The four springs sampled represent two different spring types; i.e., groundwater basin – Goodman Springs, Mill Spring, Skees KW #1 and stream cutoff – Nolynn Spring. Also, the range and spectrum of drainage area sizes, base flows and temperature regimes likely influence the communities.

Strong predictive relationships were observed between base flow and individual community metrics in this study (Figures 48, 49 and 50). All springs exhibited distinct patterns of placement for given metrics along a base flow gradient. The springs with lower base flows (Goodman, Mill and Nolynn) tended to have lower abundance and higher richness and %Chironomids than Skees KW #1, which has the highest base flow of these four. Similar studies (Smith and others, 2003) have found strong relationships between macroinvertebrate community assemblages and flow permanence in spring ecosystems. They documented greater abundance of macroinvertebrates at perennial springs with higher discharge. Conversely, they found a higher occurrence of common, ubiquitous, opportunistic early colonizers at springs with lower and/or intermittent flow, which is similar to our findings.

Temperature regime in spring ecosystems may also serve as a useful classification scheme for spring macroinvertebrate communities. Temperature is known to provide a stable environment for aquatic organisms with obligate temperature requirements such as glacial relicts, therefore it is feasible to account for this influence in spring systems. Though few statistical relationships were observed for temperature in this study, there was a pattern of variation among springs (Table 5). Skees KW #1, which has the highest base flow, showed the lowest temperature maximum (14.3°C), while Goodman, Mill and Nolynn springs had maximum temperatures of 16.2°C, 15.9°C and 18.7°C, respectively, throughout the study period. Springs with higher temperature maximums had higher richness and %Chironomids, favoring early colonizer and opportunistic taxa. In addition, Skees KW #1, Mill Spring and Goodman Springs contained a community dominant (*Gammarus bousfeldi*) known as a glacial relict. *Gammarus bousfeldi* composed 86% of the community at Skees KW #1, 42% at Goodman Springs, 33% at Mill Spring and 3% at Nolynn Spring (Figure 40). Further analysis revealed a significant negative correlation ($p \leq 0.049$, R^2=-0.94) between temperature maximum and percent community composition of *Gammarus bousfeldi*. These findings emphasize the importance of accounting for temperature regime in future biological investigations of spring ecosystems.

Ecoregion classification may also serve to organize karst spring macroinvertebrate communities into interpretable units for biological assessment. The concept of establishing aquatic ecoregions is based on similarities observed among streams in watersheds with similar characteristics (e.g. geology, drainage, vegetation, and climate) (Omernik, 1987). Streams draining watersheds of similar size, land use, ecological assembly and located in similar regions (e.g. mountains, coast) are likely to contain similar aquatic communities (Hughes and others, 1986). In this study, springs were primarily sampled in the Level III Ecoregion 72 known as the Interior River Valley and Hills (Omernik, 1987). Because of distinct separation of macroinvertebrate communities according to bioregion, ecoregion and river basin during development of the Kentucky Macroinvertebrate Biotic Index (MBI) (Pond and others, 2003), it is reasonable to assume that karst spring macroinvertebrate communities may assemble similarly. Therefore, it would benefit future karst spring studies to incorporate this concept into sampling designs with the overall goal to test the dataset for classification according to these principles.

Stressor identification and understanding benthic responses to these stressors is critical to justifying cause and source listings for aquatic resource use support determinations. Chemical (e.g. nutrients, metals, pesticides), physical (e.g. habitat, hydrologic) and climatic factors have been documented as having adverse impacts to aquatic communities when disturbed by anthropogenic activities. Most aquatic systems suffer cumulative and interactive effects caused by multiple stressors that make identification and remediation of perturbations challenging.

Nutrient enrichment is well known as a common and widespread stressor to aquatic ecosystems. In this study, the nutrient analytes evaluated had significant correlations (Figures 51, 52, 53, 54 and 55) with macroinvertebrate community metrics. These relationships may well be indicating responses of aquatic communities to cultural disturbance. Pond and others (2003) showed that the Kentucky MBI and individual metrics that compose it were reliable in distinguishing disturbance caused by the singular and interactive effects of phosphorous and nitrogen.

In individual ANOVA analyses, nitrate (as N) and total phosphorous showed distinct gradients among springs. Though significant differences between springs were not detected for total phosphorous, all data reported exceed previously recommended concentrations of phosphorous in both lotic and lentic systems (EPA, 1986). EPA (1986) reported harmful algal blooms at phosphorous concentrations $\geq$25 µg/L in lakes and reservoirs and recommended no streams entering lakes exceed 50 µg/L. Similarly, EPA (1986) proposed that nitrate levels not exceed 0.06 mg/L for protection of coldwater salmonids. Nitrate (as N) levels at all springs were elevated above background conditions and most were an order of magnitude (up to 60X) greater than EPA's proposed nitrate levels for protection of salmonids (EPA, 1986).

Stressor identification is critical for proper listing of causes and sources of impairment and effective remediation. Development of an index without understanding organism responses to stressors would not allow for proper use-support determination, thereby undermining bioassessment efforts and requiring inefficient investment of resources to determine use-support. Proper stressor testing ensures a reliable use-support decision for Clean Water Act (CWA) Section 305 (b) and 303 (d) reporting.

Development of bioassessment tools for determination of ecological condition is critical, whether managing freshwater, terrestrial or marine resources. Kentucky's karst terranes provide a unique background for development of bioassessment tools to enable resource managers and technical staff to make accurate determinations of water quality in those areas. As much of Kentucky's landmass is influenced by karst drainage, it is important to develop assessment tools that will allow for protection, conservation and restoration of freshwater resources. Because many springs may encompass unique benthic communities, it is possible that development of tools to assess these resources would be futile; however, it is important to delegate the resources for an expanded study in Kentucky's karst regions to make this determination.

This study provides a cursory evaluation of Kentucky spring benthic communities that are influenced by karst hydrogeology. The results indicate the feasibility of conducting an expanded study. Future studies will require increased sample size for better confidence, site selections that account for stratifying influences (i.e., bioregion, ecoregion, sub-ecoregion, base flow, temperature), and stressor testing that indicates the response of aquatic organisms to specific stressors to ensure accurate identification of causes and sources of impairment. Because karst hydrogeology imparts significant influence on many of Kentucky's aquatic resources, it is imperative that management allocate the appropriate resources to developing tools that monitor the status of these resources for human health, protection of the environment and stewardship of these resources for future generations.

TRACER TEST RESULTS

Of the 19 groundwater tracer tests conducted for this study, 16 were successfully recovered in 8 springs, for an 84% success rate. The assumed reason for lost dyes in two tests was the use of marginal dye injection locations such as dry sinkholes. In one case tracer dye was flushed into a sinkhole using the owner's well water and in a second case, a dry-set of solidified powder dye was deployed in a remote sinkhole. These sinkhole dye injection locations were assumed to be more risky than stream swallet injections, but were tested because of the need for delineating upland groundwater divides. A third test was recovered below the criterion of 4X the background level. However, because of the type of dye used and the fact that its sub-criterion detection occurred during two successive exchanges, this recovery is considered tentatively positive. Considering positive recoveries in 17 tests, the success rate for these tests would be 90%. These results are summarized in Table 4.

A unique four-digit identification number is provided for each spring referenced in this study. This number is derived from the Kentucky DOW's Consolidated Groundwater Database ID system. For example, Nolynn Spring (ID # 9000-**2673**) is identified simply as Nolynn (2673).

Brief descriptions of these eight basin discharge springs are given below with dye trace data, basic measurements, and figures showing digital photographs and maps. Figure 4 is a legend for the tracer data illustrated on these basin maps. Non-recovered dye injections are described under the spring to which they are hypothesized to drain. In the descriptions below, reference to an *unmapped spring* means the spring does not appear on published topographic or geologic maps. In the case of testing in the vicinity of Mill Spring, an *unmapped spring* may be inundated and obscured by the Nolin River Reservoir.

Description of Springs and Basins, with Summary of Tracer Tests

Nolynn (2673)

Nolynn Spring is located in the east-central portion of the Tonieville Quadrangle, but is unmapped on the U.S. Geologic Survey's 1:24,000 topographic or geologic maps. It discharges at about 700 ft elevation [N37.559436°/W085.788019°] through a short spring run to the north side of North Fork Nolin River, just upstream of the KY 222 bridge. Discharging from the St. Louis Limestone (Moore, 1966), Nolynn Spring is primarily a free-draining gravity spring issuing from a large bank cavity. However, an auxiliary rising spring occurs about 75 ft downstream on the right bank of the spring run. Figure 33 shows the main gravity spring. During low-flow conditions, Nolynn Spring functions as the head of North Fork Nolin River, because of a lack of flow from upstream. As described below in dye trace 06-07, the reason for the dry reach of North Fork Nolin River is an upstream subterranean cutoff route that diverts most of the stream's base flow through the subsurface to Nolynn Spring.

On 10/3/2007 a beaver dam was located about 1000 ft below the spring on the North Fork Nolin River, making the spring run too deep to be easily gaged. Therefore, Nolynn Spring's discharge was measured by DOW at a section in the river channel below the beaver dam at 4.1 ft^3/s.

Previous measurements of Nolynn Spring include 1.9 ft^3/s from Hydrologic Atlas 33 (Brown and Lambert, 1963). Lambert (1979) also reports ten discharge measurements for Nolynn Spring from 1955 through 1973, ranging from 0.58-37.0 ft^3/s. Also, the lowest average discharges of Nolynn Spring for 7 consecutive days for 2-, 10-, and 20-year recurrence intervals were calculated at 4.4, 3.6, and 3.4 ft^3/s. Based on these calculations, the recent 2007 measurement approximates a 7Q-5 estimate, or the lowest average discharge for 7 consecutive days over a five-year period.

A water-supply pump station was previously established at Nolynn Spring by the city of Hodgenville. The concrete structure is located on the right bank, near the mouth of the spring run, where an 8-inch diameter steel pipe traverses the spring channel. However, according to an adjacent landowner, the pump station was never operated for more than one day. Lambert (1979, p. 78) stated the following: *The North Fork Nolin River sinks below Hodgenville, and its water may appear again as part of the flow of Nolynn Spring used by the city when the flow of the river is insufficient. It is possible that sewage recycling may occur at the spring. A dye-travel study could confirm or disprove this hypothesis.* Perhaps the possibility of “sewage recycling” from the Hodgenville wastewater treatment plant altered the city’s plans to withdraw water from Nolynn Spring.

Lambert also describes additional sinking streams in the area: *At low flows the water in Castleman Creek above Hodgenville and Middle Creek above Tonieville sinks in a fault zone. It is uncertain where the water from Middle Creek emerges; but water from Castleman Creek may emerge as part of the flow of Nolynn Spring, Big Spring, or Heady Spring. Dye tracing could determine which of these springs, if any, is involved.* The current dye-trace project tested all three of these losing streams in order to map the watersheds of Nolynn and other springs in the vicinity. “Big Spring,” herein called Cemetery Big Spring, and “Heady Spring,” herein called Heady Big Spring, were also monitored for dye during these tests. Because direct access to Heady Big Spring was denied by the owner, this spring was monitored indirectly by bracketing Middle Creek above and below the spring at the KY 222 bridge.

Dye Test **06-06**

April 4, 2006: During moderate flow conditions, 15 oz of SRB were injected into **Berry Swallet** [N37.608107°/W085.736014°], the primary losing point of Castleman Creek, 4.5 mi northeast of Nolynn Spring. The swallet was accepting all stream flow, which was about 2 ft^3/s. Five spring and stream sites along the North Fork Nolin River and Middle Creek were monitored over two weeks. Within six days, on the first dye receptor exchange (4/10/06), Nolynn Spring was very positive for SRB (++). Cemetery Big Spring and the two Middle Creek sites were negative. An inconclusive detection of SRB (?) was recorded at North Fork of Nolin River above Nolynn Spring, at about 2.5x background. Eight days later (4/18/06) all sites were negative for SRB (consecutive positives are preferable at a dye recovery site, however, this single very positive recovery is accepted, considering the conditions of this test). The entire dye slug had traveled at least 4.5 mi and exited the system in less than six days. This test confirms Lambert's hypothesis that Castleman Creek drains to Nolynn Spring and proves that it is not connected to Cemetery Big and Heady Big springs. The inconclusive dye recovery at North Fork of Nolin River above Nolynn Spring tentatively suggests some distributary leakage upstream of the spring.

06-07

April 4, 2006: During moderate flow conditions, 5 oz of eosine dye were injected into **North Fork Nolin River Swallet** [N37.57687°/W085.75745°], 2.1 mi east-northeast of Nolynn Spring. Approximately 4 ft^3/s of flow was sinking into a bluff along the right bank, at a sharp curve in the river. Within six days, on the first dye receptor exchange (4/10/06), Nolynn Spring was very positive for eosine (++). All other monitoring points, as described above, were negative on this date. Eight days later (4/18/06) all sites were negative for eosine. The entire dye slug had traveled at least 2.1 mi through a subterranean cutoff of North Fork Nolin River and exited the system through Nolynn Spring in less than six days. This dye test confirms Lambert's hypothesis that the sink of North Fork Nolin River below Hodgenville reappears as part of the flow of Nolynn Spring. Had the city of Hodgenville utilized Nolynn Spring as a water supply, part of the city's treated sewage effluent would have been recycled because of the losing stream diversion to Nolynn Spring.

06-08

April 10, 2006: During low flow conditions, 9 oz of uranine (fluorescein) were injected at **Gardner Swallet** [N37.62767°/W085.74785°], a minor sinking stream, 5.2 mi to the north-northeast of Nolynn Spring. This swallet is located on the border of the local sinkhole plain, between the headwaters of Castleman and Middle creeks. Its elevation is 85 ft higher than Nolynn Spring. In addition to the dye monitoring locations described above, Mini-boils Spring, located within the floodplain of Middle Creek, about 0.3 mi north of Cemetery Big Spring, was also monitored.

Eight days later on the first dye receptor exchange (4/18/06), Nolynn Spring was very positive for uranine (++) and North Fork Nolin River above Nolynn Spring was inconclusive at about 2.5x background. All other monitoring sites were negative for uranine. Nolynn Spring was positive (+) on the following two dye receptor exchanges (4/24/06 & 5/5/06), and was inconclusive on the following six exchanges through 6/28/06. This tributary sinking stream probably joins the major conduit flow route formed by the Castleman Creek losing system. Also, the inconclusive uranine recovery in North Fork Nolin River above Nolynn Spring reinforces the previous inconclusive SRB recovery above Nolynn Spring. The minor distributary leakage above Nolynn Spring is confirmed by two different dyes following the same path. However, the leakage must rise beneath a deep pool in the river channel where a spring is not observable.

06-09

April 18, 2006: During moderate flow conditions, 16 oz of eosine were injected at **Middle Creek Swallet** [N37.64118°/W085.77069°], within a major losing stream reach 5.75 mi north-northeast of

Nolynn Spring. This losing reach is located about 0.6 mi upstream of a mapped fault that crosses Middle Creek (Kepferle, 1966). About 2 ft^3/s of stream flow was sinking into the left bank at several locations, about 50 ft higher in elevation than Nolynn Spring.

Six days later, on the first dye receptor exchange (4/24/06), Nolynn Spring was very positive for eosine (++), and was inconclusive on the following two exchanges (5/5/06 & 5/9/06). The bulk of the dye slug traveled at least 5.8 mi in less than six days. Five other monitoring sites, described above, were all negative during the test except for a minimal detection of eosine on the first exchange at Cemetery Big Spring. Because this detection is not significantly higher than the background, it cannot be considered a tentative dye recovery. This occurrence might be attributable to minor dye contamination during handling or processing of the dye receptor.

These successful groundwater tracer tests illustrate that all three major losing streams in the vicinity, which were identified by Lambert (1979), contribute to the Nolynn Spring groundwater basin. Likewise, most of the sinkhole plain northwest of Hodgenville in the vicinity of the mapped flow routes also drains to Nolynn Spring. Including the sub-basins of the losing streams, the entire estimated basin area is 56 mi^2 (Figure 34). Figure 34a is a map zoomed in on the tracer data to better illustrate the relationships between dye injection points and springs. Note that dashed blue overflow arrows are shown downstream of the losing stream sinkpoints on this map. This indicates that stream flow in excess of the respective swallet capacities continues downstream, by-passing the groundwater basin.

Heady Big (1843)

Heady Big Spring is located in the north-central portion of the Tonieville Quadrangle, but is unmapped on the U.S. Geologic Survey's 1:24,000 topographic or geologic maps. It discharges at about 669 ft elevation [N37.574689°/W085.819524°] through a 650-ft long spring run to the east side of Middle Creek, about 0.3 mi upstream of the KY 222 bridge. Discharging from the St. Louis Limestone (Moore, 1966), Heady Big Spring is a bluehole spring rising within a minor pocket valley. During low-flow conditions Heady Big Spring functions as the main head of Middle Creek, exceeding the minor flow from upstream by several times.

During a drought year (9/14/99), Heady Big Spring's discharge was measured by DOW near the mouth of the spring run at 1.7 ft^3/s. Previous measurements of this spring include 0.76 ft^3/s from Hydrologic Atlas 33 (Brown and Lambert, 1963). Lambert (1979) also reports twelve additional discharge measurements for Heady Big Spring from 1970 through 1973, ranging from 1.89-20.0 ft^3/s. Also, the lowest average discharges of Heady Big Spring for 7 consecutive days for 2-, 10-, and 20-year recurrence intervals were calculated at 1.7, 1.4, and 1.4 ft^3/s. Based on these calculations, the 1999 measurement approximates a 7Q-2 estimate, or the lowest average discharge for 7 consecutive days over a two-year period.

Cemetery Big (1844)

Cemetery Big Spring is located in the north-central portion of the Tonieville Quadrangle, but is unmapped on the U.S. Geologic Survey’s 1:24,000 topographic or geologic maps. It discharges at about 667 ft elevation [N37.571033°/W085.824310°] through a 0.4 mile-long spring run to the east side of Middle Creek, about 0.4 mi downstream of the KY 222 bridge. Discharging from the St. Louis Limestone (Moore, 1966), Cemetery Big Spring is a bluehole spring rising within a broad reach of Middle Creek floodplain. Near the mouth of Middle Creek, discharge from Cemetery Big Spring joins flow from Heady Big Spring and is confluent to North Fork Nolin River near Eagle Mills.

During a drought year (9/14/99), Cemetery Big Spring's discharge was measured by DOW just below the bluehole at 1.5 ft^3/s. Previous measurements of this spring include 3.0 ft^3/s from Hydrologic Atlas 33 (Brown and Lambert, 1963). Lambert (1979) also reports additional low-flow discharge measurements for Cemetery Big Spring; one during 1955: 1.55ft^3/s and a second in 1971: 1.44 ft^3/s.

During the current tracer-testing project of springs in the vicinity of Nolynn Spring, direct access was denied by the owner of Heady Big Spring. Therefore, this spring was monitored indirectly by bracketing Middle Creek above and below the spring at the KY 222 bridge. Thus far, no positive dye recoveries had been made in the two large springs to the west: Heady Big Spring and Cemetery Big Spring. The following three tests were conducted in the sinkhole plain to estimate a divide between the Nolynn Spring basin and these two springs.

Optimal sinkhole dye injection locations are typically selected near estimated groundwater divides in order to verify those boundaries. Also, hydrologically vulnerable locations susceptible to spills, such as roadside sinks, are utilized whenever possible. A roadside feature called Parkway Sinkhole was located as the next test.

06-15

May 30, 2006: During moderate to high-flow conditions, 10 oz of eosine were injected into **Parkway Sinkhole** [N37.60388°/W085.78726°], located 2.7 mi northeast of Heady Big Spring (spring #1843) at an elevation of about 755 ft. The low point of the roadside sinkhole was filled with crushed limestone aggregate, suggesting that a soil collapse had been repaired during the last few years by the county highway department. The dye was flushed with about 400 gallons of hauled water over about an hour.

Six days later on the first dye receptor exchange, Middle Creek @ KY 222 bridge was positive for eosine (+). This site was inconclusive for eosine during the next two exchanges (6/14/06 & 6/28/06). Middle Creek above spring #1843 was only slightly above background for eosine, which suggested that a slight distributary discharge of dye west to Middle Creek occurred above spring #1843. However, the vast majority of dye must have resurfaced at Heady Big Spring (spring #1843).

Also, an inconclusive recovery of eosine at about 2.7x background was detected at Nolynn Spring. This suggests that during moderate- to high-flow conditions, a minor overflow conduit connected to the Nolynn Spring system may have been active. However, because of the 4x background criterion for a positive recovery, this connection must remain tentative. Another possible reason for the inconclusive recovery of eosine in Nolynn Spring is that a heavy rain a few days prior the Parkway Sinkhole injection may have remobilized eosine stranded during the Middle Creek Swallet injection conducted almost six weeks earlier. However, this is very unlikely.

06-16 (non-recovery)

May 31, 2006: On one of the higher hills within the sinkhole plain northwest of Hodginville, during moderate flow conditions, 16 oz of SRB were injected into **Jennings Sinkhole** at about 845 ft elevation [N37.60815°/W085.76527°]. This feature is a minor soil collapse filled with chert fragments. The land owner allowed the use of his water well and garden hose to flush dye into the sinkhole. Approximately 500 gallons of well water were used over about 2 hr. However, monitoring of the six spring and stream sites over the following month yielded no dye recovery. Apparently, too much dye was retained in the soil and weathered bedrock zone to provide an adequate connection to the monitoring points.

07-14

May 23, 2007: The last tracer test in the Nolynn Spring study area was conducted the following year at **French Sinkhole** [N37.58594°/W085.79662°]. During low-flow conditions, 6 oz of uranine were injected into a meter-wide soil collapse at the bottom of a broad, shallow depression. The collapse had been filled by the farmer with chert fragments to help stabilize the soil banks. About 200 gallons of hauled water were used to flush the dye. Five spring and stream sites were monitored for this test.

Eight days later, on the first dye receptor exchange, Middle Creek @ KY 222 bridge was very positive for uranine (++). This site was very positive for uranine (++) again on the next exchange (6/6/07). The four other monitoring sites, Middle Creek above spring #1843, Cemetery Big Spring, Nolynn Spring, and North Fork above Nolynn Spring were negative. All of the dye resurfaced at Heady Big Spring (spring #1843), which was monitored indirectly. Results of these tracer tests are presented on the map with Nolynn Spring in Figure 34 and Figure 34a.

Mill (1193)

Mill Spring is named in the south-central portion of the Millerstown Quadrangle, on both the U.S. Geologic Survey's 1:24,000 topographic and geologic maps. It discharges at about 550 ft elevation [N37.383395°/W086.075196°] through a 0.2-mile long spring run to the west side of the Nolin River, just upstream of the KY 1214 bridge east of Broad Ford. Discharging from the Reelsville Limestone (Moore, 1965), Mill Spring is primarily a horizontally-draining gravity spring issuing from below an 18-ft high bedrock bluff. An auxiliary boil occurs at the left bank, just downstream of the bluff. This flow, which is re-directed from the main orifice, yields most of the spring's discharge during base flow. Figure 30 shows the main gravity spring.

Although the spring was mis-located about 0.3 mi to the north, a previous estimate of Mill Spring's discharge was 0.7 ft^3/s from Hydrologic Atlas 33 (Brown and Lambert, 1963). The spring was first gaged by DOW at 3.0 ft^3/s on 9/15/94. A second measurement during drought conditions on 9/5/07 documented a slightly reduced discharge of 2.5 ft^3/s.

The mapped geology in the Millerstown Quadrangle (Moore, 1965) indicates faulting in the vicinity of Mill Spring, which may influence the complexity of groundwater drainage. The first dye injection attempt was in the vicinity of intersecting faults, one of which trended toward Mill Spring. Three sites in addition to Mill Spring were ultimately monitored for this trace: Barton Run @ Pearman (to ascertain if flow returned to Barton Run), Hunting Fork @ KY 1356 and Pretty Spring (to monitor for flow trending to the west).

Stream reconnaissance in the vicinity of Mill Spring was conducted on 4/11/06 to identify any potential contribution to the groundwater basin. Slab Camp Creek was surveyed and found to be losing into the Beech Creek Limestone Member, about 820 ft to the north-northwest of Mill Spring. About one third of stream flow (0.1 ft^3/s) was sinking into the south bank [N37.38557°/W86.07596°], most likely draining directly to Mill Spring. This likely flow route coincides with the interpreted regional flow route described below and was considered too obvious to require verification.

The lower half mile of Laurel Run was also surveyed where the Beach Creek Limestone Member outcrops. A flow of about 0.75 ft^3/s was found to be discharging to the Nolin River with no losses observed within the reach.

06-10

April 24, 2006: During moderate flow conditions, 3 oz of SRB were injected at **Belcher Swallet** [N37.38816°/ W086.10307°], a losing point of Barton Run, 0.16 mi south of the intersection of KY 479 and KY 1214, and 1.6 mi west-northwest of Mill Spring. At this dye injection location about 0.05 ft^3/s of flow was leaking through fractured Hardinsburg Sandstone, presumably into the subjacent Haney Limestone, leaving the channel below dry. If Mill Spring is the destination of this dye test, flow would parallel (within 0.25 mi) a mapped fault trending toward Mill Spring.

On the first exchange 8 days later (5/1/06), results were negative. On the second exchange, three days after that (5/4/06), Mill Spring was inconclusive (?) at 2.6x background, while the other three sites were negative. The third exchange on 5/9/06 was also inconclusive (?) at about 2.8x background. The following two exchanges at Mill Spring were negative for SRB.

Because this dye slug required between 8 and 11 days to travel only 1.6 mi, the conduit flow path can be considered somewhat slow or sluggish for conduit drainage (between 770 and 1100 ft/d). During longer test durations, progressively greater quantities of dye are typically lost by adsorption and degradation within the aquifer. Therefore, the two successive inconclusive detections are interpreted as a positive dye recovery, and it is concluded that an inadequate amount of SRB dye was used for this flow system.

06-11

April 24, 2006: During moderate flow conditions, 4 oz of uranine were injected at **Buzzard Ridge Swallet** [N37.42160°/W086.11008°], a headwater portion of Hunting Fork. A minor flow was sinking into a southeast-trending fracture in the stream bed, within the Glen Dean Limestone. This site was located 3.3 mi to the northwest of Mill Spring. As in the previous test, three additional sites were monitored.

Seven days later on the first exchange Pretty Spring, 2.0 mi to the south-southwest, was extremely positive for uranine (+++). A downstream location, Hunting Fork @ KY 1356, was also very positive for uranine (++), having received the drainage from Pretty Spring. Ten days later, on the second exchange, Pretty Spring was positive for uranine (+) and was inconclusive on the next four exchanges through 6/14/06. Barton Run @ Pearman was negative throughout the test. Mill Spring was negative during this test except for one inconclusive detection at 2x background on 5/11/06. This single low recovery was rejected because of the potential for uranine contamination in the settlement around Broad Ford. However, replication of this trace with a different dye is recommended to fully refute any connection to Mill Spring.

Pretty Spring is a minor gravity spring discharging through a short spring run to the north side of Hunting Fork. This spring, which is located about 0.1 mi upstream of a fault that crosses Hunting Fork, may be fault-influenced or controlled. The small size of the spring (0.05 ft^3/s) and the fact that Hunting Fork is perennial above the spring suggests that karst flow is complex in this watershed, perhaps due to the faulting. Buzzard Ridge Swallet is in the distal headwaters suggesting that the 2.0 mi flow route to Pretty Spring may be relatively isolated from additional recharge.

06-12

The headwaters of Sinking Fork, 3.1 mi north of Mill Spring, are mapped as a sinking stream recharging the Reelsville Limestone. Although a possible resurgence is mapped about 0.4 mi down-valley to the northeast on both the U.S. Geologic Survey's 1:24,000 topographic and geologic maps, this sinking stream is the most important potential recharge source for Mill Spring. Reconnaissance of the mapped spring, however, revealed the feature to consist of only a dry pond. A sinking spring (from perched Haney Limestone) was observed to disappear into a sinkhole just upsteam of the dry pond. The dry pond was apparently filled by the sinking spring prior to the development of the intercepting sinkhole. This inflow was selected as the next dye injection point. Dye monitoring locations in addition to Mill Spring were west at the Nolin River at Millersburg and north on Nosey Creek @ Bridge (at Millerstown/Mt. Zion Road).

May 1, 2006: During moderate flow conditions, 4 oz of eosine were injected at **Sharp Swallet** [N37.43236°/W086.07415°]. The estimated flow 0.05 ft^3/s was sinking into a 6-ft deep soil collapse. This site is located within the Beaver Bend & Paoli Limestones. On the first and second exchanges, three and eight days later, all three monitoring sites were negative. Ten days after injection on the third exchange (5/11/06), Mill Spring was very positive for eosine (++). Mill Spring was also positive for eosine (+) on the fourth exchange (5/17/06) and inconclusive on the fifth (5/31/06). Two weeks later (6/14/06) Mill Spring was negative. The two other sites were negative during this test and were removed on 5/31/06.

The dye traveled 3.4 mi in greater than 8 days but less than 10 days. If dye arrived in nine days, the straight-line flow velocity was about 2000 ft/d.

06-13

May 4, 2006: During moderate flow conditions, 1.5 oz of uranine were injected at **Williams Swallet** [N37.45165°/W086.09673°] 4.9 mi to the north-northwest of Mill Spring. The headwaters of Berry Run, a tributary of Nosey Creek, are crossed by two fault lines, one of which underlies Williams Swallet. This test was designed to determine if these headwaters just to the west of Sinking Fork drain to Mill Spring. The same three monitoring points were utilized as in the previous test (#06-12: Sharp Swallet).

On the first exchange (5/9/06), Nosey Creek @ Bridge was very positive for uranine (++). This site was inconclusive during the second exchange on 5/17/06. Apparently, the uranine emerged from a small spring about 150 m northeast of the injection point and remained within the Nosey Creek watershed. Nolin River @ Millerstown was negative during this test. However, a single low-level detection (2.3x background) occurred at Mill Spring on 5/11/06, seven days after injection. This single low-level recovery was rejected for three reasons: 1) Minimal dye was used, and it was strongly detected in Nosey Creek. Most likely, all of the uranine would have been required for a detection at Mill Spring, 6 mi distant. 2) The dye flow velocity would have exceeded that from the nearer Sharp Swallet; 3) A potential exists for uranine contamination from the settlement around Broad Ford. Replication of this trace with a different dye is recommended to fully refute any connection to Mill Spring.

06-14

In a further effort to evaluate the Sinking Fork watershed, this dye test was introduced at a losing point along a northwest tributary of Sinking Fork.

May 17, 2006: During moderate flow conditions, 11 oz of SRB was injected at **Oldham Swallet** [N37.44532°/W86.07466°] a minor sinking spring of 0.02 ft^3/s, 4.3 mi north of Mill Spring. Mill Spring and Nolin River @ Millerstown were monitored for this test. Fourteen days later on the first exchange (5/31/06), Mill Spring was just less than positive for SRB (?), at about 3.6x background, while Nolin River @ Millerstown was negative. Fourteen days later – 28 days post-injection – on the second exchange (6/14/06) Mill Spring remained inconclusive for SRB (?) at 3.3x background. On the third exchange, six weeks after injection (6/28/06), Mill Spring continued to be inconclusive for SRB (?) at 2.8x background. Finally, by 7/19/06 Mill Spring was negative for SRB (**-**).

Even though these SRB dye recoveries were less than optimal, they reinforce each other and can be considered a positive trace. Part of the recovery problem may have been due to a moderate flood that occurred soon after dye injection. This event may have diluted the initial dye cloud at Mill Spring and partially stranded some dye within the conduit flow route, producing a lengthy recovery period at a low concentration. The map in Figure 31 shows the results of these tracer tests.

06-17 (non-recovery)

A potential recharge area for Mill Spring is a large sinkhole located 1.5 mi to the southwest. This sink coincides with a mapped fault trending northwest/southeast. However, dye monitoring to the south is not possible because of the impounded waters of Nolin Reservoir. Therefore, only Mill Spring and Barton Run @ Carmel Clemons Road were monitored for this test. Because of the remoteness of the sinkhole, a “dry set” of uranine was deployed in the throat of the sinkhole. This dry set apparatus consisted of a 12-inch length of 4-inch diameter PVC pipe, which was enclosed on both ends with hardware cloth (wire mesh).

June 14, 2006: During dry weather, 8.5 oz of solidified uranine was secured in the section of pipe with hardware cloth and lodged in a low soil pipe drain feature within **Alvie Sinkhole** [N37.37224°/W086.09801°]. Runoff into the sinkhole at a later date would flow into the drain and through the pipe, dissolving and flushing the uranine into the groundwater system. The Mill Spring dye receptor was exchanged six times over the next four months (ending on October 11, 2006) with no recovery of the uranine. Even though a known runoff event occurred prior to 8/16/06, the dye was not recovered at either monitoring site. The amount of dye used was 3-4 times that needed for a trace of 1.5 mi to Mill Spring. The conclusion reached was that even if the dye introduction was less than optimal, such as partial injection over multiple runoff events, the uranine must have eventually flowed to the unmonitored Nolin Reservoir. Therefore, Alvie Sinkhole is excluded from the Mill Spring recharge area.

Goodman Springs (0230)

Goodman Springs is described in the water quality section of this report. Tracer tests conducted in the 1980s by Quinlan and Ray delineated this spring’s basin (Ray and others, 2009). Additionally, the lower section of this spring basin flows through Bland Cave, which was mapped and described by Stephens and others (1983). This cave map provided excellent information used to select groundwater monitoring points and modify the existing groundwater basin boundary. Tracer tests in this study were conducted to better define the groundwater basin boundary between Goodman Springs and Waddell Spring basins.

08-01

May 1, 2008: **Bland Swallet** [N37.516598º/W085.990859º] is a large swallow hole at the lowest elevation within a compound sink, located 4 miles northeast of Goodman Springs. It was hypothesized that this injection point would help delineate the northern extent of Goodman Springs' basin. Following a relatively dry spell, 16 ounces of SRB were injected into the open throat at the base of this sink and flushed with 200 gallons of hauled water. A significant rain event occurred on May 2nd and 3rd, helping to further flush dye into the subsurface. Dye receptors were exchanged six days later on May 7. Goodman Springs, as well as numerous karst windows and cave streams up gradient, showed positive recoveries of SRB (+). Subsequent exchanges showed only weak dye recoveries that were deemed inconclusive. However, this tracer test is considered a positive result due to dye recovery at 11 sequential groundwater monitoring points. Inconclusive dye recovery in subsequent exchanges is attributed to an efficient groundwater flow system that discharged most of the dye within one week. Figure 10 is a map of all tracer data for Goodman Springs. This map includes tracer data for Hawkins Bluehole and Copelin Spring, discussed below.

Waddell Spring (1066)

Waddell Spring [N37.555935º/W085.004725º] is named *St. Ignatius Spring* on the USGS 7.5-minute Summit Topographic Quadrangle. The spring is a large bluehole, discharging through alluvium in an abandoned meander loop of the Nolin River. Initial tracer tests and basin delineation were carried out by Crawford and Dotson (1989) (Ray and others, 2009). During the traces conducted in this study, Skees KW #1 was used as a monitoring point rather than Waddell Spring. Skees KW #1 and its relation to Waddell Spring are described in the water quality section of this report.

While this spring basin was fairly well defined by previous investigation, the southern and eastern boundary along the Goodman Springs basin needed some refinement.

08-02

May 1, 2008: **Olive Hill Church Sinkhole** [N37.513658º/W085.967841º] is located adjacent to Silver Mine Road approximately 3 miles south-southeast of Skees Karst Window. This is a large, deep sink with a single collapse feature at the base. For this trace, 8 ounces of uranine were flushed into the bottom of the sinkhole with 200 gallons of hauled water. Skees KW #1 and Bland Mill Cave were both very positive for uranine (++) on the first dye receptor exchange, six days later. Both of these sites were still positive (+) on the second exchange on May 13. Two later dye receptor exchanges showed inconclusive results.

08-03

May 7, 2008: **Hodges Swallet** [N37.50861º/W085.929279º] is the terminus of a small, unnamed sinking creek and is located approximately 4 miles southeast of Skees KW #1. A rain event created enough runoff to activate the swallet with a natural flow estimated to be 0.05 ft^3/s. Eight ounces of eosine were introduced into the swallet. The first dye receptor exchange on May 13 showed no dye recovery at any of the monitored sites. However, Skees KW #1 and Bland Mill Cave were both positive for eosine (+) on May 20 and again on June 6 (+). A map of all tracer data for this spring is presented in Figure 37.

The two tracer tests discussed above aided in delineation of the southern extent of the Waddell Spring basin where it meets the Goodman Spring basin.

Hawkins Bluehole (3798)

Hawkins Bluehole [N37.529213º/W086.044029º] is located in the southeastern portion of the USGS 7.5-minute Summit Quadrangle, but is not shown on either the topographic or geologic maps. The spring was found during a spring survey of the Nolin River. This spring discharges from alluvium as a small bluehole adjacent to the left bank of the Nolin River at an elevation of 580 feet. The spring was monitored for tracer tests designed to refine the basin boundaries of Goodman and Waddell springs.

08-05

June 6, 2008: A large sinkhole with a minor cover-collapse was identified near the intersection of Lees School Road and Hogan Road. **Lee-Hogan Rds Sinkhole** [N37.513421º/W086.022686º] is approximately 2.5 miles northeast of Goodman Spring and 1.5 miles southeast of Hawkins Bluehole. It was chosen as an injection point to delimit the northeastern end of the Goodman Spring basin. A total of one pound of SRB was injected with 200 gallons of hauled water. On July 2, twenty-six days later, Hawkins Bluehole was positive for SRB (+). Two subsequent analyses on July 10 and 18 showed that Hawkins Bluehole was still positive for SRB (+). Dye was also recovered at Copelin Spring, which is discussed below.

08-06

June 6, 2008: A large, boulder-filled sinkhole was found on the Masterson Farm, located approximately 2 miles due east of Hawkins Bluehole. **Masterson Sinkhole** [N37.527751º/W086.000959º] was in proximity to the southeastern boundary for the Waddell Spring basin. For this test, 13 ounces of uranine were injected into the sinkhole with 200 gallons of hauled water. On June 12, Hawkins Bluehole was extremely positive for uranine (+++). Hawkins Bluehole showed uranine recovery on the next five dye receptor exchanges over the course of one month.

These two tracer tests were used to refine the eastern boundaries of both Waddell and Goodman springs' basins. They also served to delineate groundwater basin boundaries for Hawkins Bluehole and Copelin Spring. Results of these tracer tests are shown on the map in Figure 10.

Copelin Spring (0258)

Copelin Spring [N37.491044º/W086.054903º] is located in the northeastern corner of the USGS 7.5-minute Millerstown Quadrangle, but does not appear on the topographic or geologic maps. Previous tracer tests at this spring were conducted by Quinlan and Ray in 1983 (Ray and others, 2009). The spring issues from a small conduit at an elevation of 600 feet near the base of a steep hill in the Beaver Bend and Paoli Limestones (Moore, 1965). The spring discharges to the Nolin River via a spring run approximately 500 feet long. The point where this spring run meets the Nolin River is the mouth of an abandoned meander loop, filled with alluvium. This spring was monitored during tracer tests designed to refine the basin boundaries for Waddell and Goodman springs. The spring has been mistakenly referred to as "Copeland" in some literature.

08-05

The details of this tracer test are discussed above under Hawkins Bluehole. For most of the monitoring period no dye was recovered at Copelin Spring. On July 18, which was 42 days after the dye injection, Copelin Spring showed positive recovery of SRB (+). A sample analyzed five days after that was also positive for SRB (+). This revealed a groundwater bifurcation and that the sinkhole injection point was located at the groundwater divide between Copelin Spring and Hawkins Bluehole. The tracer data and groundwater basin for this spring are included on the map in Figure 10.

Table 5 is a summary of the nineteen tracer tests conducted for this study. Four tests were interpreted as positive recoveries when at least two or more successive dye detections were determined at less than the criterion of 4x the background value. Inferred groundwater flow routes are illustrated as minimum straight-line to curvilinear distances, which are less than actual conduit pathways. Groundwater flow velocities are ratios of the interpreted flow path to the recovery-time interval. This interval is usually the time elapsed between dye injection and the first dye receptor exchange. Consequently, actual velocities are typically 2-3 times greater than shown.

Dye Injection Number	Dye Injection Site	Injection Site Coordinates (Decimal Degrees)	Dye Recovery Site(s)	Interpreted GW-Flow Path (mi)	GW-Flow Velocity (mi/day)
06-06	Berry Swallet	N37.60811°/W085.73601°	Nolynn Spring, North Fork above Nolynn(?)	4.75	>0.7
06-07	North Fork Nolin River Swallet	N37.57687°/W085.75745°	Nolynn Spring	2.9	>0.5
06-08	Gardner Swallet	N37.62767°/W085.74785°	Nolynn Spring, North Fork above Nolynn*	5.4	>0.72
06-09	Middle Creek Swallet	N37.64118°/W085.77069°	Nolynn Spring	6.6	>1.2
06-10	Belcher Swallet	N37.38816°/W086.10307°	Mill Spring*	1.6	>0.2; <0.24
06-11	Buzzard Ridge Swallet	N37.42160°/W086.11008°	Pretty Spring	2.1	>0.3
06-12	Sharp Swallet	N37.43236°/W086.07415°	Mill Spring	3.5	>0.3; <0.4
06-13	Williams Swallet	N37.45165°/W086.09673°	Nosey Creek @ Bridge via minor cutoff spring	2.2 (creek) 0.09	>0.4 (cr.) -
06-14	Oldham Swallet	N37.44532°/W086.07466°	Mill Spring*	4.3	>0.3
06-15	Parkway Swallet	N37.60388°/W085.78726°	Heady Big Spring/Nolynn*	2.75	>0.4
06-16	Jennings Sinkhole	N37.60815°/W085.76527°	Nolynn?/Heady Big Spring?	-	-
06-14	Alvie Sinkhole (dry set)	N37.37224°/W086.09801°	Nolin River Reservoir?	-	-
07-14	French Sinkhole	N37.58594°/W085.79662°	Heady Big Spring	1.5	>0.2
08-01	Bland Swallet	N37.51659°/W085.99086°	Goodman Spring	4.9	>0.7
08-02	Olive Hill Ch. Sinkhole	N37.51366°/W085.96784°	Skees KW (Waddell Sp)	4.0	>0.6
08-03	Hodges Swallet	N37.50861°/W085.92928°	Skees KW (Waddell Sp)	5.5	>0.4
08-04	Elbow Karst Window	N37.48569°/W086.03008°	Goodman Spring	1.4	>0.2
08-05	Lee-Hogan Rds Sinkhole	N37.51342°/W086.02269°	Hawkins Bluehole and Copelin Spring	2.2 2.5	>0.07 >0.07
08-06	Masterson Sinkhole	N37.52775°/W086.00096°	Hawkins Bluehole	2.5	>0.4

Table 7. Summary of groundwater tracer tests. *Dye non-recovery emphasized in yellow, including most likely destination of drainage (?). *Tests interpreted to be positive at less than the standard criterion of 4X background.*

Karst Flow Deviation and Hydrologic Unit Code (HUC) Assessment

Groundwater and surface water systems are conjunctive, the interconnections being very direct in karst regions. Surface runoff into stream swallets and sinkholes influences groundwater quantity and quality. Likewise, stream discharge is maintained by springs during low flow, which impart characteristics on the surface water. However, the configuration of karst drainage basins may or may not conform to hydrologic boundaries, as delineated from topographic divides, such as HUC boundaries. White and Schmidt (1966) employed the term "misbehaved" karst to describe these deviations, such as groundwater flow paths beneath topographic divides. Ray and others (2006) and Blair and others (2009) refined this definition based on confirmed conduit flow passing beneath a delineated HUC boundary. This assessment will compare verified (traced or cave-surveyed) groundwater flow that passes underneath a 12-digit or lower HUC and the accompanying karst groundwater basin delineation.

The discussion below of karst drainage deviation from HUC boundaries and unit base flow of spring basins in the Green River watershed is presented with the *caveat* that only a small portion of the karst area is represented. The mapped drainage areas for the 12 springs in this study represent a fraction of the total mapped karst groundwater basins in the Green River basin. The 12 springs referred to are those 10 springs assessed for water quality and two additional springs whose groundwater basins were delineated through tracer tests for this project. The sum of mapped karst groundwater basins draining to the Green River is 1,266 square miles and the total drainage area for the 12 springs assessed is 523 square miles (41%). The total area of soluble, carbonate rocks with karst development potential in Green River basin is 4,535 square miles. Thus, the 12 study area spring basins represent only 12% of the total area of likely karst development within the Green River basin. Measurements of the total Green River basin area from various level HUC delineations (6- to 12-digit) vary between 9,135 square miles and 9,276 square miles. For the purposes of this report, we will split the difference at 9,200 square miles for the size of the Green River Basin. In which case, approximately 50% of the land within Green River Basin has the potential for karst drainage. Further, total mapped karst groundwater basins represent about 14% of the total surface drainage area for the Green River and the 12 study area spring basins represent about 6%. Karst basin areas that deviate from HUCs are counted only once and are referenced according to the smallest-digit HUC boundary. For example, if a karst basin deviates from an 8-digit HUC, then it will also deviate from the subordinate 10- and 12-digit HUCs within that boundary. However, that particular spring basin area is counted only once as deviating from the 8-digit HUC.

The map in Figure 57 shows the location of study area spring basins and the portion of each that deviates from and/or conforms to the HUC boundaries. To make the map easier to read the actual HUC boundaries have been removed following GIS analysis. The most prominent karst groundwater deviations occur in Graham, Lost River Rise, Nolynn and Gorin Mill springs' basins. Graham Springs basin is a total of 122 square miles and 120 square miles (98%) of contributing drainage passes beneath a 10-digit HUC boundary. The groundwater basin for Lost River Rise is 58.8 square miles and 45.3 square miles (77%) of karst drainage flows under a 12-digit HUC boundary. Nolynn Spring is partly a subterranean cutoff of the North Fork Nolin River with a total karst basin area of 56.4 square miles. However, 39.9 square miles (71%) of this basin's drainage underflows both 10- and 12-digit HUC boundaries. Gorin Mill Spring, the largest known spring in Kentucky (Ray and Blair, 2005), has a karst basin area of approximately 152 square miles. Nearly 10 square miles of its groundwater basin are attributed to the Barren River where groundwater flows beneath an 8-digit HUC boundary. Perhaps the most confusing karst deviation occurs in the Head of Rough Spring basin. This spring basin does not deviate from the 10- and 12-digit HUC boundaries. However, when compared to the 6- and 8-digit HUC boundaries approximately 3 square miles of area in the southeastern corner of the basin are misbehaved. In this particular area the 6- and 8-digit HUC boundary deviate from the other mapped hydrologic boundaries. This is due to the scale of maps employed to delineate each of the various level HUCs. The 10- and 12-digit HUCS were created using 1:24,000 scale maps, which provided better resolution and more reliable delineation.

Overall, approximately 250 square miles (49%) of mapped karst groundwater basins for springs in this study deviate from the surface water basins delineated by topographic divides. A little over 3 square miles of karst drainage area deviates from the 6-digit HUC for Green River. Looking at 8-digit HUCs, almost 10 square miles of karst drainage deviation occurs. The majority of karst drainage deviation, 159 square miles, occurs relative to the 10-digit HUCs. Karst deviation from the 12-digit HUCs is on the order of 82 square miles. Due to the size of the Green River Basin and the extent of karst development potential, it is difficult to accurately determine the total karst deviation. However, one could assume that any given watershed in the Mississippian Plateau would be roughly equivalent to the areas discussed here. Karst groundwater flow deviations from HUC boundaries have serious implications for TMDL development, flow modeling and response to environmental emergencies. Recognizing these implications, the KGS and KDOW have developed the Karst Atlas Map Series. These maps, available as hard copy and GIS layers, should be consulted when conducting water quality and quantity assessments in karst regions of Kentucky.

Table 8 lists each spring with its base flow, basin size, unit base flow calculations, the amount of that basin that deviates from surface drainage divides and the level of HUC delineation on which the deviation occurs.

Spring Name	**AKGWA**	**Base Flow (ft^3/s)**	**Basin Area (mi^2)**	**Unit Base Flow ($ft^3/s/mi^2$)**	**Misbehaved Karst (mi^2) and [HUC Level]**	
Gorin Mill Spring	0793	24.0	152.4	0.16	9.7	[8-digit]
Graham Spring	0051	19.8	122	0.16	120.2	[10-digit]
McCoy Bluehole	0792	12.7	34.1	0.37	18.5	[10-digit]
Lost River Rise	0054	12.4	58.8	0.21	45.3	[12-digit]
Skees Karst Window #1	1398	6.4	27.5	0.23	1.2	[12-digit]
Nolynn Spring	2673	4.6	56.4	0.08	39.9	[10- and 12-digit]
Goodman Springs	0230	4.6	14.7	0.31	8.2	[12-digit]
Mill Spring	1193	3.0*	7.1	0.42	4.4	[10-digit]
Head of Rough River	1011	4.0	17.7	0.23	3.1	[6-digit]
Mahurin Spring	0202	2.1*	25.3	0.08	1.5	[12-digit]
Hawkins Bluehole	3798	1.0*	4.1	0.24	2.6	[12-digit]
Copelin Spring	0258	0.25*	2.4	0.1		None

Table 8. Spring Unit Base Flow and HUC Assessment. *Based upon limited data

Unit Base Flow Assessment

Unit Base Flow (UBF) is the ratio of a spring's minimum annual flow (base flow) to its apparent basin size, which yields a normalized flow per unit area. UBF assessment is predicated on the assumption that watershed units within similar hydrogeologic settings will yield approximately the same amount of base flow groundwater discharge. When calibrated by base flow measurements, UBF assessment of springs in a given region can aid in estimating the size of unknown recharge areas of springs and characterizing the hydrogeologic settings. Following spring basin delineation, excess and deficit UBF can be identified when compared to reference values (Ray and others, 2006).

Based on a population of 25 springs, Ray and others (2006) determined that UBF for the Mississippian Plateau is about 0.2 $ft^3/s/mi^2$. Unit base flow for springs in this project ranges from 0.08 to 0.42 $ft^3/s/mi^2$, with a median of 0.22 $ft^3/s/mi^2$. Significant UBF excesses are noted for McCoy Bluehole and Mill Spring. Deficits are noted for Copelin, Nolynn and Mahurin springs. A scatter plot of UBF for all 12 springs is presented in Figure 58. The R^2 value of 0.87 shows a positive correlation and supports the idea that base flow discharge and basin area have a direct relationship.

The excess UBF noted for McCoy Spring is most likely due to an unusually large storage capacity in the overlying Brownsville Channel sand and gravel (Quinlan and Ray, 1995 and Schindel and others, 1995). Mill Spring's excess UBF is possibly because a portion of the recharge area of the groundwater basin remains unidentified. Additionally, the base flow of 3.0 ft^3/s is based on limited data. However, if the base flow of 3.0 ft^3/s is roughly correct then there may be as much as 50% of the basin not yet delineated. Because the northern sub-basin of the identified recharge area near Millerstown is delineated very near the southern bank of the Nolin River, it cannot be ruled out that minor flow leaks from the river south into the karst basin. This hypothesis suggests a 4.8-mile subterranean cutoff of the Nolin River. The southern bank of the Nolin River in this area was searched for any visible swallet feature, but none was located. Nevertheless, the hypothesis could be tested by introducing tracer dye into the river upstream of the suspected leakage point.

Potential reasons behind UBF deficits for Copelin, Nolynn and Mahurin springs are speculative. The majority of the Copelin Spring basin is formed in the Ste. Genevieve

Limestone and the basin delineation seems quite reasonable, but could be exaggerated. Nolynn Spring is partly a subterranean cutoff spring, which may affect its UBF. Ray and Blair (2005) note that six of the twenty largest springs in Kentucky are cutoff springs. Of those six, two show UBF excess and three show UBF deficits, some of which can be explained by variation in hydrogeologic settings and therefore groundwater runoff. Some low-yield hydrogeologic settings, such as sandstone, may reduce groundwater flow to Mahurin Spring, which drains from a highly faulted zone.

CONCLUSIONS

This report describes the initial project in Kentucky's Mississippian Plateau karst region to integrate surface water and groundwater quality assessment approaches to better define the nexus between the two flow systems. Surface water and groundwater are conjunctive systems, no more directly so than in karst terranes. Surface water assessments (§305b report) in the well-developed karst areas of Kentucky are limited due to a relative lack of flowing surface streams. Particularly in the sinkhole plain of south-central Kentucky, karst spring basins represent large areas of contribution to the Green River that were previously un-assessed for water quality. Subsurface streams that drain these basins were assessed via their discharges to surface waters at discrete springs. The new strategy for assessing these springs meets the requirements for surface water assessment protocols.

An integrated approach addresses the deficiencies of inadequately assessed "stream segments" and provides needed information on spring conditions relative to nonpoint source impacts to surface water and groundwater in Kentucky. Such assessments have implications relative to listing and delisting springs as water bodies in the 305(b)/303(d) integrated report, TMDLs, watershed planning, and the availability of grant funds (e.g. §319(h)) for watershed projects in these areas. This study focused on ten large springs in the Green River basin, applying this holistic watershed approach. Water quality samples (including major ions, nutrients, TOC, TSS, TDS, pH, alkalinity, metals, VOCs, and pesticides) were collected monthly for one year from each spring. Total coliform and *E. coli* bacteria samples were collected monthly from May through October. Of the ten springs assessed in the Green River basin, nine springs were "Not Supporting" for Primary Contact Recreation (PCR), and one spring – Graham Spring – was "Partially Supporting" for PCR. Five of these springs – Mahurin, Goodman, Mill, McCoy and Lost River Rise – were "Fully Supporting" for Aquatic Life Use; the other five springs were "Partially Supporting." Assessment of the macroinvertebrate communities at four of these springs revealed relationships between spring discharge, temperature regime, nutrient levels and macroinvertebrate abundance and richness. This project will serve as a model for subsequent groundwater assessments in Kentucky's karst regions conducted by KDOW.

Comparison of hydrologic maps developed using dye trace data with the USGS 8-, 10- and 12-digit Hydrologic Unit Code (HUC) boundaries indicates that significant amounts of mapped karst groundwater basins deviate from hydrologic boundaries based on topographic divides. Of the 523 square miles of mapped karst groundwater basins assessed for this study, 254 square miles (49%) deviate from surface hydrologic boundaries. Accurate hydrologic mapping is necessary to calculate water budgets and in developing watershed models for TMDLs, for implementing watershed-based solutions to water quality and quantity problems, and for first responders to spills.

The median Unit Base Flow (UBF) for the assessed springs was 0.22 $ft^3/s/mi^2$, which agrees with the UBF assessment from previous investigations in this region. However, of the 12 spring basins assessed two were found to have excess UBF while three showed deficits. This represents 42% of the assessed spring basins that deviate significantly from the median UBF value.

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Appendix A. Financial and Administrative Closeout

Workplan Outputs

The [former] Groundwater Branch has committed to the following outputs:

- Identification of suitable groundwater monitoring sites in the Green and Tradewater River basins
- Collection of samples from 10 sites monthly for one year and delivering these samples to the laboratory for analysis for several parameters, including major inorganic ions, nutrients, pesticides, metals, volatile organic compounds and residues
- Data analysis, including data collected within these basins for other projects
- Production of a report summarizing all relevant groundwater data for this BMU
- Delivering hard-copies of the basin report to the River Basin Teams, local conservation districts, Natural Resource Conservation Service, Agricultural Water Quality Authority, Agricultural Extension offices and interested stakeholders
- Posting the report on the Division of Water's internet site

Budget Summary

- Total project budget is $140,000
- Budget has been expended in personnel costs approximately equivalent to 1.23 person years
- Groundwater Branch has managed the project, including:
    - ✓ researching background data
    - ✓ conducting on-site inspections to identify sampling sites
    - ✓ collecting groundwater samples
    - ✓ transporting samples to the laboratory
    - ✓ interpreting sample results
    - ✓ preparing maps and reports
    - ✓ providing reports to interested parties

- Time code used for this project was:

ACT MOAM/MODA

PROJECT NPS0503Z

Project Budget:

The total project budget is $140,000. The budget will be expended in personnel costs reflecting a total equivalent of approximately 2.85 person years. The [former] Groundwater Branch personnel will manage the project, research background data, conduct on-site inspections and groundwater sampling, transport samples, interpret sample results, prepare maps and reports, and present the summary information to stakeholders and other interested parties. The Environmental Services Branch (ESB) lab personnel will conduct chemical analysis. A time code will be established to track personnel time spent on the project. Match for this grant will be provided by DOW and ESB personnel costs, including fringe and overhead.

Budget Summary:

Budget Categories	BMP Implementation	Project Management	Public Educatio n	Monitoring	Technical Assistance	Other	Total
Personnel	$	$	$	$98,042	$	$	$98,042
Supplies							
Equipment							
Travel							
Contractual							
Operating Costs				$41,958			$41,958
Other							
TOTAL	$	$	$	**$140,000**	**$**	**$**	**$140,000**

Detailed Budget

Budget Categories	Section 319(h)	Non-Federal Match	Total
Personnel	$58,825	$39,217	$98,042
Supplies	$	$	$
Equipment	$	$	$
Travel	$	$	$
Contractual	$	$	$
Operating Costs	$25,175	$16,783	$41,958
Other	$	$	$
TOTAL	$**84,000**	**$56,000**	**$140,000**

Funds Expended

All funds for this project were expended using personnel dollars.

Equipment Summary

No equipment was purchased for this project.

Special Grant Conditions

No special grant conditions were placed on this project by the EPA.

Appendix B. Quality Assurance / Quality Control for Water Monitoring

QA/QC Plan for Integrated Surface Water and Groundwater Assessment of Large Springs in the Green River Basin (Basin Management Unit 4)

Prepared by

Peter T. Goodmann, Manager, Groundwater Branch
James S. Webb, Supervisor, Groundwater Branch
Joseph A. Ray, Geologist-Registered, Groundwater Branch

Kentucky Division of Water

1. Title Section

A. Project Name

Integrated Surface Water and Groundwater Assessment of Large Springs in the Green River Basin (Basin Management Unit 4).

B. QA/QC Plan Preparers

Peter T. Goodmann, Manager, [former] Groundwater Branch
James S. Webb, Supervisor, [former] Groundwater Branch
Joseph A. Ray, Geologist-Registered, [former] Groundwater Branch
Kentucky Division of Water
200 Fair Oaks Lane
Frankfort, Kentucky 40601
(502) 564-3410

C. Date

January 31, 2005

D. Project Description

The project is part of the Green/Tradewater River Strategic Watershed Monitoring Plan. The Kentucky Division of Water currently conducts quarterly nonpoint source groundwater monitoring at approximately 70 sites across the state. This project will expand that monitoring effort in the Tradewater and Green River Basins by increasing the number of monitoring sites and focusing additional efforts of the existing monitoring network in these watersheds. This project is intended to work in coordination with other members of the River Basin Team who are conducting surface water and biological sampling.

The goal of this project is to identify the impacts of nonpoint source pollution on the groundwater in the Tradewater and Green River Basins. The objective of this study is to identify aquifers that have been impacted by nonpoint source pollution. Problems in these areas will be identified in order that future nonpoint source resources may be properly focused regarding nonpoint source pollution prevention and pollution abatement.

2. Project Organization and Responsibility

A. Key Personnel

The Technical Services Section of the [former] Groundwater Branch will coordinate this project in cooperation with Data Management Section staff of the [former] Groundwater Branch, Kentucky Division of Water.

The [former] Groundwater Branch, Kentucky Division of Water, will scout and select suitable sampling locations. Staff of the [former] Groundwater Branch will perform sampling and sample delivery. The Kentucky Department for Environmental Protection's Division of Environmental Services laboratory will be responsible for sample analysis. All data generated will be delivered to the Kentucky Department for Environmental Protection's Consolidated Groundwater Database and will be forwarded to the Kentucky Geological Survey's Groundwater Data Repository.

Robert J. Blair, P.G., will be the Project Officer, QA Officer, and Field Sampling Officer. Address: 200 Fair Oaks Lane, Frankfort, KY 40601. Phone (502)-564-3410.

B. Laboratory

Environmental Services Branch
100 Sower Boulevard
Frankfort, Kentucky 40601
(502) 564-6120

C. Participating Agencies

The [former] Groundwater Branch, Division of Water currently conducts statewide ground water monitoring for the Ambient Groundwater Monitoring Program.

This project will cooperate with the Division of Water's Watershed Initiative, the Tradewater and Green River Basins Teams, and the Division of Water's Water Quality Branch.

3. Watershed Information

A. Stream Names

Tradewater River, Green River and their tributaries.

B. Major River Basins

Tradewater and Green River Basins.

USGS Hydrologic Unit Number (HUC)

Tradewater River Basin:	05130205
Green River Basin:	05110001 05110002 05110003 05110004 05110005 05110006
Minor Ohio River Tributaries (MORT)	05140201 05140202 05140203 05140206 05140104

C. Stream Order

This project encompasses basins of the Tradewater and Green River.

D. Counties in the Study Area

Tradewater River Basin: Caldwell, Christian, Crittenden, Henderson, Hopkins, Livingston, Union, and Webster.

Green River Basin: Adair, Allen, Barren, Butler, Breckinridge, Casey, Christian, Daviess, Edmonson, Grayson, Green, Hancock, Hardin, Hart, Henderson, Hopkins, Larue, Lincoln, Logan, McLean, Metcalf, Monroe, Muhlenberg, Ohio, Pulaski, Russell, Simpson, Taylor, Todd, Warren, and Webster.

Minor Ohio River Tributaries (MORT): Breckinridge, Ballard, Crittenden, Daviess, Hancock, Henderson, Livingston, Marshall, McCracken, and Union.

4. Monitoring Objectives

- Determine impacts of nonpoint source pollution on groundwater resources in selected areas of basins of the Tradewater and Green Rivers.
- Integrate surface water assessment protocols into groundwater monitoring programs.
- Provide guidance for the nonpoint source program to focus future resources relating to nonpoint source pollution of groundwater.
- Support other programs, such as the Wellhead Protection program, the Groundwater Protection Plan program and the Agriculture Water Quality Authority.
- Provide additional data useful for the long-term management of the resource.

5. Study Area Description

The Tradewater River and Green River basins occur mainly in the Western Kentucky Coal Field and the Mississippian Plateau physiographic provinces of western Kentucky. The Western Coal Field is underlain by Pennsylvanian shale, sandstone, siltstone, coal, and limestone and is characterized by gently rolling topography. The Mississippian Plateau is underlain by thick sequences of Mississippian limestone with well-developed karst topography. In addition, wide alluvial valleys characterize the lower portions of these basins. Minor portions of the project area are located within the Ohio River Alluvium. (McDowell, et al., 1988)

Late Pliocene and Pleistocene unconsolidated sand, gravel, silt, and clay characterize the Ohio River Alluvium. Groundwater flow regimes vary within the project area. Karst areas in the Mississippian Plateau are dominated by conduit flow in the subsurface. Areas of interbedded clastic sediments, as found in the Western Coal Field, are primarily fracture-flow regimes. Systems characterized by unconsolidated sediments, such as the Ohio River Alluvium, are dominated by intergranular flow (Ray, et al., 1994). All three of these flow regimes occur within the study area and will be assessed.

Approximately 70% of the land in the project area is used for agriculture. Therefore, constituents such as pesticides and nutrients, which are potential groundwater contaminants in agricultural areas, will be sampled. Other land uses within the project area include urban, abandoned mine lands, coal mining, both current and historical, oil and gas production, and silviculture. Impacts of these land uses on groundwater will be assessed. For example, constituents related to abandoned mine lands, such as heavy metals, sulfate, pH, and residues will be analyzed. Other examples include chloride pollution due to oil and gas production, and nutrient pollution from on-site sewage disposal.

The Western Kentucky Coal Field consists of relatively flat-lying, repetitive sequences of sandstone, shale, coal, and underclay, with minor amounts of limestone. These strata are highly dissected by streams, resulting in topographic relief of 100 to 500 ft. between ridge tops and valley bottoms. Most domestic wells are completed in fractured bedrock at depths less than 100 ft.

The Mississippian Plateaus (Pennyroyal) region consists primarily of limestone strata with minor shales and siltstones, fractured sandstone, and unconsolidated alluvium along major rivers. Limestone in this region is characterized by solution-enlarged sinkholes, caves, and caverns. Karst springs are the most common sources of ground water, although shallow (<150 ft.) wells in alluvium or fractured bedrock also provide water to some residents.

The Tradewater/Green River Basins, along with some areas that drain directly to the Ohio River, have been targeted as priority basins in the fourth year of the watershed initiative. For the purposes of the watershed initiative, these adjacent Minor Ohio River Tributaries (MORT) are included within the study area. This project will conduct quarterly groundwater monitoring at thirty sites within the Tradewater/Green and adjacent MORT basins.

6. Monitoring Program/Technical Design

A. Monitoring Approaches

Monitoring of approximately 10 sites will begin in April 2006. Specific sample sites will be selected after the Division of Water's groundwater database has been reviewed for candidate sites and field inspection has confirmed that the candidate sites are suitable for monitoring. For all selected sites, either a Kentucky Water Well Record or a Kentucky Spring Inventory Form (examples attached as

Appendix 1) will be placed on record with the Division of Water. Duplicate samples will be collected for at least 10% of all samples in order to check reproducibility and provide QA/QC.

Field reconnaissance will be conducted prior to final site selection to assess the suitability and accessibility of each site. The appropriate Well Inspection or Spring Inventory records will be completed. Site locations will be plotted on 7.5-minute topographic maps, and identified by a site name and unique identification number (AKGWA number) for incorporation into the Department for Environmental Protection's Consolidated Groundwater Data Base and the Kentucky Geological Survey's Groundwater Data Repository.

B. Monitoring Station Location Strategy

All monitoring station locations will be in addition to other stations currently sampled in the basin. All monitoring sites will be karst groundwater basin springs or karst windows, fracture springs, contact springs or water wells.

C. Sample Frequency and Duration

Monitoring will begin in April 2006 and samples will be collected quarterly through March 2007.

D. Sample Parameters, Containerization, Preservation, and Handling

Consistent with other monitoring efforts, samples will be collected at each spring or well and analyzed for some or all of the following: major inorganic ions; nutrients; total organic carbon; pesticides, including the most commonly used herbicides, insecticides, and fungicides; and dissolved and total metals. The analytical methods, containers, volumes collected, preservation, and sample transport will be consistent with the Division of Water's Standard Operating Procedures for Nonpoint Source Surface Water Quality Monitoring Projects, prepared by the Water Quality Branch (August, 1995) and current guidance from the Division of Environmental Services. Parameters to be measured, volume required for analysis, container type, preservative (if any), holding times (if any), and analytical methods are shown on the attached Chain-of-Custody Form.

Major inorganic ions are used to establish background groundwater chemistry and also used to measure impacts from nonpoint source pollutants such as abandoned mine lands and abandoned oil and gas production operations by measuring pH, alkalinity, chloride, sulfate, and fluoride. Nutrients and total organic carbon are used to measure impacts from agricultural operations (ammonia, nitrate, nitrite, TKN, and orthophosphate) and/or improper sewage disposal (nitrates, ammonia). Where sewage is suspected as a nonpoint source pollutant, unbleached cotton fabric swatches may be used to detect optical brighteners, the whitening agents used in laundry products and commonly found in sewage (Quinlan, 1987). Pesticides are measured to determine both rural agriculture and urban domestic- and commercial-use impacts on ground water. Metals are used to establish the rock-groundwater chemistry, establish local and regional backgrounds for metals, and determine nonpoint source impacts from abandoned coal mine operations.

All samples will be analyzed by Environmental Services Branch laboratory according to the appropriate EPA method.

7. Chain-of-Custody Procedures

Sample containers will be labeled with the site name and well or spring identification number, sample collection date and time, analysis requested, preservation method, and collector's initials. Sampling personnel will complete a Chain-of-Custody Record, developed in conjunction with the ESB laboratory, for each sample. The ESB laboratory will be responsible for following approved laboratory QA/QC procedures, conducting analyses within the designated holding times, following EPA-approved analytical techniques, and reporting analytical results to the [former] Groundwater Branch.

A sample Chain-of-Custody Form is attached.

8. Quality Assurance/Quality Control Procedures

A. Decontamination Protocols

All sampling supplies that come in contact with the sample will be new, disposable equipment, or will be decontaminated prior to and after each use, using the following protocols.

Sample Collection and Filtration Equipment

Whenever possible, sample collection is conducted using the sample container, except for dissolved metals, which are filtered on site. Sample collection equipment such as bailers and buckets will consist of Teflon. Pesticide samples will be collected using the sample container or a stainless steel bailer or bucket, in order to avoid the problem of pesticide adsorption to the sampling device (as is considered to occur with Teflon instruments). Any reusable equipment will be decontaminated by rinsing with a 10% hydrochloric acid (HCl) solution, triple rinsed with deionized water, and triple rinsed with water from the source to be sampled prior to collecting a sample. After sampling is complete, excess sample will be disposed of, and the equipment will again be rinsed with the 10% HCl solution and triple rinsed with deionized water.

New 0.45 micron filters will be used at each sampling site. Any tubing that contacts the sample will also be new. Any reusable filter apparatus will be decontaminated in the same manner as sample collection equipment. Additionally, any intermediary collection vessel will be triple rinsed with filtrate prior to use.

Field Meters

Field meter probes will be rinsed with deionized water prior to and after each use.

B. Equipment Calibration

Field meters will be calibrated in accordance with the manufacturers instructions.

C. Sample Collection and Preservation/Contamination Prevention

Water samples will be fresh groundwater collected prior to any type of water treatment. Samples not requiring field filtration will be collected directly in the sampling container. Samples requiring field filtration will be collected directly into a new clean sampling container and will be transferred to the appropriate new clean sample container during the filtration process container. New disposable single use filters and tubing will be used in the filtration process. Pesticide samples will be collected using the sample container or a stainless steel bailer or bucket, wherever necessary.

Sample containers will be obtained from approved vendors, and will be new or laboratory-decontaminated in accordance with Division of Environmental Services accepted procedures. Sample containerization, preservation, and holding time requirements are outlined in the Division of Water's Standard Operating Procedures for Nonpoint Source Surface Water Quality Monitoring Projects, prepared by the Water Quality Branch (August, 1995) and current guidance from the Division of Environmental Services. Necessary preservatives will be added in the field; preservatives for dissolved constituents will be added after field filtration. Samples will be stored in coolers packed with ice for transport to the Division of Environmental Services laboratory.

Sample containers will be labeled with the site name and identification number, sample collection date and time, analysis requested, preservation method, and collector's initials. Sampling personnel will complete a Chain-of-Custody Record for each sample. The Division of Environmental Services laboratory will be responsible for following approved laboratory QA/QC procedures, conducting analyses within the designated holding times, following EPA-approved analytical techniques, and reporting analytical results to the Groundwater Branch.

Wells will be purged until conductivity readings stabilize prior to sampling, in order to ensure that groundwater, rather than water that has been standing in the well bore, is being sampled. Spring samples will be collected as close to the spring resurgence as possible. If inhospitable terrain prohibits spring access, a decontaminated Teflon bucket attached to a new polypropylene rope may be lowered to the spring to collect the sample. Samples for pesticide analysis will be collected using a stainless steel bucket.

Duplicates and Blanks

Duplicate samples will be collected for at least 10% of all samples in order to check reproducibility and provide QA/QC control. At least one duplicate sample will be submitted with each batch of samples, regardless of the number of samples in the batch. Blanks of deionized water will be submitted at least once per quarter. Blanks will be collected, filtered, and preserved in the same manner as a sample. According to Division of Environmental Services accepted procedures, duplicate analyses will be accepted if they are within 20 % rsd. If unacceptable results are found, samples will be re-analyzed and field records will be examined to determine the cause.

Field Measurements

Conductivity, temperature, and pH will be measured in the field at each site using portable automatic temperature compensating meters, and recorded in a field log book. Meters will be calibrated according to the manufacturer's specifications, using standard buffer solutions. Meter probes will be decontaminated according to decontamination protocols for field meters and stored according to the manufacturer's recommendations.

9. References

Kentucky Division of Water, 1995, Standard operating procedures for nonpoint source surface water quality monitoring projects: Kentucky Natural Resources and Environmental Protection Cabinet, Frankfort, KY, 138 p.

McDowell, Robert C., Grabowski, Gilbert J, Moore, Samuel L., 1988, Geologic Map of Kentucky, Sesquicentennial Edition of the Kentucky Geological Survey, by U.S. Geological Survey, Daniel Peck, Director, and in cooperation with the Kentucky Geological Survey, Donald C. Haney, State Geologist and Director. Compiled by Martin C. Noger, Kentucky Geological Survey.

Quinlan, J. F., ed., 1987, Qualitative water-tracing with dyes in karst terrains – Practical karst hydrogeology, with emphasis on groundwater monitoring, National Water Well Association 26 p.

Ray, Joseph, Webb, James, S., and O'dell, Phillip W., 1994, Groundwater Sensitivity Regions of Kentucky, Kentucky Department for Environmental Protection, Division of Water, Groundwater Branch, map.

CHAIN OF CUSTODY RECORD
NATURAL RESOURCES AND ENVIRONMENTAL PROTECTION CABINET
DIVISION OF WATER - GROUNDWATER BRANCH - NPS Green/Tradewater River Basin Project - Funding Source A-40

Site Identification	**Collection Date/Time**	**Field Measurements**
Location: County: AKGWA #:	Date: _______________ Time: _______________	Temp: _______________ °C pH: _______________ Cond: _______________ umhos

Sampler ID: ___________________________________

Division for Environmental Services Samples

Analysis Requested	**Container Size, Type**	**Preservation Method**	**Parameters**	**Analysis Requested**	**Container Size, Type**	**Preservation Method**	**Parameters**
	1000 ml Plastic	Cool to 4°C	**Bulk Parameters** **IC Scan** (includes Chloride, Fluoride, Nitrate-N, Nitrite-N, Sulfate, Ortho-P), **Alkalinity, Conductivity, pH, TSS, TDS**		1000 ml Plastic	Filtered HNO_3 Cool to 4°C	**Dissolved Metals by ICP** plus Arsenic, Lead, Mercury, Selenium
	1000 ml Plastic	H_2SO_4 Cool to 4°C	**NH_3/TKN/TOC Total P**		1000 ml Plastic	HNO_3 Cool to 4°C	**Total Metals by ICP** plus Arsenic, Lead, Mercury, Selenium
					1000 ml Glass	Cool to 4°C	**N/P Pesticides** Method 507
					1000 ml Glass	Cool to 4°C	**Pesticides/PCBs** Method 508
					1000 ml Glass	Cool to 4°C	**Herbicides** Method 515.1

Signatures:

Relinquished by: ___________________ Date: ________ Time: ________

Received by: _______________________________________

Relinquished by: ___________________ Date: ________ Time: ________

Received by: _______________________________________

Sample #: _______________ Report #: _______________

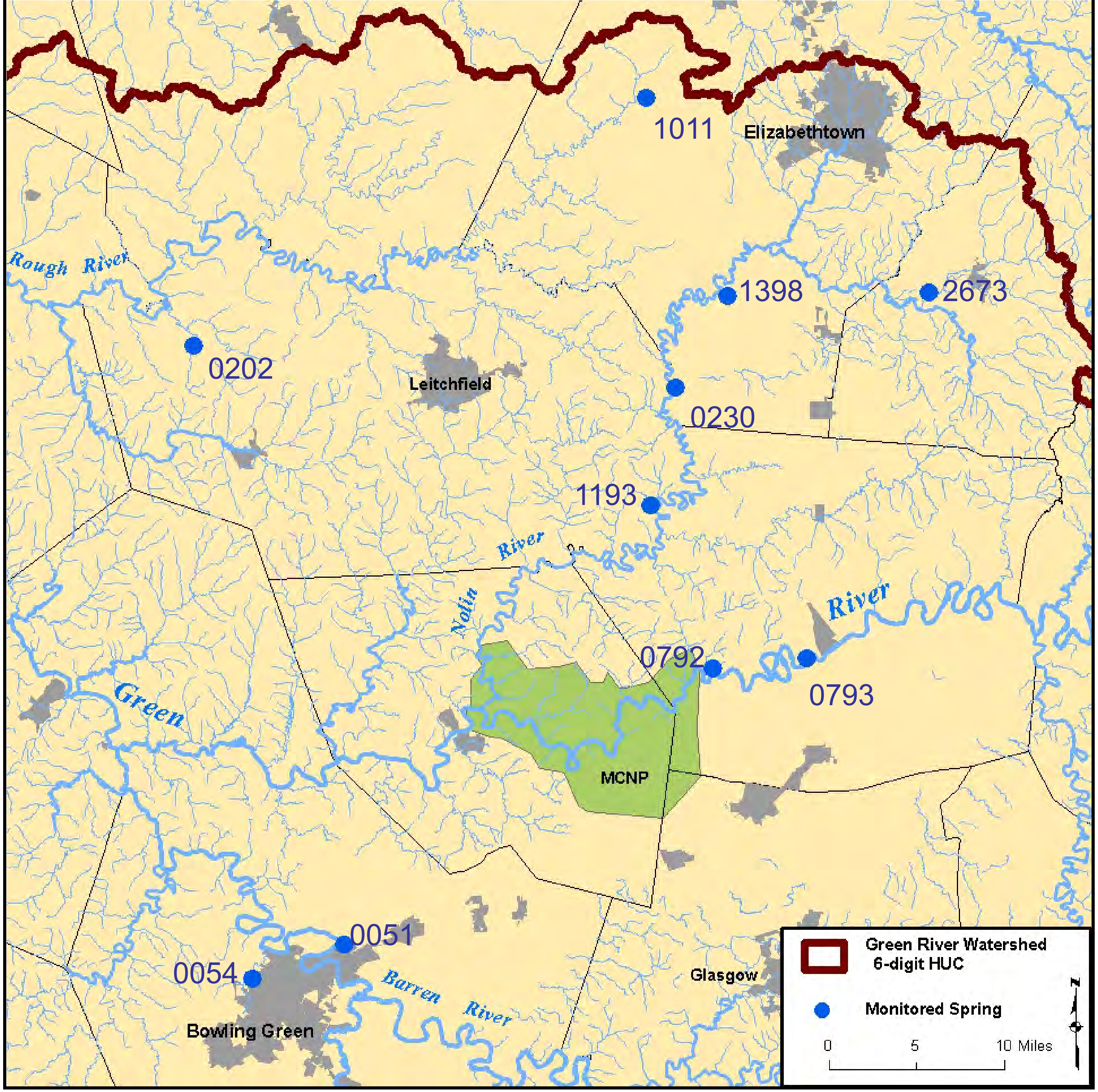


Figure 1. Base map of Study Area showing Assessed Springs with AKGWA Numbers

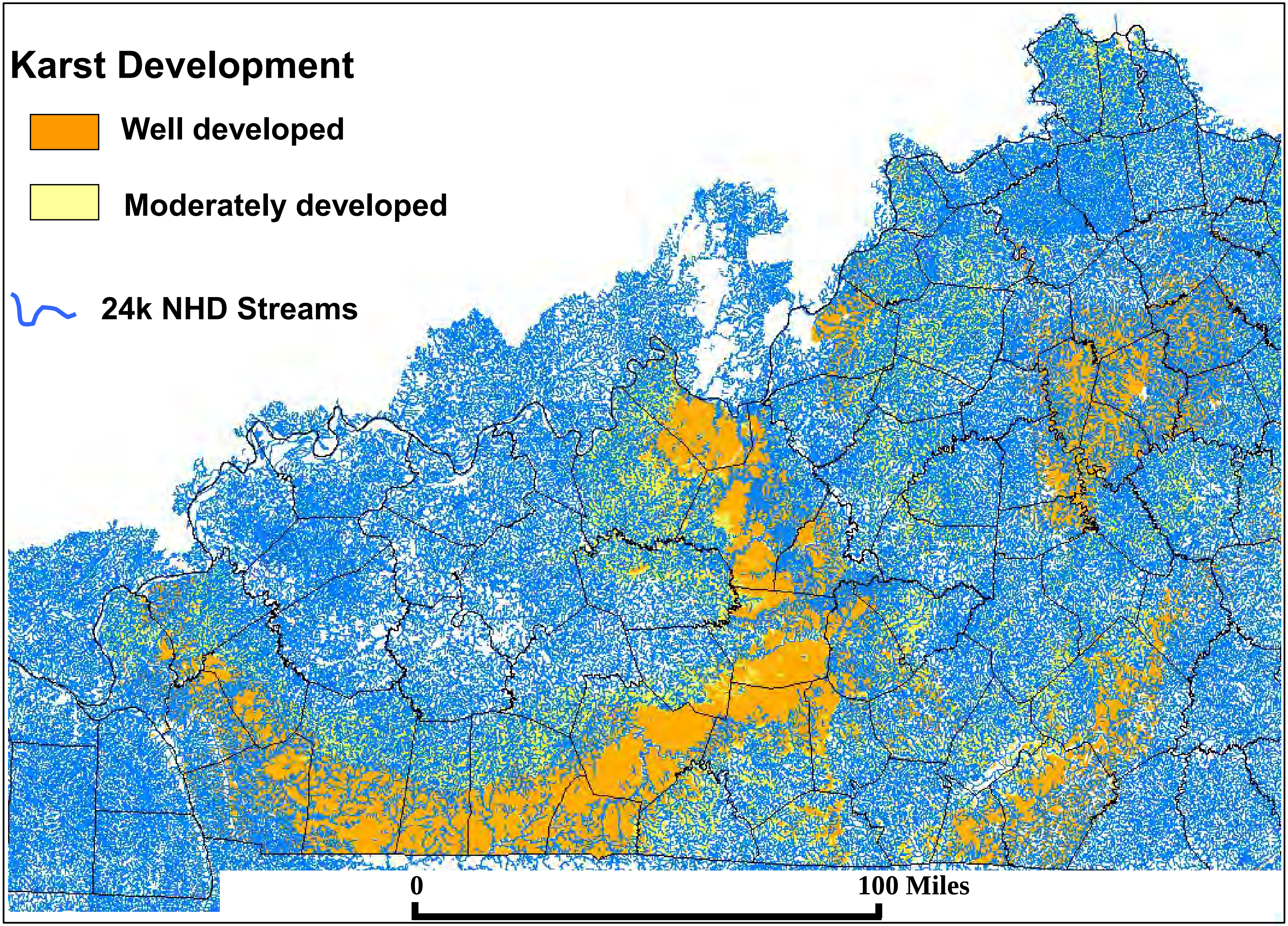


Figure 2. Lack of Surface Drainage in Mississippian Plateau Karst Region

401 KAR 10:031. Section 4, Section 6 & Section 7-Allowable instream concentrations of pollutants						Impairment Level ?10%=Not 11-25%=Partial >25%=Impaired
Pollutant	CAS[1] Number	Water Quality Criteria µg/L[2]				
		Human Health:		Warm Water Aquatic Habitat[3]:		
		DWS[4]	Fish[5]	Acute	Chronic	
Aldrin	309002	0.000049	0.00005	3		
Alkalinity (as $CaCO_3$)				Reduction >25%		
alpha-Endosulfan	959988	62	89	0.22	0.056	
Ammonia, un-ionized (mg/L) Y < 0.05 mg/L				Y=1.2(Ammonia-N)/(1+10pKa-pH)	pKa=0.0902+(2730/273.2+TC))	
Arsenic	7440382	10		340	150	
Beta-Endosulfan	33213659	62	89	0.22	0.056	
Cadmium	7440439	5		e(1.0166 (ln Hard*)-3.924)	e(0.7409 (ln Hard*)-4.719)	
Chlordane	57749	0.0008	0.00081	2.4	0.0043	NO DATA
Chloride	16887006	250,000		1,200,000	600,000	
Chloropyrifos	2921882			0.083	0.041	
Chromium (III)	16065831			e(0.8190 (ln Hard*)+3.7256)	e(0.8190 (ln Hard*)+0.6848)	NO DATA
Chromium (VI)	18540299			16	11	NO DATA
Copper	7440508	1,300		e(0.9422 (ln Hard*)-1.7)	e(0.8545 (ln Hard*)-1.702)	
Cyanide, Free	57125	700	220,000	22	5.2	NO DATA
Demeton	8065483				0.1	NO DATA
Dieldrin	60571	0.000052	0.000054	0.24	0.056	
Endrin	72208	0.76	0.81	0.086	0.036	
gamma-BHC (Lindane)	58899	0.019	0.063	0.95		
Guthion	86500				0.01	NO DATA
Heptachlor	76448	0.000079	0.000079	0.52	0.0038	
Heptachlor epoxide	1024573	0.000039	0.000039	0.52	0.0038	
Iron[6]	7439896			4,000	1,000	
Lead	7439921	15		e(1.273 (ln Hard*)-1.46)	e(1.273 (ln Hard*)-4.705)	
Malathion	121755				0.1	
Mercury	7439976	2	0.051	1.7	0.91	
Methoxychlor	72435	40			0.03	
Mirex	2385855				0.001	
Nickel	7440020	610	4,600	e(0.8460 (ln Hard*)+ 2.255)	e(0.8460 (ln Hard*)+ 0.0584)	
Parathion	56382			0.065	0.013	NO DATA
Pentachlorophenol	87865	0.27	3	e(1.005(pH)-4.869)	e(1.005(pH)-5.134)	
pH		6.5-8.5		6.0 - 9.0		
Phthalate esters	N/A				3	NO DATA
Phenol	108952	21,000	1,700,000			NO DATA
PolychlorinatedBiphenyls (PCBs)	N/A	0.000064	0.000064		0.0014	
Selenium	7782492	170	4,200	20	5	
Silver	7440224			e(1.72 (ln Hard*)-6.59)		
Hydrogen Sulfide, Undissociated	7783064				2	NO DATA
Temperature				See Temp-Month Table		
TDS and TSS	N/A	750,000		No adverse effects on aquatic life		
Toxaphene	8001352	0.00028	0.00028	0.73	0.0002	
Zinc	7440666	7,400	26,000	e(0.8473 (ln Hard*)+0.884)	e(0.8473 (ln Hard*)+0.884)	
4,4'-DDT	50293	0.00022	0.00022	1.1	0.001	
E. Coli (Sec7-Primary Contact)		< 1		240 CFU (20% of samples)		

Figure 3. 401 KAR 10:031 Water Quality Standards – Simplified Checklist

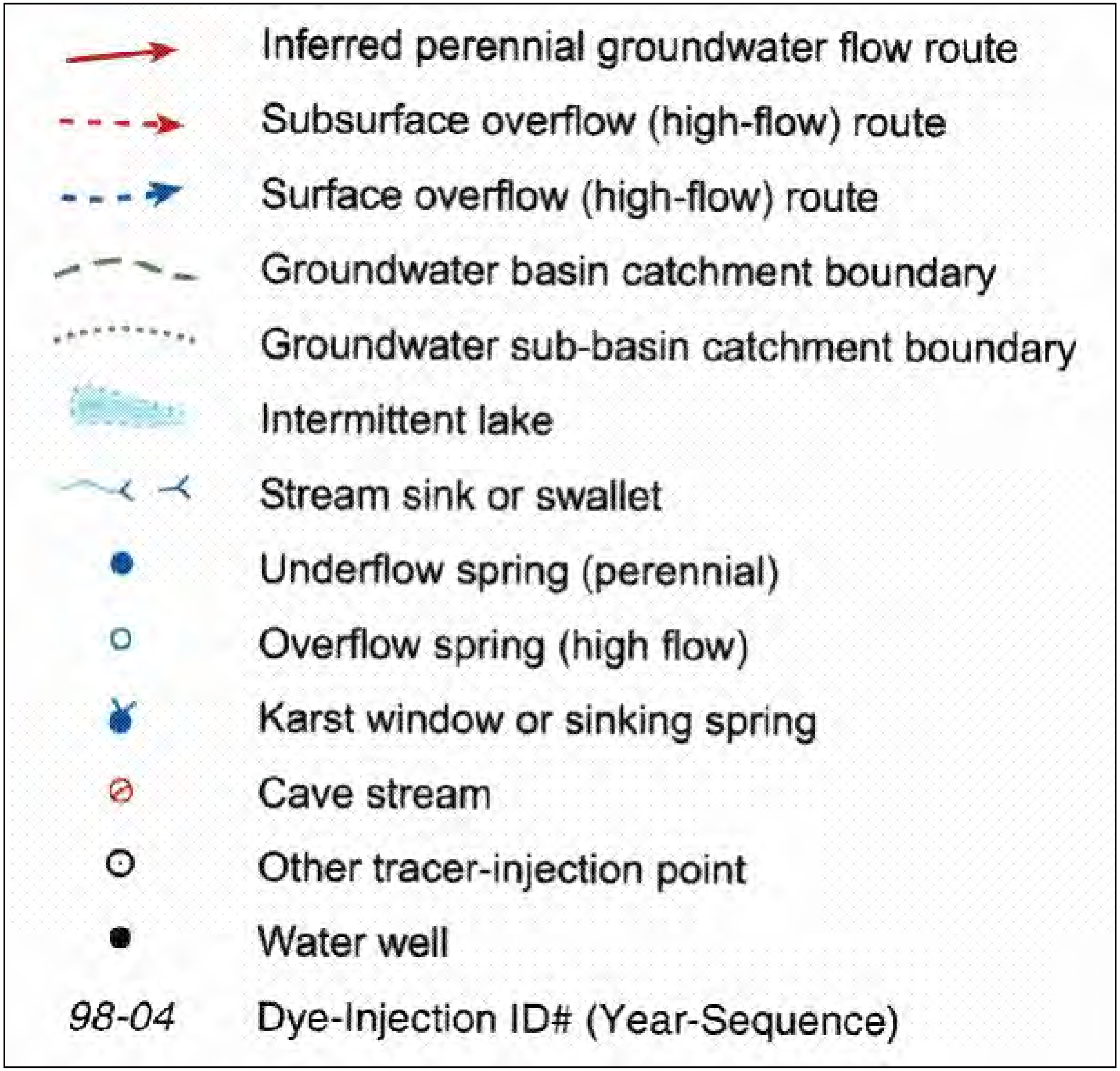


Figure 4. Karst Atlas Map Legend

Figure 5. Activated charcoal packet attached by trot-line clip to “Quinlan Gumdrop” or brick fitted with #10 copper wire. Devices secured to retrieval point with nylon cord.

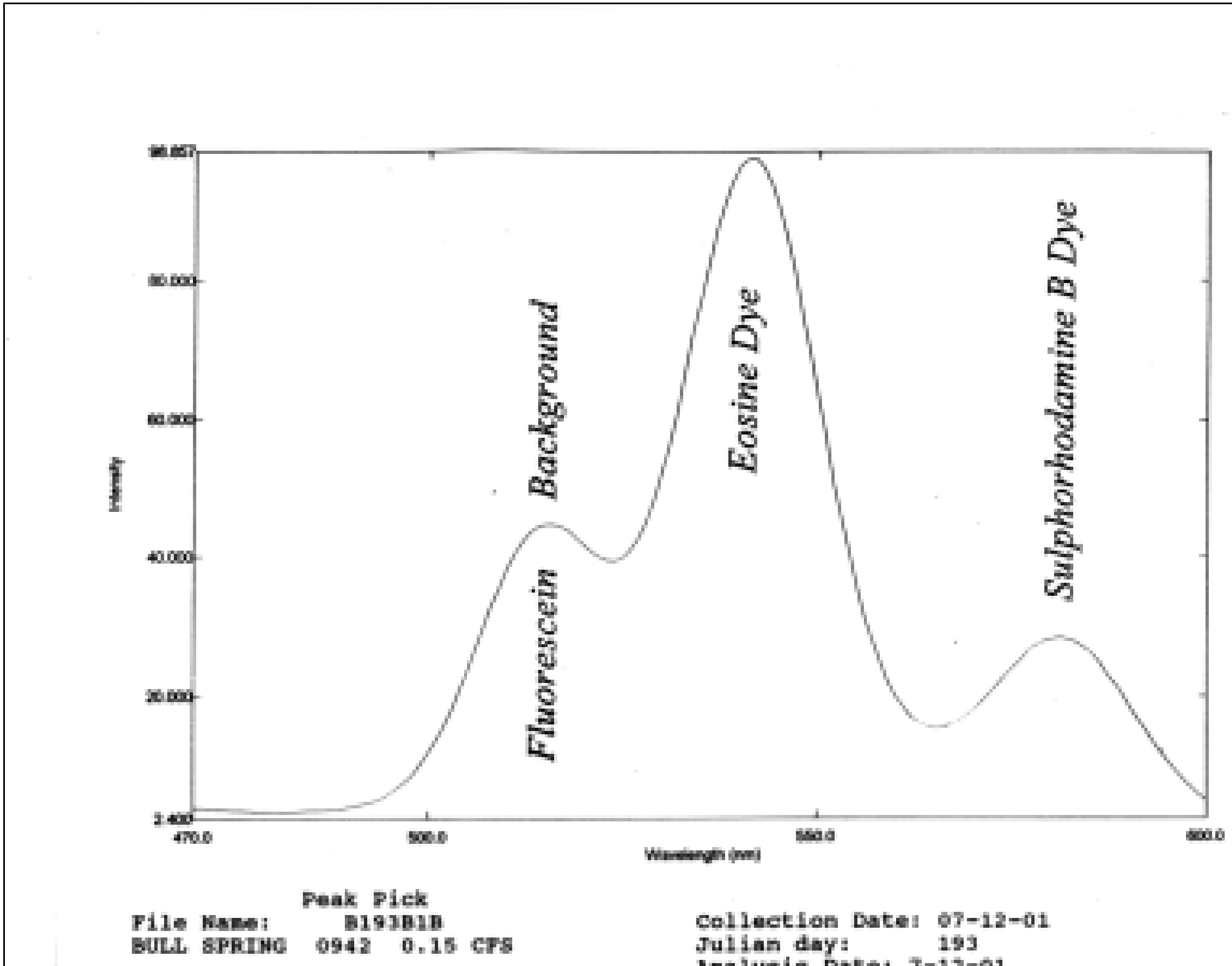


Figure 6. Typical Dye Curve on Spectrofluorophotometer

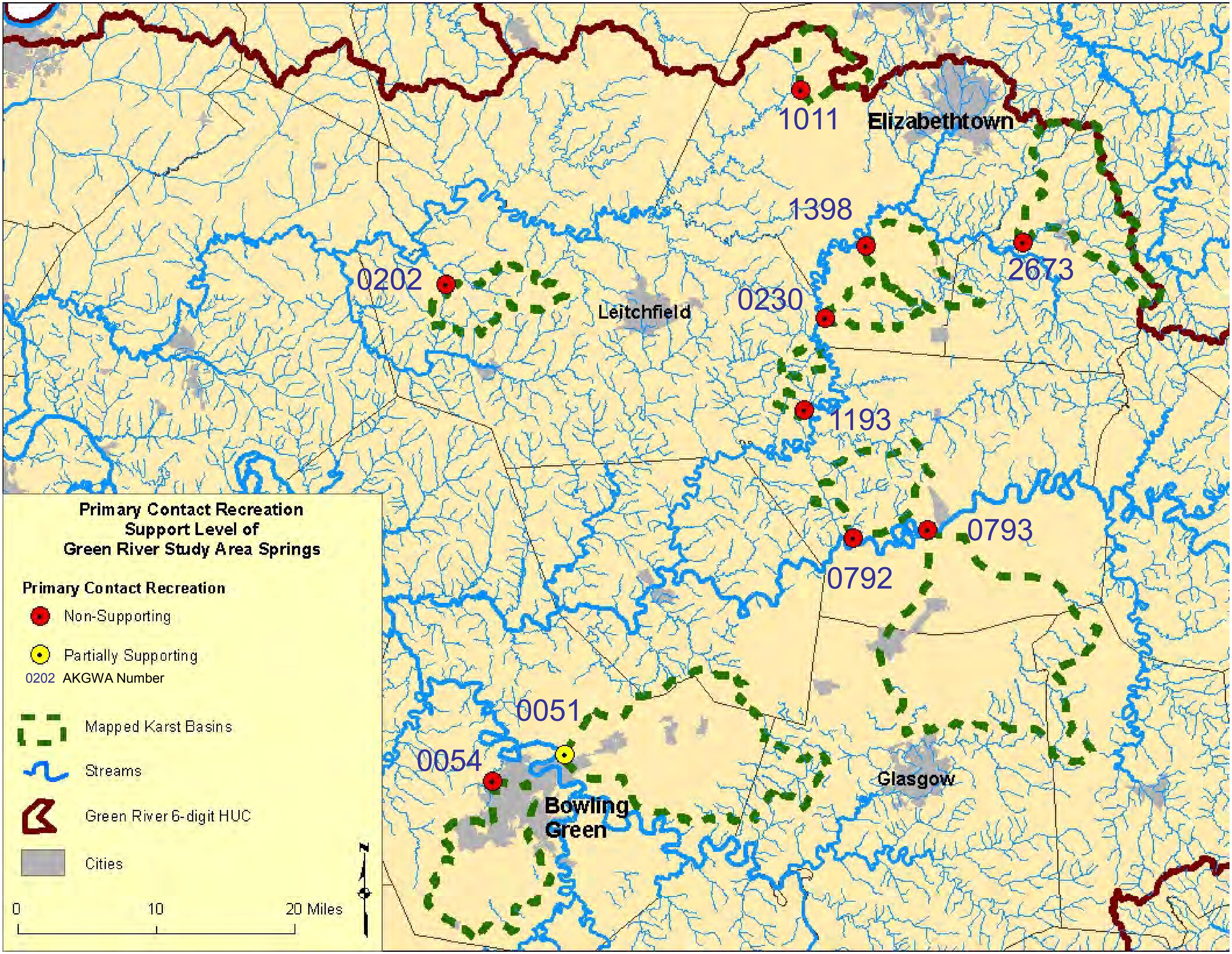


Figure 7. Primary Contact Recreation Assessment for Springs

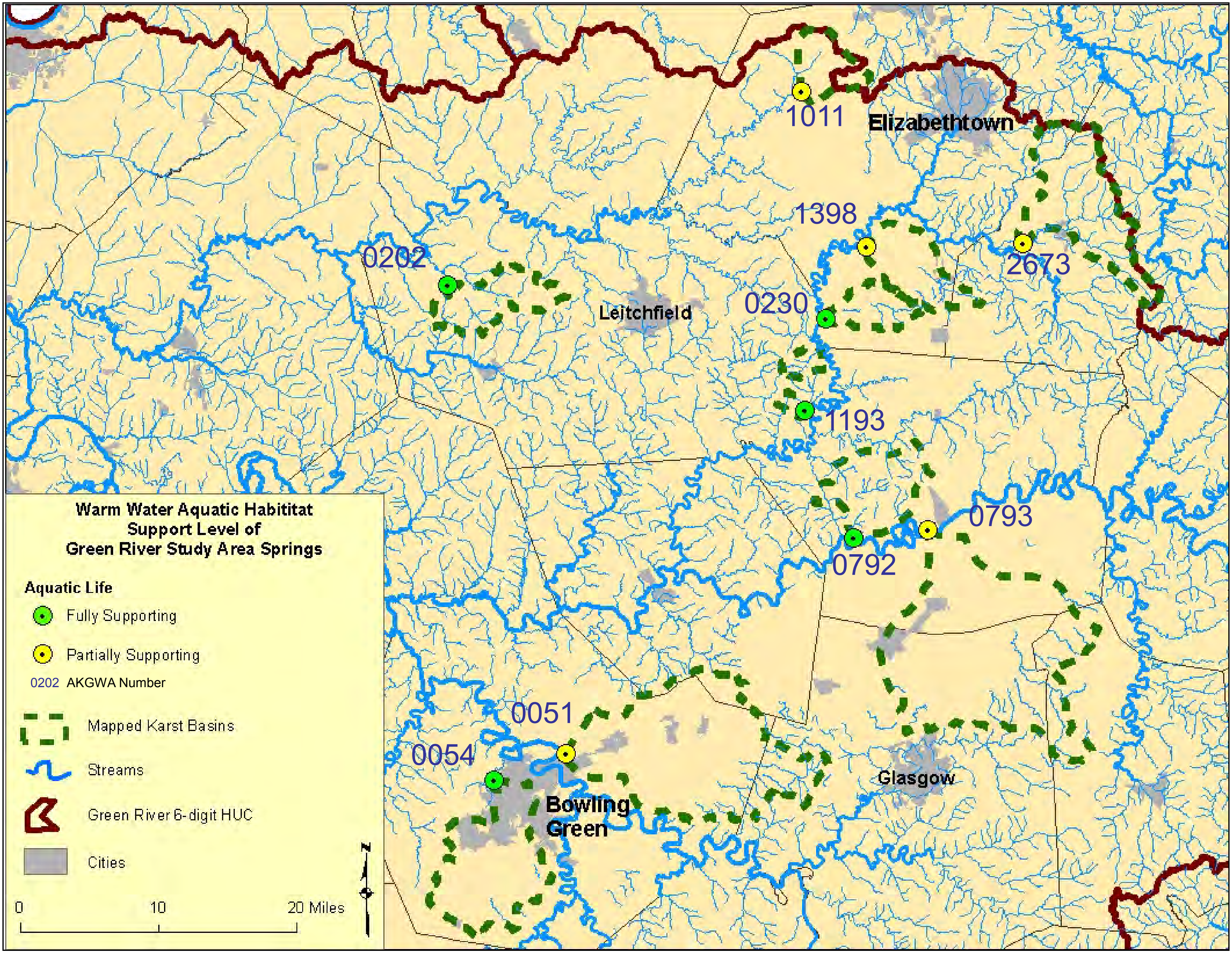


Figure 8. Warm-water Aquatic Habitat Assessment for Springs

Figure 9. Goodman Springs Photograph

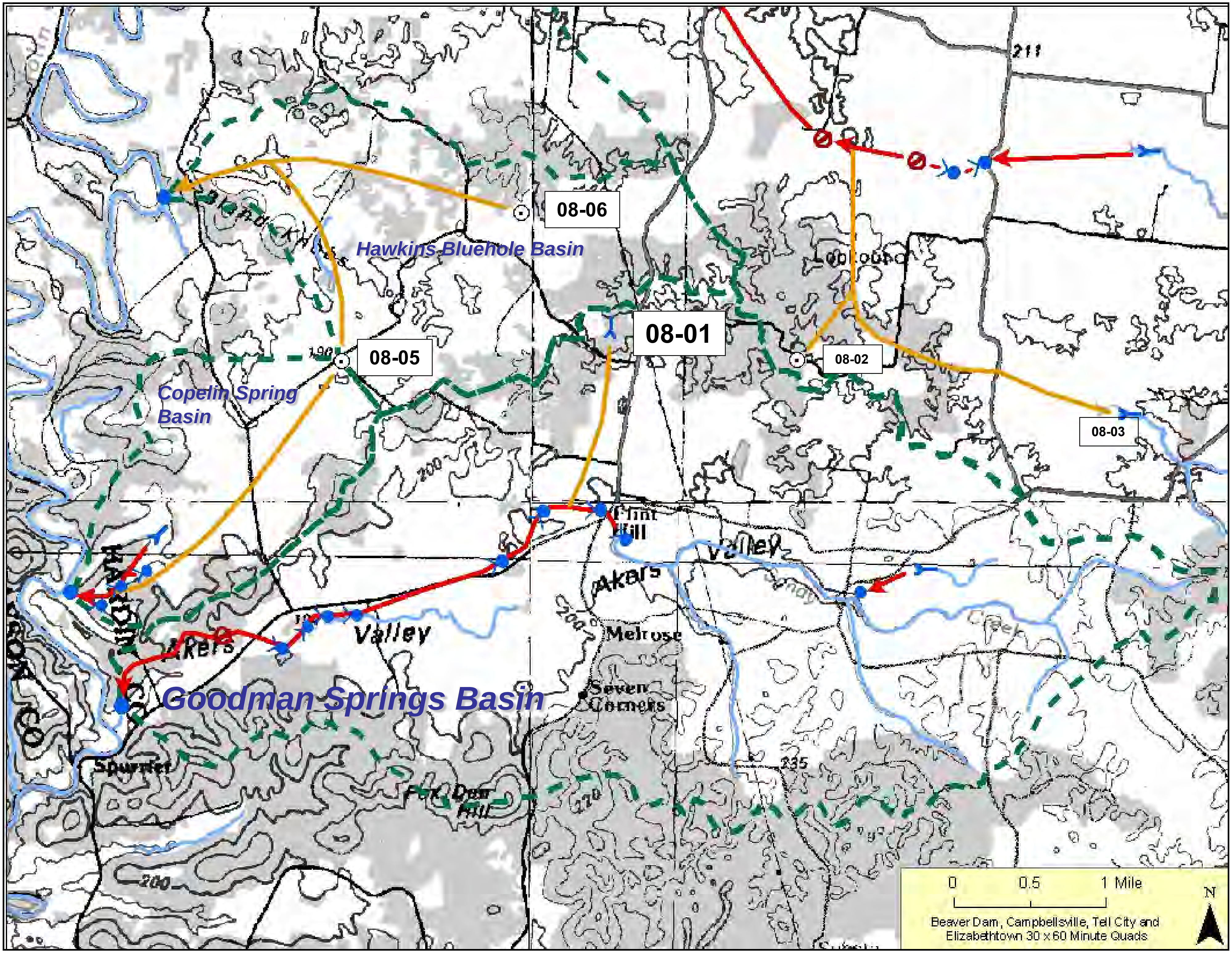
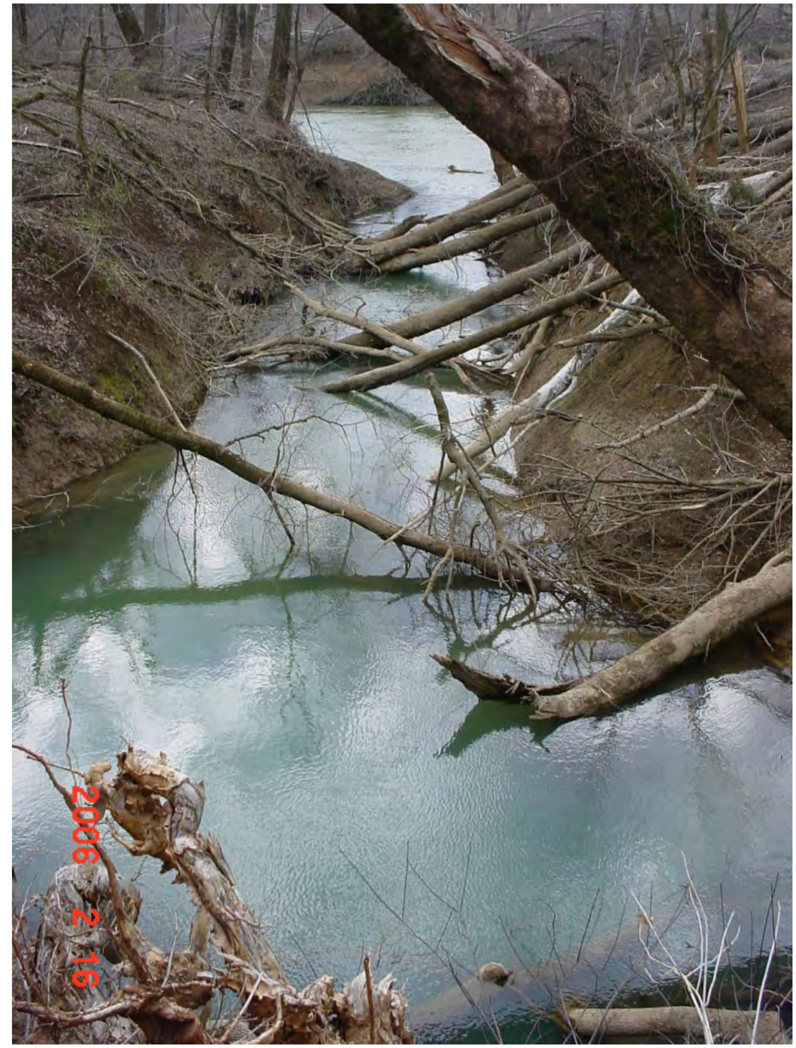


Figure 10. Goodman Springs Groundwater Basin Map (Hawkins Bluehole and Copelin Spring to North)

Goodman Spring (0230)	Hart Co.					
401 KAR 10:031. Section 4, Section 6 & Section 7-Allowable instream concentrations of pollutants						Impairment Level ≤10%=Not 11-25%=Partial >25%=Impaired
Pollutant	CAS[1] Number	Water Quality Criteria µg/L[2]				
		Human Health:		Warm Water Aquatic Habitat[3]:		
		DWS[4]	Fish[5]	Acute	Chronic	
Aldrin	309002	0.000049	0.00005	3		All Data Non-detect **(NOT)**
Alkalinity (as $CaCO_3$)				Reduction >25%		Largest Reduction = 17% **(NOT)**
alpha-Endosulfan	959988	62	89	0.22	0.056	All Data Non-detect **(NOT)**
Ammonia, un-ionized (mg/L) Y < 0.05 mg/L				Y=1.2(Ammonia-N)/(1+10pKa-pH)	pKa=0.0902+(2730/(273.2+T))	All Data Non-detect **(NOT)**
Arsenic	7440382	10		340	150	All Detects < Standards **(NOT)**
Beta-Endosulfan	33213659	62	89	0.22	0.056	All Data Non-detect **(NOT)**
Cadmium	7440439	5		e(1.0166 (ln Hard*)-3.924)	e(0.7409 (ln Hard*)-4.719)	All Data Non-detect **(NOT)**
Chlordane	57749	0.0008	0.00081	2.4	0.0043	NO DATA
Chloride	16887006	250,000		1,200,000	600,000	All Detects < Standards **(NOT)**
Chloropyrifos	2921882			0.083	0.041	All Data Non-detect **(NOT)**
Chromium (III)	16065831			e(0.8190 (ln Hard*)+3.7256)	e(0.8190 (ln Hard*)+0.6848)	NO DATA
Chromium (VI)	18540299			16	11	NO DATA
Copper	7440508	1,300		e(0.9422 (ln Hard*)-1.7)	e(0.8545 (ln Hard*)-1.702)	All Detects < Standards **(NOT)**
Cyanide, Free	57125	700	220,000	22	5.2	NO DATA
Demeton	8065483				0.1	NO DATA
Dieldrin	60571	0.000052	0.000054	0.24	0.056	All Data Non-detect **(NOT)**
Endrin	72208	0.76	0.81	0.086	0.036	All Data Non-detect **(NOT)**
gamma-BHC (Lindane)	58899	0.019	0.063	0.95		All Data Non-detect **(NOT)**
Guthion	86500				0.01	NO DATA
Heptachlor	76448	0.000079	0.000079	0.52	0.0038	Acute > DL > Chronic; All Non-detects
Heptachlor epoxide	1024573	0.000039	0.000039	0.52	0.0038	Acute > DL > Chronic; All Non-detects
Iron[6]	7439896			4,000	1,000	1/12 Samples > Chronic **(NOT)**
Lead	7439921	15		e(1.273 (ln Hard*)-1.46)	e(1.273 (ln Hard*)-4.705)	All Detects < Standards **(NOT)**
Malathion	121755				0.1	All Data Non-detect **(NOT)**
Mercury	7439976	2	0.051	1.7	0.91	2 Detects < Standards **(NOT)**
Methoxychlor	72435	40			0.03	1/12 Samples > Chronic **(NOT)**
Mirex	2385855				0.001	All Data Non-detect **(NOT)**
Nickel	7440020	610	4,600	e(0.8460 (ln Hard*)+ 2.255)	e(0.8460 (ln Hard*)+ 0.0584)	All Detects < Standards **(NOT)**
Parathion	56382			0.065	0.013	NO DATA
Pentachlorophenol	87865	0.27	3	e(1.005(pH)-4.869)	e(1.005(pH)-5.134)	All Data Non-detect **(NOT)**
pH		6.5-8.5		6.0 - 9.0		6.5 - 8.99 **(NOT)**
Phthalate esters	N/A				3	NO DATA
Phenol	108952	21,000	1,700,000			NO DATA
PolychlorinatedBiphenyls (PCBs)	N/A	0.000064	0.000064		0.0014	All Data Non-detect **(NOT)**
Selenium	7782492	170	4,200	20	5	8/12 Samples > Standards **(Impaired)**
Silver	7440224			e(1.72 (ln Hard*)-6.59)		All Data Non-detect **(NOT)**
Hydrogen Sulfide, Undissociated	7783064				2	NO DATA
Temperature				31.7 ° C		**NOT**
TDS and TSS	N/A	750,000		No adverse effects on aquatic life		
Toxaphene	8001352	0.00028	0.00028	0.73	0.0002	All Data Non-detect (NOT)
Zinc	7440666	7,400	26,000	e(0.8473 (ln Hard*)+0.884)	e(0.8473 (ln Hard*)+0.884)	All Detects < Standards **(NOT)**
4,4'-DDT	50293	0.00022	0.00022	1.1	0.001	Acute > DL > Chronic; All Non-detects
E. Coli (Sec7-Primary Contact)		< 1		240 CFU (20% of samples)		6/6 >240CFU/100mL **(IMPAIRED)**
Nutrient Issues as Narrative				Determined by WQB		**NOT**

Figure 11. 305(b) Assessment Checklist for Goodman Springs

View from bluff above spring looking down at blue hole and spring run to the Green River



View from head of blue hole looking down spring run to Green River

Figure 12. Gorin Mill Spring Photographs

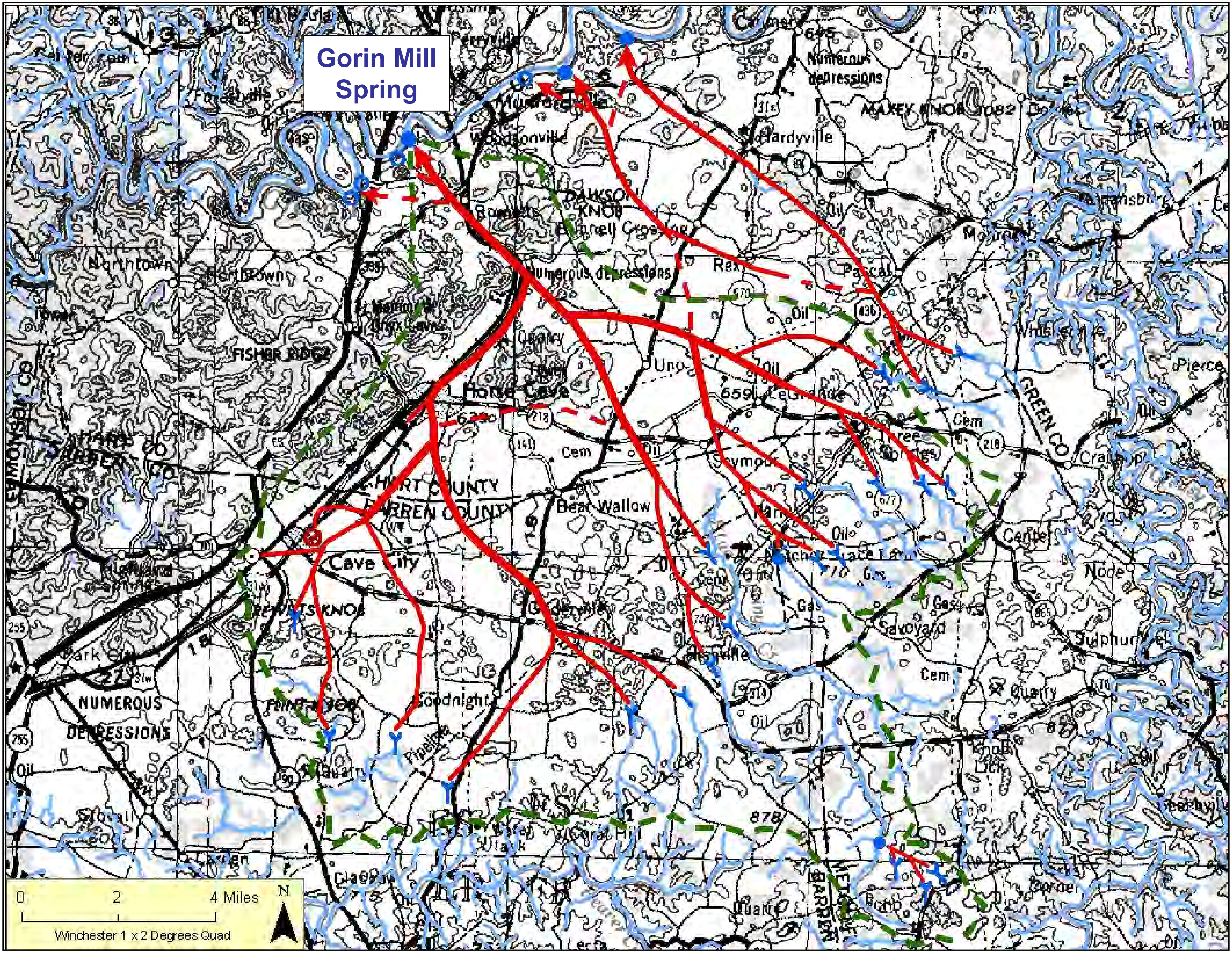


Figure 13. Gorin Mill Spring Groundwater Basin Map

Gorin Mill Spring (0793)	Hart Co.					
401 KAR 10:031. Section 4, Section 6 & Section 7-Allowable instream concentrations of pollutants						Impairment Level ≤10%=Not 11-25%=Partial >25%=Impaired
Pollutant	CAS[1] Number	Water Quality Criteria µg/L[2]				
		Human Health:		Warm Water Aquatic Habitat[3]:		
		DWS[4]	Fish[5]	Acute	Chronic	
Aldrin	309002	0.000049	0.00005	3		All Data Non-detect **(NOT)**
Alkalinity (as $CaCO_3$)				Reduction >25%		Largest Reduction = 24%
alpha-Endosulfan	959988	62	89	0.22	0.056	All Data Non-detect **(NOT)**
Ammonia, un-ionized (mg/L) Y < 0.05 mg/L				Y=1.2(Ammonia-N)/(1+10pKa-pH)	pKa=0.0902+(2730/(273.2+T))	One detect, Y < 0.05 mg/L **(NOT)**
Arsenic	7440382	10		340	150	All Detects < Standards **(NOT)**
Beta-Endosulfan	33213659	62	89	0.22	0.056	All Data Non-detect **(NOT)**
Cadmium	7440439	5		e(1.0166 (ln Hard*)-3.924)	e(0.7409 (ln Hard*)-4.719)	DL > Chronic; All detects < Acute
Chlordane	57749	0.0008	0.00081	2.4	0.0043	NO DATA
Chloride	16887006	250,000		1,200,000	600,000	All Detects < Standards **(NOT)**
Chloropyrifos	2921882			0.083	0.041	All Data Non-detect **(NOT)**
Chromium (III)	16065831			e(0.8190 (ln Hard*)+3.7256)	e(0.8190 (ln Hard*)+0.6848)	NO DATA
Chromium (VI)	18540299			16	11	NO DATA
Copper	7440508	1,300		e(0.9422 (ln Hard*)-1.7)	e(0.8545 (ln Hard*)-1.702)	All Detects < Standards **(NOT)**
Cyanide, Free	57125	700	220,000	22	5.2	NO DATA
Demeton	8065483				0.1	NO DATA
Dieldrin	60571	0.000052	0.000054	0.24	0.056	All Data Non-detect **(NOT)**
Endrin	72208	0.76	0.81	0.086	0.036	All Data Non-detect **(NOT)**
gamma-BHC (Lindane)	58899	0.019	0.063	0.95		All Data Non-detect **(NOT)**
Guthion	86500				0.01	NO DATA
Heptachlor	76448	0.000079	0.000079	0.52	0.0038	Acute > DL > Chronic; All Non-detects
Heptachlor epoxide	1024573	0.000039	0.000039	0.52	0.0038	Acute > DL > Chronic; All Non-detects
Iron[6]	7439896			4,000	1,000	2/12 (17%) > Chronic **(Partial)**
Lead	7439921	15		e(1.273 (ln Hard*)-1.46)	e(1.273 (ln Hard*)-4.705)	All Detects < Standards **(NOT)**
Malathion	121755				0.1	All Data Non-detect **(NOT)**
Mercury	7439976	2	0.051	1.7	0.91	1/12 (8%) > Chronic **(NOT)**
Methoxychlor	72435	40			0.03	All Data Non-detect **(NOT)**
Mirex	2385855				0.001	All Data Non-detect **(NOT)**
Nickel	7440020	610	4,600	e(0.8460 (ln Hard*)+ 2.255)	e(0.8460 (ln Hard*)+ 0.0584)	All Detects < Standards **(NOT)**
Parathion	56382			0.065	0.013	NO DATA
Pentachlorophenol	87865	0.27	3	e(1.005(pH)-4.869)	e(1.005(pH)-5.134)	All Data Non-detect **(NOT)**
pH		6.5-8.5		6.0 - 9.0		6.37 - 8.47 **(NOT)**
Phthalate esters	N/A				3	NO DATA
Phenol	108952	21,000	1,700,000			NO DATA
PolychlorinatedBiphenyls (PCBs)	N/A	0.000064	0.000064		0.0014	DL > Chronic (All Non-detect)
Selenium	7782492	170	4,200	20	5	All Detects < Standards **(NOT)**
Silver	7440224			e(1.72 (ln Hard*)-6.59)		All Data Non-detect **(NOT)**
Hydrogen Sulfide, Undissociated	7783064				2	NO DATA
Temperature				31.7 ° C		**NOT**
TDS and TSS	N/A	750,000		No adverse effects on aquatic life		
Toxaphene	8001352	0.00028	0.00028	0.73	0.0002	Acute > DL > Chronic; All Non-detects
Zinc	7440666	7,400	26,000	e(0.8473 (ln Hard*)+0.884)	e(0.8473 (ln Hard*)+0.884)	All Detects < Standards **(NOT)**
4,4'-DDT	50293	0.00022	0.00022	1.1	0.001	Acute > DL > Chronic; All Non-detects
E. Coli (Sec7-Primary Contact)		< 1		240 CFU (20% of samples)		5/6 >240 CFU/100 mL **(IMPAIRED)**
Nutrient Issues as Narrative				Determined by WQB		NO3-N and TOC **(IMPAIRED)**

Figure 14. 305(b) Assessment Checklist for Gorin Mill Spring

Figure 15. Graham Spring Photograph – rise pool and sink point of Graham Spring Karst Window

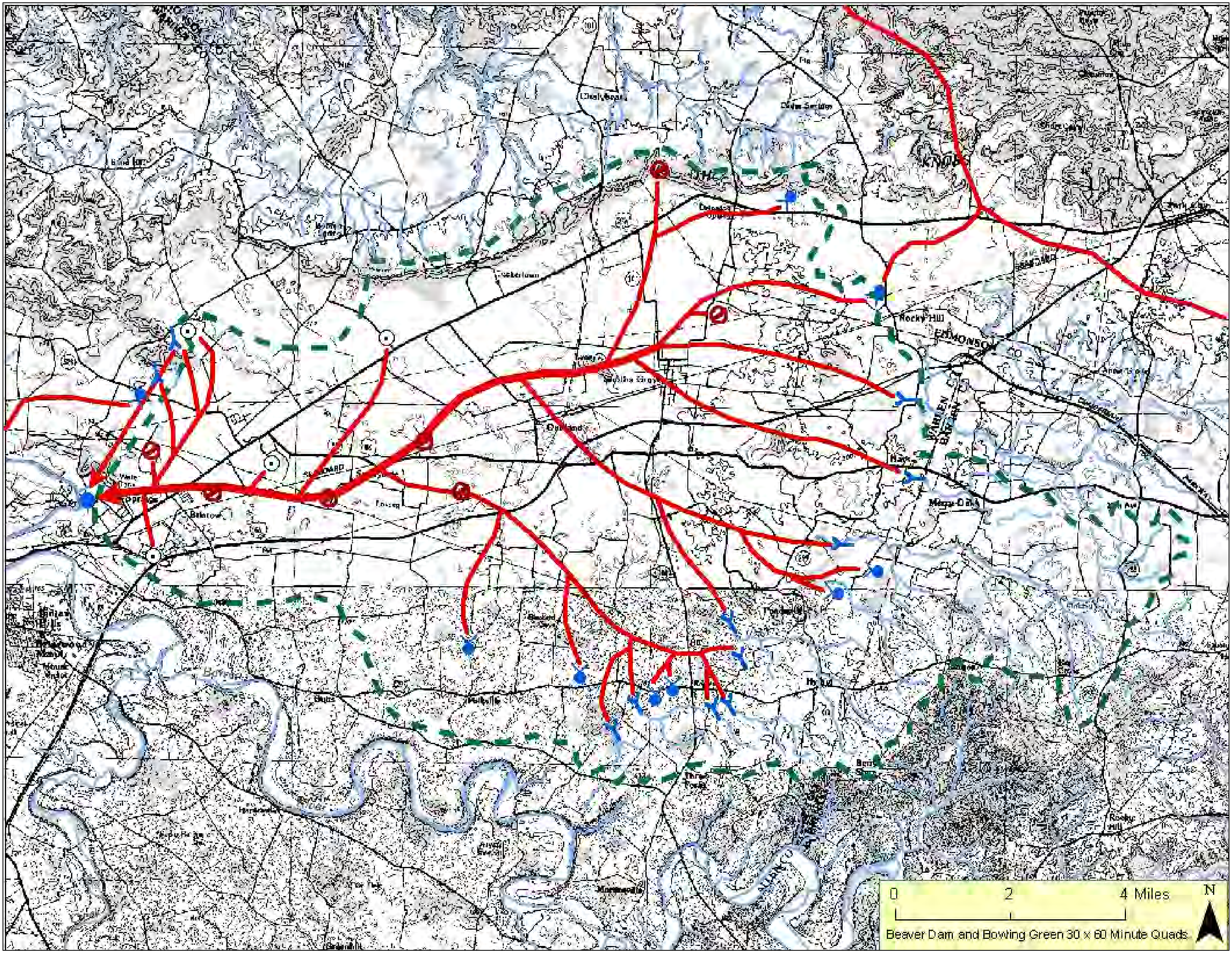
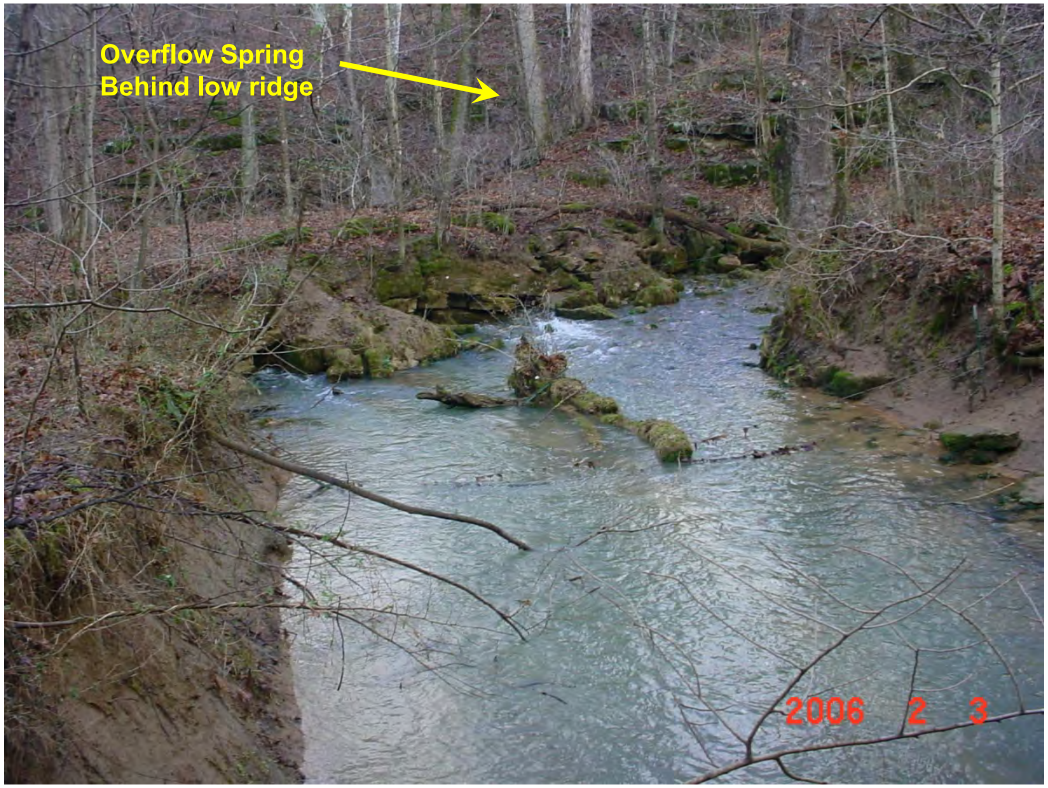


Figure 16. Graham Springs Groundwater Basin Map (Wilkins Bluehole)

Graham Spring (0051)	Warren Co.					
401 KAR 10:031. Section 4, Section 6 & Section 7-Allowable instream concentrations of pollutants						Impairment Level ≤10%=Not 11-25%=Partial >25%=Impaired
Pollutant	CAS[1] Number	Water Quality Criteria µg/L[2]				
		Human Health:		Warm Water Aquatic Habitat[3]:		
		DWS[4]	Fish[5]	Acute	Chronic	
Aldrin	309002	0.000049	0.00005	3		All Data Non-detect **(NOT)**
Alkalinity (as $CaCO_3$)				Reduction >25%		Largest Reduction = 22%
alpha-Endosulfan	959988	62	89	0.22	0.056	All Data Non-detect **(NOT)**
Ammonia, un-ionized (mg/L) Y < 0.05 mg/L				Y=1.2(Ammonia-N)/(1+10pKa-pH)	pKa=0.0902+(2730/(273.2+T))	4 detects, Y < 0.05 mg/L
Arsenic	7440382	10		340	150	All Detects < Standards **(NOT)**
Beta-Endosulfan	33213659	62	89	0.22	0.056	All Data Non-detect (NOT)
Cadmium	7440439	5		e(1.0166 (ln Hard*)-3.924)	e(0.7409 (ln Hard*)-4.719)	Acute > DL > Chronic; All Non-Detect
Chlordane	57749	0.0008	0.00081	2.4	0.0043	NO DATA
Chloride	16887006	250,000		1,200,000	600,000	All Detects < Standards **(NOT)**
Chloropyrifos	2921882			0.083	0.041	All Data Non-detect **(NOT)**
Chromium (III)	16065831			e(0.8190 (ln Hard*)+3.7256)	e(0.8190 (ln Hard*)+0.6848)	NO DATA
Chromium (VI)	18540299			16	11	NO DATA
Copper	7440508	1,300		e(0.9422 (ln Hard*)-1.7)	e(0.8545 (ln Hard*)-1.702)	All Detects < Standards **(NOT)**
Cyanide, Free	57125	700	220,000	22	5.2	NO DATA
Demeton	8065483				0.1	NO DATA
Dieldrin	60571	0.000052	0.000054	0.24	0.056	All Data Non-detect **(NOT)**
Endrin	72208	0.76	0.81	0.086	0.036	All Data Non-detect **(NOT)**
gamma-BHC (Lindane)	58899	0.019	0.063	0.95		All Data Non-detect **(NOT)**
Guthion	86500				0.01	NO DATA
Heptachlor	76448	0.000079	0.000079	0.52	0.0038	Acute > DL > Chronic; All Non-Detect
Heptachlor epoxide	1024573	0.000039	0.000039	0.52	0.0038	Acute > DL > Chronic; All Non-Detect
Iron[6]	7439896			4,000	1,000	2/12 (17%) > Chronic **(Partial)**
Lead	7439921	15		e(1.273 (ln Hard*)-1.46)	e(1.273 (ln Hard*)-4.705)	All Detects < Standards **(NOT)**
Malathion	121755				0.1	All Data Non-detect **(NOT)**
Mercury	7439976	2	0.051	1.7	0.91	All Data Non-detect **(NOT)**
Methoxychlor	72435	40			0.03	All Data Non-detect **(NOT)**
Mirex	2385855				0.001	DL > Chronic; All Non-Detect
Nickel	7440020	610	4,600	e(0.8460 (ln Hard*)+ 2.255)	e(0.8460 (ln Hard*)+ 0.0584)	All Detects < Standards **(NOT)**
Parathion	56382			0.065	0.013	NO DATA
Pentachlorophenol	87865	0.27	3	e(1.005(pH)-4.869)	e(1.005(pH)-5.134)	All Data Non-detect **(NOT)**
pH		6.5-8.5		6.0 - 9.0		6.48 - 8.2 **(NOT)**
Phthalate esters	N/A				3	NO DATA
Phenol	108952	21,000	1,700,000			NO DATA
PolychlorinatedBiphenyls (PCBs)	N/A	0.000064	0.000064		0.0014	DL > Chronic; All Non-Detect
Selenium	7782492	170	4,200	20	5	All Detects < Standards **(NOT)**
Silver	7440224			e(1.72 (ln Hard*)-6.59)		All Data Non-detect **(NOT)**
Hydrogen Sulfide, Undissociated	7783064				2	NO DATA
Temperature				31.7 ° C		**NOT**
TDS and TSS	N/A	750,000		No adverse effects on aquatic life		
Toxaphene	8001352	0.00028	0.00028	0.73	0.0002	Acute > DL > Chronic; All Non-Detect
Zinc	7440666	7,400	26,000	e(0.8473 (ln Hard*)+0.884)	e(0.8473 (ln Hard*)+0.884)	All Detects < Standards **(NOT)**
4,4'-DDT	50293	0.00022	0.00022	1.1	0.001	Accute > DL > Chronic; All Non-Detect
E. Coli (Sec7-Primary Contact)		< 1		240 CFU (20% of samples)		2/6 > 240 CFU/100mL **(IMPAIRED)**
Nutrient Issues as Narrative				Determined by WQB		NO3-N and TOC **(IMPAIRED)**

Figure 17. 305(b) Assessment Checklist for Graham Spring



Head of Rough River Perennial Spring

Head of Rough River Overflow Spring located about 50 feet north of perennial spring

Figure 18. Head of Rough River Spring Photographs

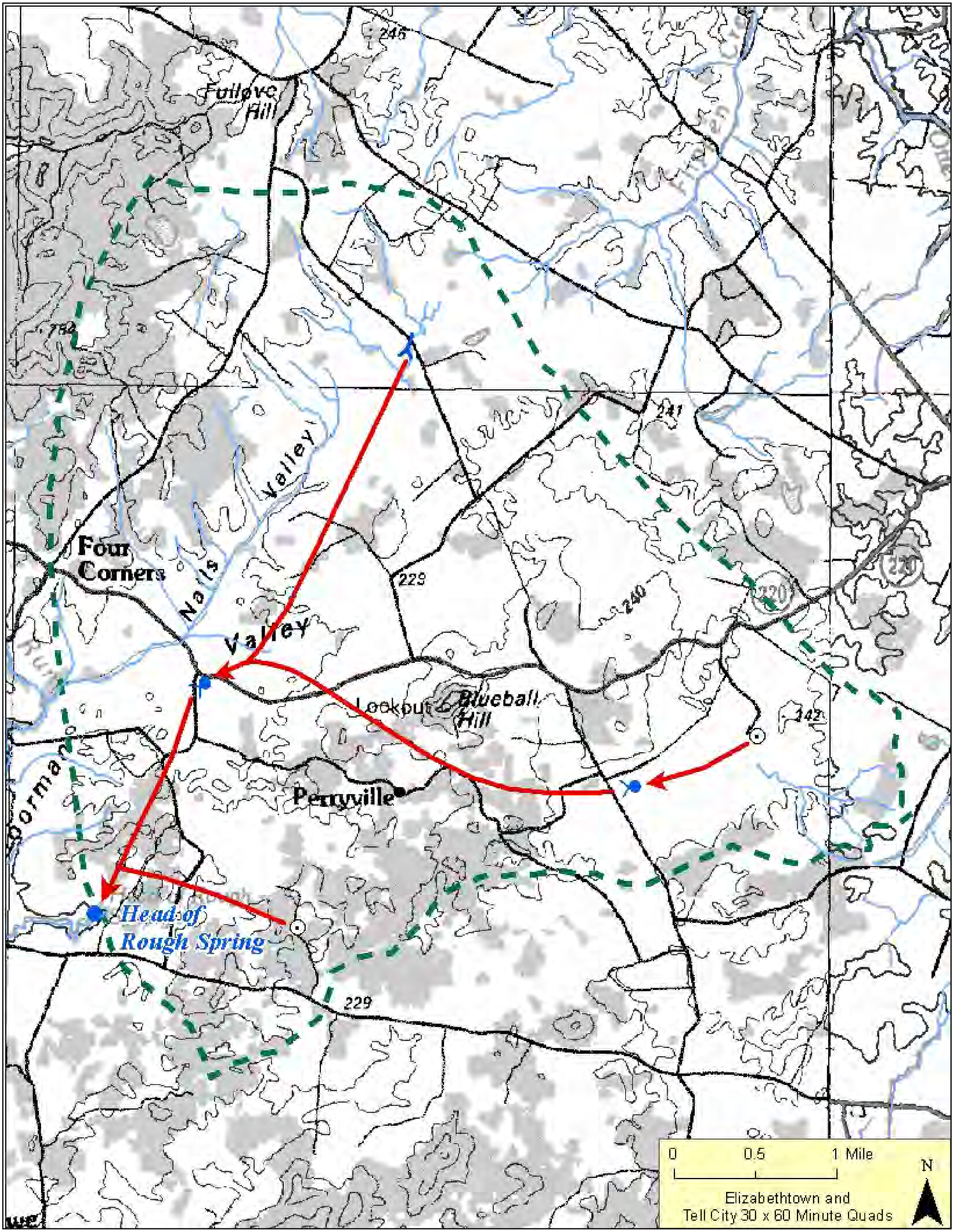


Figure 19. Head of Rough River Spring Groundwater Basin Map

Head of Rough Spring (1011)	Hardin Co.					
401 KAR 10:031. Section 4, Section 6 & Section 7-Allowable instream concentrations of pollutants						Impairment Level ≤10%=Not 11-25%=Partial >25%=Impaired
Pollutant	CAS[1] Number	Water Quality Criteria μg/L[2]				
		Human Health:		Warm Water Aquatic Habitat[3]:		
		DWS[4]	Fish[5]	Acute	Chronic	
Aldrin	309002	0.000049	0.00005	3		All Data Non-detect **(NOT)**
Alkalinity (as $CaCO_3$)				Reduction >25%		**NOT**
alpha-Endosulfan	959988	62	89	0.22	0.056	All Data Non-detect **(NOT)**
Ammonia, un-ionized (mg/L) Y < 0.05 mg/L				Y=1.2(Ammonia-N)/(1+10pKa-pH)	pKa=0.0902+(2730/(273.2+T))	1 Detect; Y < 0.05 mg/L **(NOT)**
Arsenic	7440382	10		340	150	All Detects < Standards **(NOT)**
Beta-Endosulfan	33213659	62	89	0.22	0.056	All Data Non-detect **(NOT)**
Cadmium	7440439	5		e(1.0166 (ln Hard*)-3.924)	e(0.7409 (ln Hard*)-4.719)	Acute > DL > Chronic; All Non-detect
Chlordane	57749	0.0008	0.00081	2.4	0.0043	NO DATA
Chloride	16887006	250,000		1,200,000	600,000	All Detects < Standards **(NOT)**
Chloropyrifos	2921882			0.083	0.041	All Data Non-detect **(NOT)**
Chromium (III)	16065831			e(0.8190 (ln Hard*)+3.7256)	e(0.8190 (ln Hard*)+0.6848)	NO DATA
Chromium (VI)	18540299			16	11	NO DATA
Copper	7440508	1,300		e(0.9422 (ln Hard*)-1.7)	e(0.8545 (ln Hard*)-1.702)	All Detects < Standards **(NOT)**
Cyanide, Free	57125	700	220,000	22	5.2	NO DATA
Demeton	8065483				0.1	NO DATA
Dieldrin	60571	0.000052	0.000054	0.24	0.056	All Data Non-detect **(NOT)**
Endrin	72208	0.76	0.81	0.086	0.036	All Data Non-detect **(NOT)**
gamma-BHC (Lindane)	58899	0.019	0.063	0.95		All Data Non-detect **(NOT)**
Guthion	86500				0.01	NO DATA
Heptachlor	76448	0.000079	0.000079	0.52	0.0038	All Data Non-detect **(NOT)**
Heptachlor epoxide	1024573	0.000039	0.000039	0.52	0.0038	All Data Non-detect **(NOT)**
Iron[6]	7439896			4,000	1,000	2/12 (17%) > Chronic **(PARTIAL)**
Lead	7439921	15		e(1.273 (ln Hard*)-1.46)	e(1.273 (ln Hard*)-4.705)	All Detects < Standards **(NOT)**
Malathion	121755				0.1	All Data Non-detect **(NOT)**
Mercury	7439976	2	0.051	1.7	0.91	1 Detect < Standards **(NOT)**
Methoxychlor	72435	40			0.03	1/12 (8%) > Chronic **(NOT)**
Mirex	2385855				0.001	DL > Chronic; All Non-detects
Nickel	7440020	610	4,600	e(0.8460 (ln Hard*)+ 2.255)	e(0.8460 (ln Hard*)+ 0.0584)	All Detects < Standards **(NOT)**
Parathion	56382			0.065	0.013	NO DATA
Pentachlorophenol	87865	0.27	3	e(1.005(pH)-4.869)	e(1.005(pH)-5.134)	1 Detect < Standards **(NOT)**
pH		6.5-8.5		6.0 - 9.0		6.16 - 8.51 **(NOT)**
Phthalate esters	N/A				3	NO DATA
Phenol	108952	21,000	1,700,000			NO DATA
PolychlorinatedBiphenyls (PCBs)	N/A	0.000064	0.000064		0.0014	DL > Chronic; All Non-detects
Selenium	7782492	170	4,200	20	5	All Detects < Standards **(NOT)**
Silver	7440224			e(1.72 (ln Hard*)-6.59)		All Data Non-detect **(NOT)**
Hydrogen Sulfide, Undissociated	7783064				2	NO DATA
Temperature				31.7 ° C		**NOT**
TDS and TSS	N/A	750,000		No adverse effects on aquatic life		
Toxaphene	8001352	0.00028	0.00028	0.73	0.0002	Acute > DL > Chronic; All Non-detect
Zinc	7440666	7,400	26,000	e(0.8473 (ln Hard*)+0.884)	e(0.8473 (ln Hard*)+0.884)	All Detects < Standards **(NOT)**
4,4'-DDT	50293	0.00022	0.00022	1.1	0.001	Acute > DL > Chronic; All Non-detect
E. Coli (Sec7-Primary Contact)		< 1		240 CFU (20% of samples)		5/6 > 240 CFU/100mL **(IMPAIRED)**
Nutrient Issues as Narrative				Determined by WQB		NO3-N, TOC and TKN **(IMPAIRED)**

Figure 20. 305(b) Assessment Checklist for Head of Rough River Spring

Figure 21. Lost River Rise Photograph

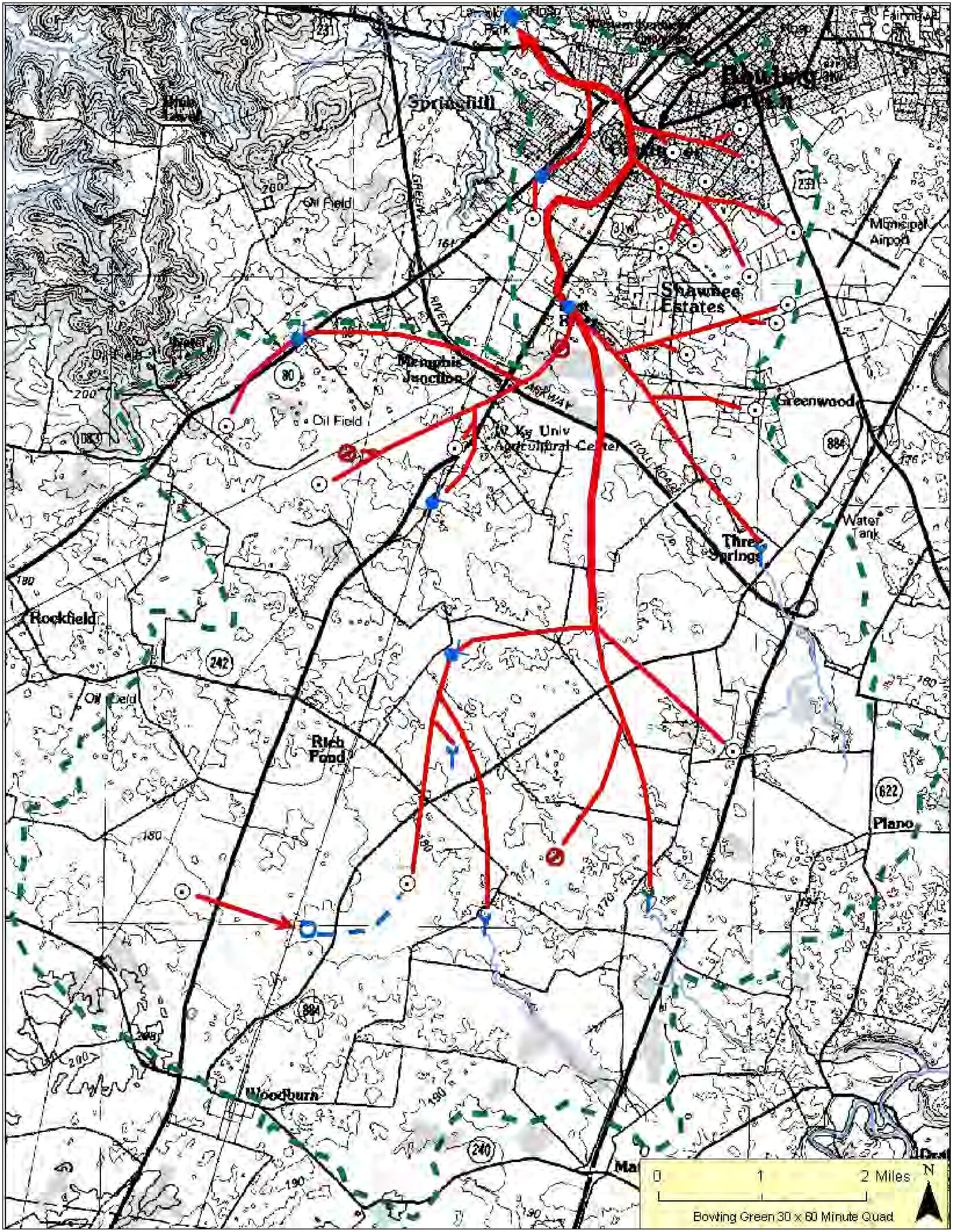


Figure 22. Lost River Rise Groundwater Basin Map

Lost River Rise (0054)	Warren Co.					
401 KAR 10:031. Section 4, Section 6 & Section 7-Allowable instream concentrations of pollutants						Impairment Level ≤10%=Not 11-25%=Partial >25%=Impaired
Pollutant	CAS[1] Number	Water Quality Criteria µg/L[2]				
		Human Health:		Warm Water Aquatic Habitat[3]:		
		DWS[4]	Fish[5]	Acute	Chronic	
Aldrin	309002	0.000049	0.00005	3		All Data Non-detect **(NOT)**
Alkalinity (as $CaCO_3$)				Reduction >25%		**NOT**
alpha-Endosulfan	959988	62	89	0.22	0.056	All Data Non-detect **(NOT)**
Ammonia, un-ionized (mg/L) Y < 0.05 mg/L				Y=1.2(Ammonia-N)/(1+10pKa-pH)	pKa=0.0902+(2730/(273.2+T))	3 Detects; Y < 0.05 mg/L **(NOT)**
Arsenic	7440382	10		340	150	All Detects < Standards **(NOT)**
Beta-Endosulfan	33213659	62	89	0.22	0.056	All Data Non-detect **(NOT)**
Cadmium	7440439	5		e(1.0166 (ln Hard*)-3.924)	e(0.7409 (ln Hard*)-4.719)	Acute > DL > Chronic; All Non-detects
Chlordane	57749	0.0008	0.00081	2.4	0.0043	NO DATA
Chloride	16887006	250,000		1,200,000	600,000	All Detects < Standards **(NOT)**
Chloropyrifos	2921882			0.083	0.041	All Data Non-detect **(NOT)**
Chromium (III)	16065831			e(0.8190 (ln Hard*)+3.7256)	e(0.8190 (ln Hard*)+0.6848)	NO DATA
Chromium (VI)	18540299			16	11	NO DATA
Copper	7440508	1,300		e(0.9422 (ln Hard*)-1.7)	e(0.8545 (ln Hard*)-1.702)	All Detects < Standards **(NOT)**
Cyanide, Free	57125	700	220,000	22	5.2	NO DATA
Demeton	8065483				0.1	NO DATA
Dieldrin	60571	0.000052	0.000054	0.24	0.056	All Data Non-detect **(NOT)**
Endrin	72208	0.76	0.81	0.086	0.036	All Data Non-detect **(NOT)**
gamma-BHC (Lindane)	58899	0.019	0.063	0.95		All Data Non-detect **(NOT)**
Guthion	86500				0.01	NO DATA
Heptachlor	76448	0.000079	0.000079	0.52	0.0038	All Data Non-detect **(NOT)**
Heptachlor epoxide	1024573	0.000039	0.000039	0.52	0.0038	All Data Non-detect **(NOT)**
Iron[6]	7439896			4,000	1,000	All Detects < Standards **(NOT)**
Lead	7439921	15		e(1.273 (ln Hard*)-1.46)	e(1.273 (ln Hard*)-4.705)	All Detects < Standards **(NOT)**
Malathion	121755				0.1	All Data Non-detect **(NOT)**
Mercury	7439976	2	0.051	1.7	0.91	1 Detect < Standards **(NOT)**
Methoxychlor	72435	40			0.03	1/12 (8%) > Chronic **(NOT)**
Mirex	2385855				0.001	DL > Chronic; All Non-detects
Nickel	7440020	610	4,600	e(0.8460 (ln Hard*)+ 2.255)	e(0.8460 (ln Hard*)+ 0.0584)	All Detects < Standards **(NOT)**
Parathion	56382			0.065	0.013	NO DATA
Pentachlorophenol	87865	0.27	3	e(1.005(pH)-4.869)	e(1.005(pH)-5.134)	All Data Non-detect **(NOT)**
pH		6.5-8.5		6.0 - 9.0		6.57 - 7.83 **(NOT)**
Phthalate esters	N/A				3	NO DATA
Phenol	108952	21,000	1,700,000			NO DATA
PolychlorinatedBiphenyls (PCBs)	N/A	0.000064	0.000064		0.0014	DL > Chronic; All Non-detects
Selenium	7782492	170	4,200	20	5	All Detects < Standards **(NOT)**
Silver	7440224			e(1.72 (ln Hard*)-6.59)		All Data Non-detect **(NOT)**
Hydrogen Sulfide, Undissociated	7783064				2	NO DATA
Temperature				31.7 ° C		**NOT**
TDS and TSS	N/A	750,000		No adverse effects on aquatic life		
Toxaphene	8001352	0.00028	0.00028	0.73	0.0002	Acute > DL > Chronic; All Non-detects
Zinc	7440666	7,400	26,000	e(0.8473 (ln Hard*)+0.884)	e(0.8473 (ln Hard*)+0.884)	All Detects < Standards **(NOT)**
4,4'-DDT	50293	0.00022	0.00022	1.1	0.001	Acute > DL > Chronic; All Non-detects
E. Coli (Sec7-Primary Contact)		< 1		240 CFU (20% of samples)		5/6 > 240 CFU/100mL **(IMPAIRED)**
Nutrient Issues as Narrative				Determined by WQB		**NOT**

Figure 23. 305(b) Assessment Checklist for Lost River Rise

Figure 24. Mahurin Spring Photograph

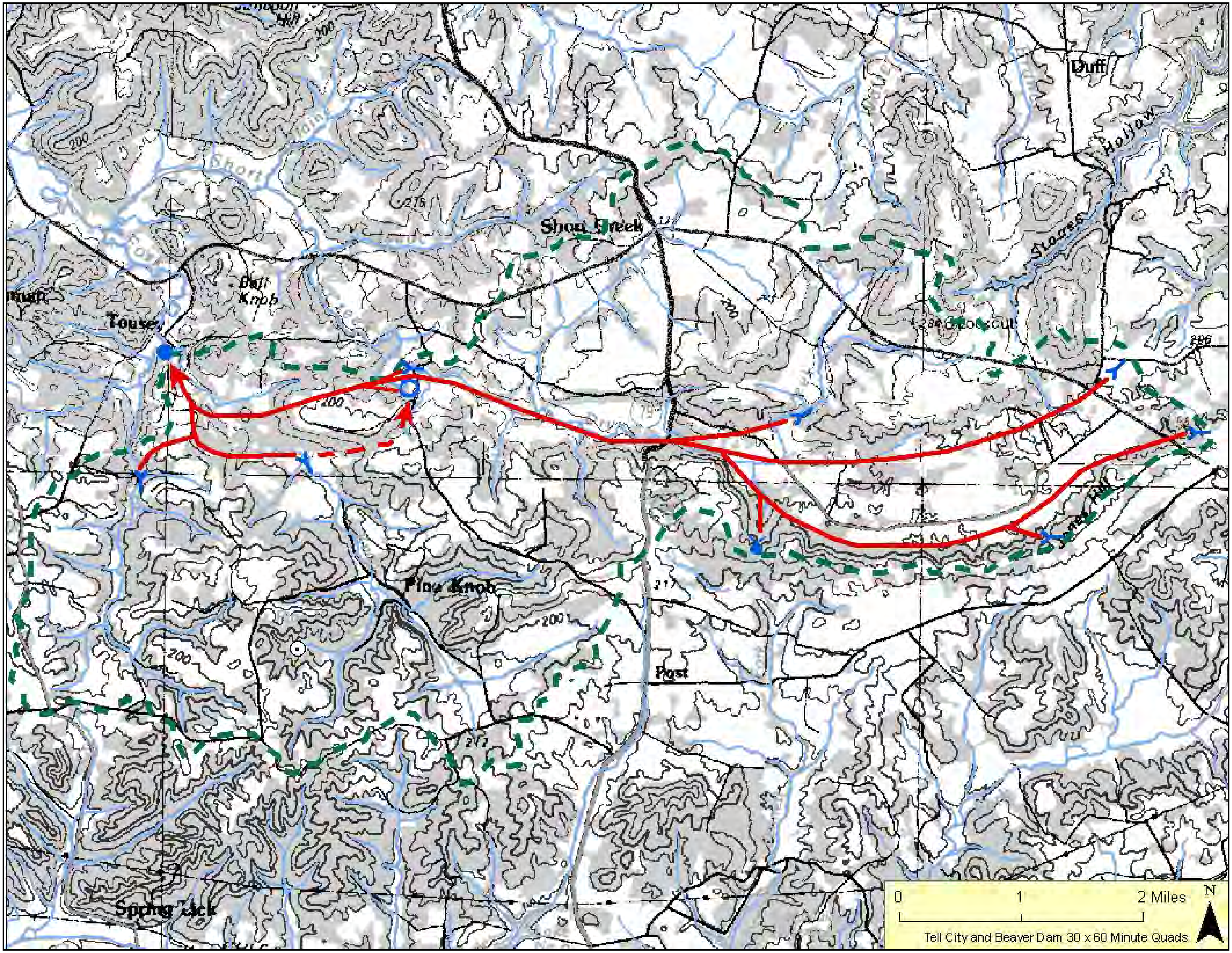


Figure 25. Mahurin Spring Groundwater Basin Map

Mahurin Spring (0202)	Grayson Co.					
401 KAR 10:031. Section 4, Section 6 & Section 7-Allowable instream concentrations of pollutants						Impairment Level ≤10%=Not 11-25%=Partial >25%=Impaired
Pollutant	**CAS[1] Number**	**Water Quality Criteria μg/L[2]**				
		Human Health:		**Warm Water Aquatic Habitat[3]:**		
		DWS[4]	Fish[5]	**Acute**	**Chronic**	
Aldrin	309002	0.000049	0.00005	3		All Data Non-detect **(NOT)**
Alkalinity (as $CaCO_3$)				Reduction >25%		**NOT**
alpha-Endosulfan	959988	62	89	0.22	0.056	1 Detect < Standards **(NOT)**
Ammonia, un-ionized (mg/L) Y < 0.05 mg/L				Y=1.2(Ammonia-N)/(1+10pKa-pH)	pKa=0.0902+(2730/(273.2+T))	1 Detect; Y < 0.05 mg/L **(NOT)**
Arsenic	7440382	10		340	150	All Detects < Standards **(NOT)**
Beta-Endosulfan	33213659	62	89	0.22	0.056	1 Detect < Standards **(NOT)**
Cadmium	7440439	5		e(1.0166 (ln Hard*)-3.924)	e(0.7409 (ln Hard*)-4.719)	Acute > DL > Chronic; All Non-detects
Chlordane	57749	0.0008	0.00081	2.4	0.0043	NO DATA
Chloride	16887006	250,000		1,200,000	600,000	All Detects < Standards **(NOT)**
Chloropyrifos	2921882			0.083	0.041	All Data Non-detect **(NOT)**
Chromium (III)	16065831			e(0.8190 (ln Hard*)+3.7256)	e(0.8190 (ln Hard*)+0.6848)	NO DATA
Chromium (VI)	18540299			16	11	NO DATA
Copper	7440508	1,300		e(0.9422 (ln Hard*)-1.7)	e(0.8545 (ln Hard*)-1.702)	All Detects < Standards **(NOT)**
Cyanide, Free	57125	700	220,000	22	5.2	NO DATA
Demeton	8065483				0.1	NO DATA
Dieldrin	60571	0.000052	0.000054	0.24	0.056	1 Detect < Standards **(NOT)**
Endrin	72208	0.76	0.81	0.086	0.036	All Data Non-detect **(NOT)**
gamma-BHC (Lindane)	58899	0.019	0.063	0.95		All Data Non-detect **(NOT)**
Guthion	86500				0.01	NO DATA
Heptachlor	76448	0.000079	0.000079	0.52	0.0038	Acute > DL > Chronic; All Non-detects
Heptachlor epoxide	1024573	0.000039	0.000039	0.52	0.0038	Acute > DL > Chronic; All Non-detects
Iron[6]	7439896			4,000	1,000	2/12 (17%) > Chronic (PARTIAL)
Lead	7439921	15		e(1.273 (ln Hard*)-1.46)	e(1.273 (ln Hard*)-4.705)	All Detects < Standards **(NOT)**
Malathion	121755				0.1	All Data Non-detect **(NOT)**
Mercury	7439976	2	0.051	1.7	0.91	1 Detect < Standards **(NOT)**
Methoxychlor	72435	40			0.03	All Data Non-detect **(NOT)**
Mirex	2385855				0.001	DL > Chronic; All Non-detects
Nickel	7440020	610	4,600	e(0.8460 (ln Hard*)+ 2.255)	e(0.8460 (ln Hard*)+ 0.0584)	All Detects < Standards **(NOT)**
Parathion	56382			0.065	0.013	NO DATA
Pentachlorophenol	87865	0.27	3	e(1.005(pH)-4.869)	e(1.005(pH)-5.134)	All Data Non-detect **(NOT)**
pH		6.5-8.5		6.0 - 9.0		6.06 - 8.52 **(NOT)**
Phthalate esters	N/A				3	NO DATA
Phenol	108952	21,000	1,700,000			NO DATA
PolychlorinatedBiphenyls (PCBs)	N/A	0.000064	0.000064		0.0014	DL > Chronic; All Non-detects
Selenium	7782492	170	4,200	20	5	All Detects < Standards **(NOT)**
Silver	7440224			e(1.72 (ln Hard*)-6.59)		All Data Non-detect **(NOT)**
Hydrogen Sulfide, Undissociated	7783064				2	NO DATA
Temperature				31.7 ° C		**NOT**
TDS and TSS	N/A	750,000		No adverse effects on aquatic life		
Toxaphene	8001352	0.00028	0.00028	0.73	0.0002	Acute > DL > Chronic; All Non-detects
Zinc	7440666	7,400	26,000	e(0.8473 (ln Hard*)+0.884)	e(0.8473 (ln Hard*)+0.884)	All Detects < Standards **(NOT)**
4,4'-DDT	50293	0.00022	0.00022	1.1	0.001	Acute > DL > Chronic; All Non-detects
E. Coli (Sec7-Primary Contact)		< 1		240 CFU (20% of samples)		3/6 > 240 CFU/100 mL **(IMPAIRED)**
Nutrient Issues as Narrative				Determined by WQB		**NOT**

Figure 26. 305(b) Assessment Checklist for Mahurin Spring

Figure 27. McCoy Bluehole Photograph

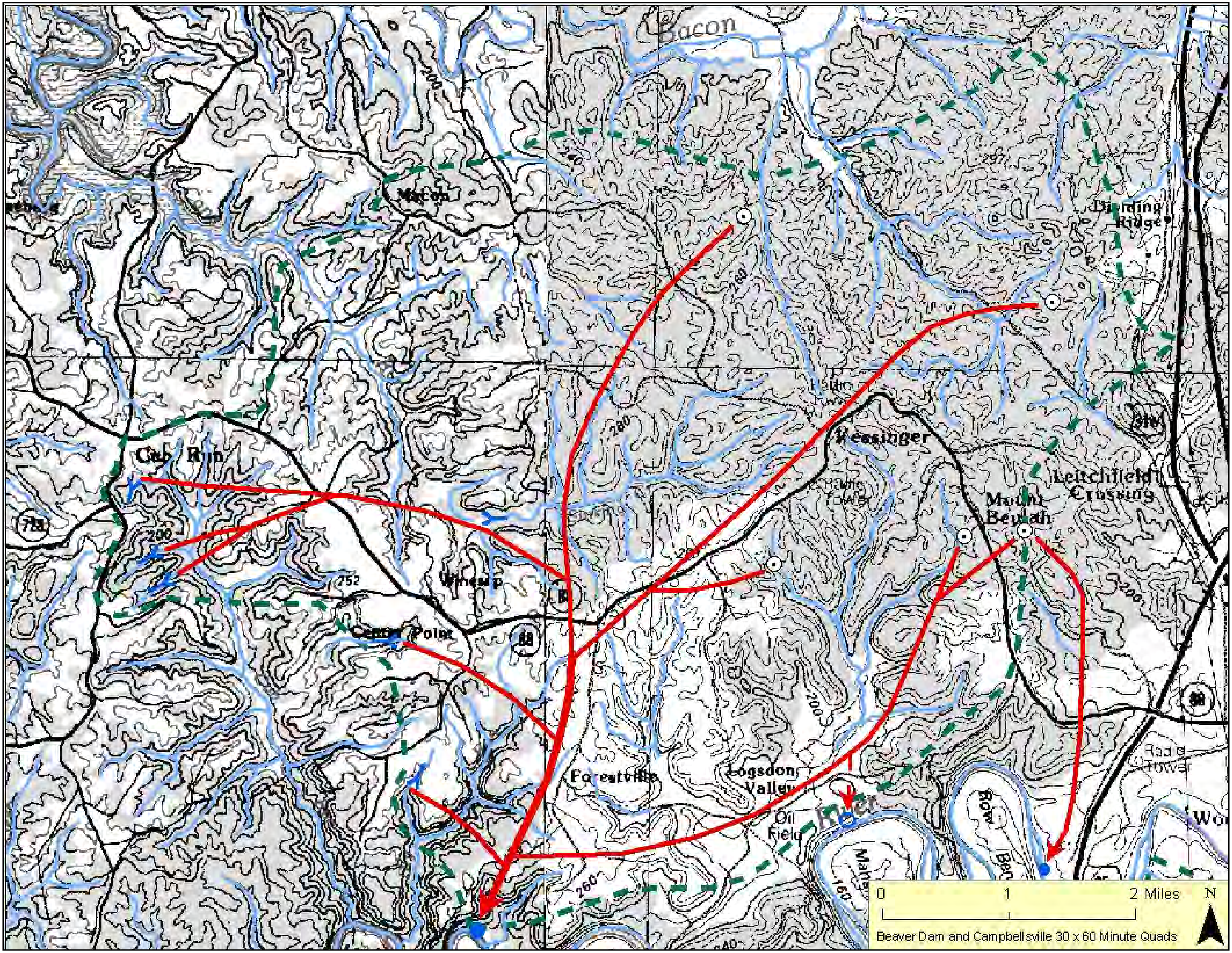


Figure 28. McCoy Bluehole Groundwater Basin Map

McCoy Bluehole (0792)	Hart Co.					
401 KAR 10:031. Section 4, Section 6 & Section 7-Allowable instream concentrations of pollutants						Impairment Level ≤10%=Not 11-25%=Partial >25%=Impaired
Pollutant	**CAS[1] Number**	**Water Quality Criteria μg/L[2]**				
		Human Health:		**Warm Water Aquatic Habitat[3]:**		
		DWS[4]	Fish[5]	**Acute**	**Chronic**	
Aldrin	309002	0.000049	0.00005	3		All data Non-detect **(NOT)**
Alkalinity (as $CaCO_3$)				Reduction >25%		Largest Reduction = 15% **(NOT)**
alpha-Endosulfan	959988	62	89	0.22	0.056	All data Non-detect **(NOT)**
Ammonia, un-ionized (mg/L) Y < 0.05 mg/L				Y=1.2(Ammonia-N)/(1+10pKa-pH)	pKa=0.0902+(2730/(273.2+T))	One detect, Y<0.05 mg/L **(NOT)**
Arsenic	7440382	10		340	150	Max = 0.829 μg/L **(NOT)**
Beta-Endosulfan	33213659	62	89	0.22	0.056	Max = 0.0197 μg/L **(NOT)**
Cadmium	7440439	5		e(1.0166 (ln Hard*)-3.924)	e(0.7409 (ln Hard*)-4.719)	Acute > DL > Chronic; All Non-detects
Chlordane	57749	0.0008	0.00081	2.4	0.0043	NO DATA
Chloride	16887006	250,000		1,200,000	600,000	Max = 3390 μg/L **(NOT)**
Chloropyrifos	2921882			0.083	0.041	All data Non-detect **(NOT)**
Chromium (III)	16065831			e(0.8190 (ln Hard*)+3.7256)	e(0.8190 (ln Hard*)+0.6848)	NO DATA
Chromium (VI)	18540299			16	11	NO DATA
Copper	7440508	1,300		e(0.9422 (ln Hard*)-1.7)	e(0.8545 (ln Hard*)-1.702)	5 detects<Standards **(NOT)**
Cyanide, Free	57125	700	220,000	22	5.2	NO DATA
Demeton	8065483				0.1	NO DATA
Dieldrin	60571	0.000052	0.000054	0.24	0.056	All data Non-detect **(NOT)**
Endrin	72208	0.76	0.81	0.086	0.036	All data Non-detect **(NOT)**
gamma-BHC (Lindane)	58899	0.019	0.063	0.95		All data Non-detect **(NOT)**
Guthion	86500				0.01	NO DATA
Heptachlor	76448	0.000079	0.000079	0.52	0.0038	Acute > DL > Chronic; All Non-detects
Heptachlor epoxide	1024573	0.000039	0.000039	0.52	0.0038	Acute > DL > Chronic; All Non-detects
Iron[6]	7439896			4,000	1,000	1/12 Samples > Chronic **(NOT)**
Lead	7439921	15		e(1.273 (ln Hard*)-1.46)	e(1.273 (ln Hard*)-4.705)	3 detects < Standards **(NOT)**
Malathion	121755				0.1	All data Non-detect **(NOT)**
Mercury	7439976	2	0.051	1.7	0.91	One detect<Standards **(NOT)**
Methoxychlor	72435	40			0.03	All data Non-detect **(NOT)**
Mirex	2385855				0.001	All data Non-detect **(NOT)**
Nickel	7440020	610	4,600	e(0.8460 (ln Hard*)+ 2.255)	e(0.8460 (ln Hard*)+ 0.0584)	11 detects < Standards **(NOT)**
Parathion	56382			0.065	0.013	NO DATA
Pentachlorophenol	87865	0.27	3	e(1.005(pH)-4.869)	e(1.005(pH)-5.134)	One detect<Standards **(NOT)**
pH		6.5-8.5		6.0 - 9.0		6.78 - 8.82 **(NOT)**
Phthalate esters	N/A				3	NO DATA
Phenol	108952	21,000	1,700,000			NO DATA
PolychlorinatedBiphenyls (PCBs)	N/A	0.000064	0.000064		0.0014	1/12 Samples > Chronic **(NOT)**
Selenium	7782492	170	4,200	20	5	Three detect<Standards **(NOT)**
Silver	7440224			e(1.72 (ln Hard*)-6.59)		All data Non-detect **(NOT)**
Hydrogen Sulfide, Undissociated	7783064				2	NO DATA
Temperature				31.7 ° C		**NOT**
TDS and TSS	N/A	750,000		No adverse effects on aquatic life		
Toxaphene	8001352	0.00028	0.00028	0.73	0.0002	Acute > DL > Chronic; All Non-detects
Zinc	7440666	7,400	26,000	e(0.8473 (ln Hard*)+0.884)	e(0.8473 (ln Hard*)+0.884)	11 detects < Standards **(NOT)**
4,4'-DDT	50293	0.00022	0.00022	1.1	0.001	Acute > DL > Chronic; All Non-detects
E. Coli (Sec7-Primary Contact)		< 1		240 CFU (20% of samples)		3/6 >240 CFU
Nutrient Issues as Narrative				Determined by WQB		**NOT**

Figure 29. 305(b) Assessment Checklist for McCoy Bluehole

Figure 30. Mill Spring Photograph

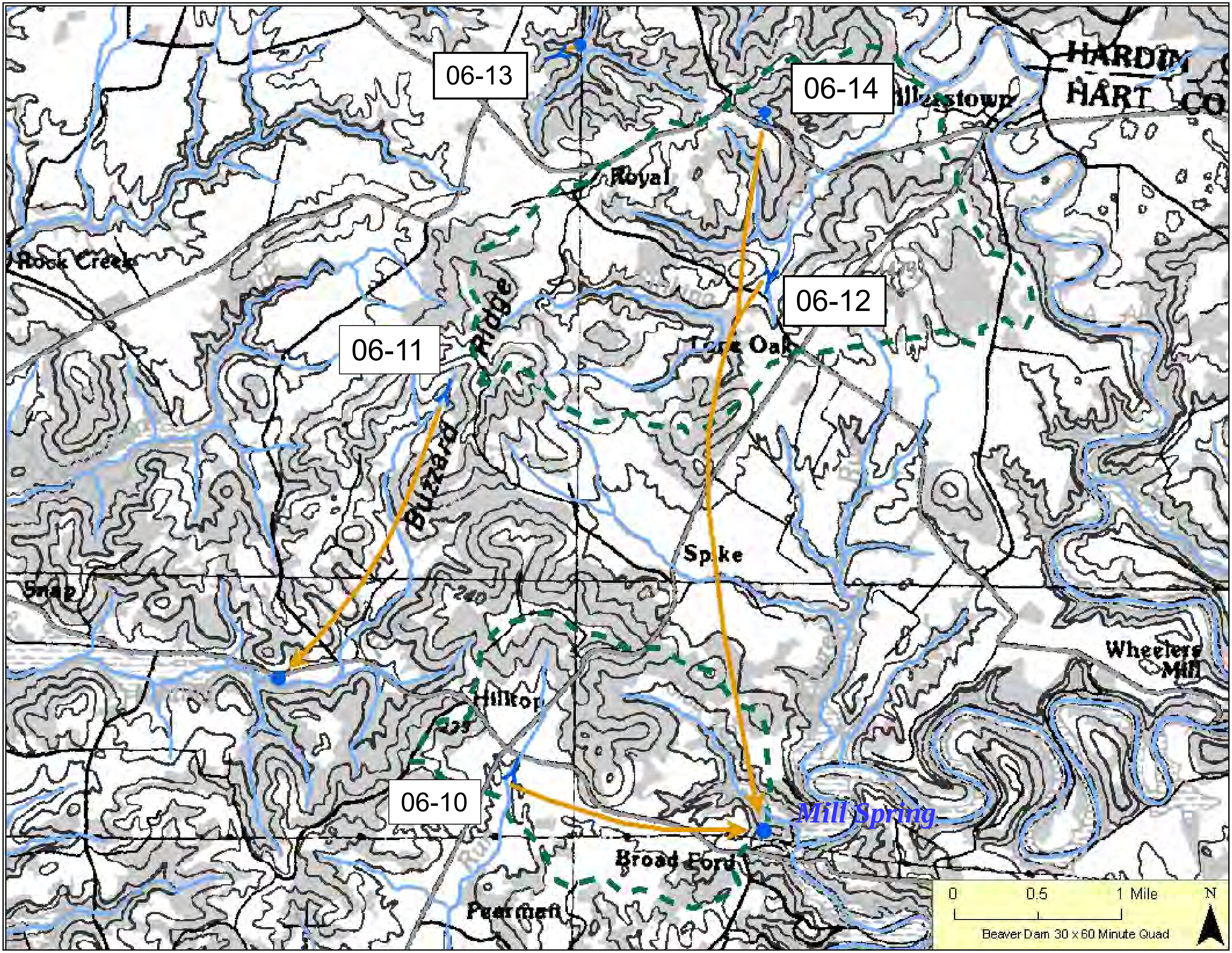


Figure 31. Mill Spring Groundwater Basin Map (Pretty Spring trace on west)

Mill Spring (1193)	Grayson Co.					
401 KAR 10:031. Section 4, Section 6 & Section 7-Allowable instream concentrations of pollutants						Impairment Level ≤10%=Not 11-25%=Partial >25%=Impaired
Pollutant	CAS[1] Number	Water Quality Criteria µg/L[2]				
		Human Health:		Warm Water Aquatic Habitat[3]:		
		DWS[4]	Fish[5]	Acute	Chronic	
Aldrin	309002	0.000049	0.00005	3		All Data Non-detect **(NOT)**
Alkalinity (as $CaCO_3$)				Reduction >25%		**NOT**
alpha-Endosulfan	959988	62	89	0.22	0.056	All Data Non-detect **(NOT)**
Ammonia, un-ionized (mg/L) Y < 0.05 mg/L				Y=1.2(Ammonia-N)/(1+10pKa-pH)	pKa=0.0902+(2730/(273.2+T))	2 Detects; Y < 0.05 mg/L **(NOT)**
Arsenic	7440382	10		340	150	All Detects < Standards **(NOT)**
Beta-Endosulfan	33213659	62	89	0.22	0.056	All Data Non-detect **(NOT)**
Cadmium	7440439	5		e(1.0166 (ln Hard*)-3.924)	e(0.7409 (ln Hard*)-4.719)	Acute > DL > Chronic; All Non-detects
Chlordane	57749	0.0008	0.00081	2.4	0.0043	NO DATA
Chloride	16887006	250,000		1,200,000	600,000	All Detects < Standards **(NOT)**
Chloropyrifos	2921882			0.083	0.041	All Data Non-detect **(NOT)**
Chromium (III)	16065831			e(0.8190 (ln Hard*)+3.7256)	e(0.8190 (ln Hard*)+0.6848)	NO DATA
Chromium (VI)	18540299			16	11	NO DATA
Copper	7440508	1,300		e(0.9422 (ln Hard*)-1.7)	e(0.8545 (ln Hard*)-1.702)	All Detects < Standards **(NOT)**
Cyanide, Free	57125	700	220,000	22	5.2	NO DATA
Demeton	8065483				0.1	NO DATA
Dieldrin	60571	0.000052	0.000054	0.24	0.056	All Data Non-detect **(NOT)**
Endrin	72208	0.76	0.81	0.086	0.036	All Data Non-detect **(NOT)**
gamma-BHC (Lindane)	58899	0.019	0.063	0.95		All Data Non-detect **(NOT)**
Guthion	86500				0.01	NO DATA
Heptachlor	76448	0.000079	0.000079	0.52	0.0038	Acute > DL > Chronic; All Non-detects
Heptachlor epoxide	1024573	0.000039	0.000039	0.52	0.0038	Acute > DL > Chronic; All Non-detects
Iron[6]	7439896			4,000	1,000	2/12 (17%) > Chronic **(PARTIAL)**
Lead	7439921	15		e(1.273 (ln Hard*)-1.46)	e(1.273 (ln Hard*)-4.705)	All Detects < Standards **(NOT)**
Malathion	121755				0.1	All Data Non-detect **(NOT)**
Mercury	7439976	2	0.051	1.7	0.91	3 Detects < Standards **(NOT)**
Methoxychlor	72435	40			0.03	All Data Non-detect **(NOT)**
Mirex	2385855				0.001	DL > Chronic; All Non-detects
Nickel	7440020	610	4,600	e(0.8460 (ln Hard*)+ 2.255)	e(0.8460 (ln Hard*)+ 0.0584)	All Detects < Standards **(NOT)**
Parathion	56382			0.065	0.013	NO DATA
Pentachlorophenol	87865	0.27	3	e(1.005(pH)-4.869)	e(1.005(pH)-5.134)	All Detects < Standards **(NOT)**
pH		6.5-8.5		6.0 - 9.0		6.57 - 8.63 **(NOT)**
Phthalate esters	N/A				3	NO DATA
Phenol	108952	21,000	1,700,000			NO DATA
PolychlorinatedBiphenyls (PCBs)	N/A	0.000064	0.000064		0.0014	DL > Chronic; All Non-detects
Selenium	7782492	170	4,200	20	5	All Detects < Standards **(NOT)**
Silver	7440224			e(1.72 (ln Hard*)-6.59)		All Data Non-detect **(NOT)**
Hydrogen Sulfide, Undissociated	7783064				2	NO DATA
Temperature				31.7 ° C		**NOT**
TDS and TSS	N/A	750,000		No adverse effects on aquatic life		
Toxaphene	8001352	0.00028	0.00028	0.73	0.0002	Acute > DL > Chronic; All Non-detects
Zinc	7440666	7,400	26,000	e(0.8473 (ln Hard*)+0.884)	e(0.8473 (ln Hard*)+0.884)	All Detects < Standards **(NOT)**
4,4'-DDT	50293	0.00022	0.00022	1.1	0.001	Acute > DL > Chronic; All Non-detects
E. Coli (Sec7-Primary Contact)		< 1		240 CFU (20% of samples)		3/6 > 240 CFU/100 mL **(IMPAIRED)**
Nutrient Issues as Narrative				Determined by WQB		**NOT**

Figure 32. 305(b) Assessment Checklist for Mill Spring

Figure 33. Nolynn Spring Photograph – note unused pump station and pipe

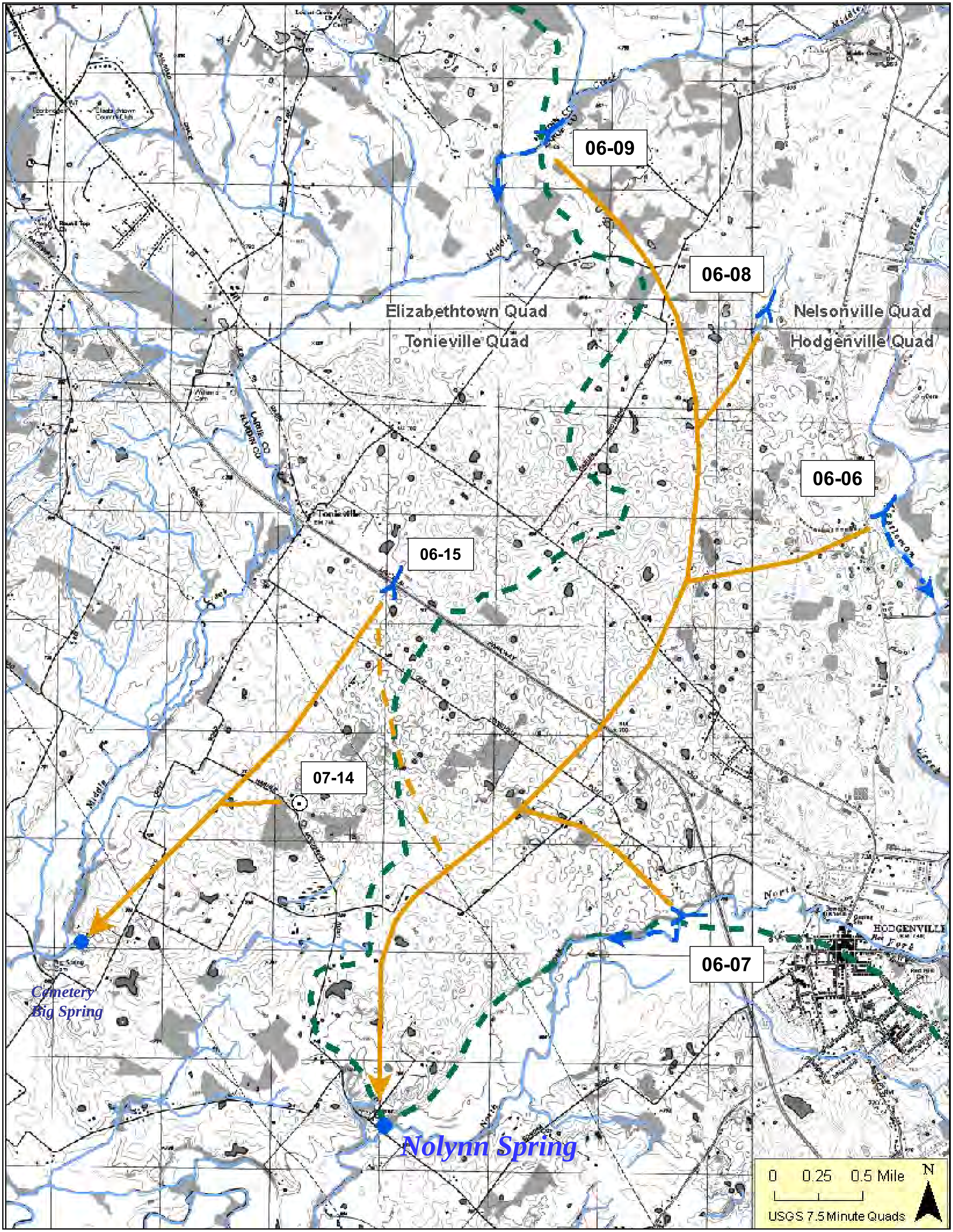


Figure 34a. Nolynn Spring Tracer Data Close Up (Cemetery Big Spring on west)

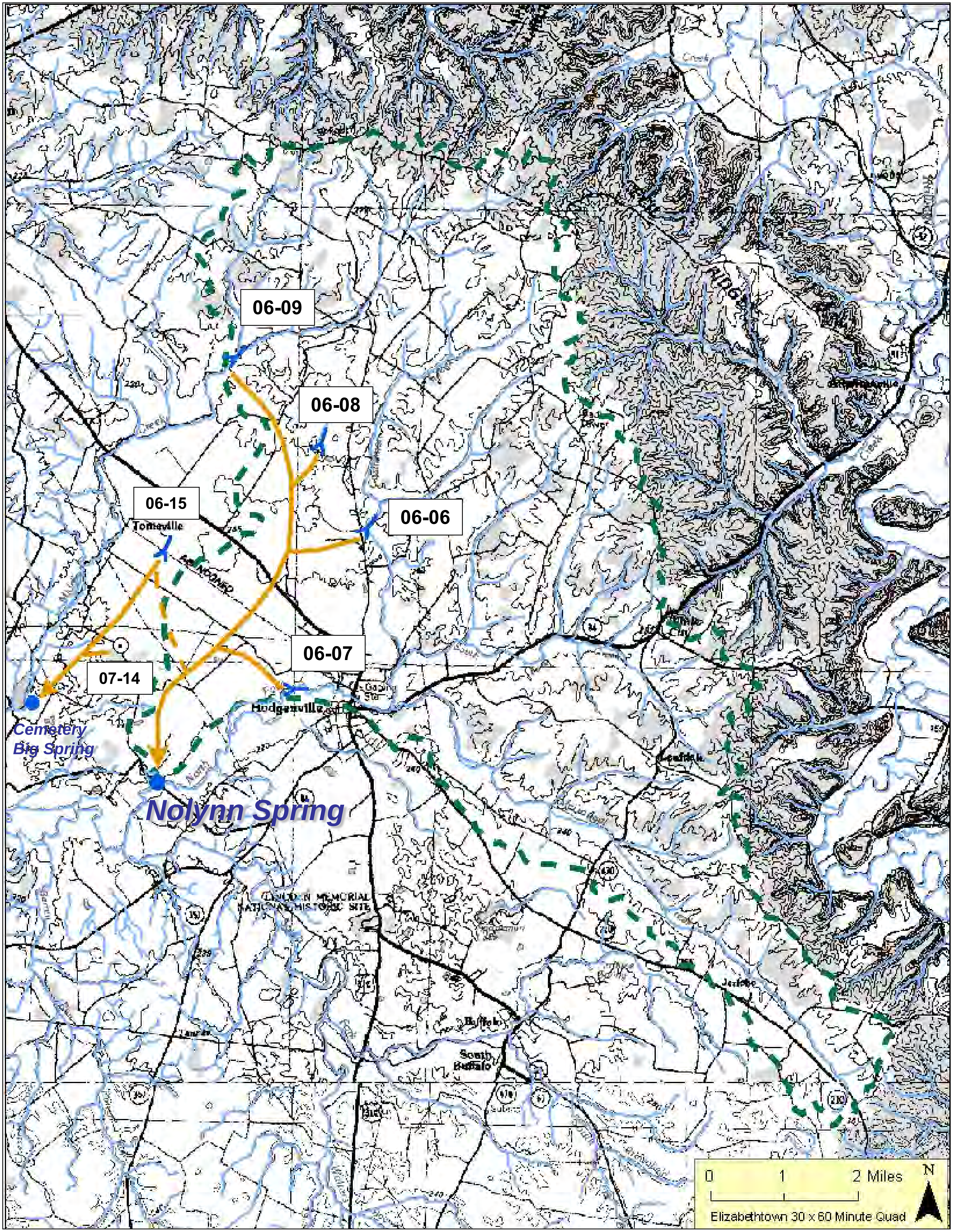


Figure 34. Nolynn Spring Groundwater Basin Map (Cemetery Big Spring on west)

Nolynn Spring (2673)	Larue Co.					
401 KAR 10:031. Section 4, Section 6 & Section 7-Allowable instream concentrations of pollutants						Impairment Level ≤10%=Not 11-25%=Partial >25%=Impaired
Pollutant	**CAS[1] Number**	**Water Quality Criteria µg/L[2]**				
		Human Health:		**Warm Water Aquatic Habitat[3]:**		
		DWS[4]	Fish[5]	**Acute**	**Chronic**	
Aldrin	309002	0.000049	0.00005	3		All Data Non-detect **(NOT)**
Alkalinity (as $CaCO_3$)				Reduction >25%		**NOT**
alpha-Endosulfan	959988	62	89	0.22	0.056	All Data Non-detect **(NOT)**
Ammonia, un-ionized (mg/L) Y < 0.05 mg/L				Y=1.2(Ammonia-N)/(1+10pKa-pH)	pKa=0.0902+(2730/(273.2+T))	2 Detects; y < 0.05 mg/L **(NOT)**
Arsenic	7440382	10		340	150	All Detects < Standards **(NOT)**
Beta-Endosulfan	33213659	62	89	0.22	0.056	All Data Non-detect **(NOT)**
Cadmium	7440439	5		e(1.0166 (ln Hard*)-3.924)	e(0.7409 (ln Hard*)-4.719)	Acute > DL > Chronic; All Non-detects
Chlordane	57749	0.0008	0.00081	2.4	0.0043	NO DATA
Chloride	16887006	250,000		1,200,000	600,000	All Detects < Standards **(NOT)**
Chloropyrifos	2921882			0.083	0.041	All Data Non-detect **(NOT)**
Chromium (III)	16065831			e(0.8190 (ln Hard*)+3.7256)	e(0.8190 (ln Hard*)+0.6848)	NO DATA
Chromium (VI)	18540299			16	11	NO DATA
Copper	7440508	1,300		e(0.9422 (ln Hard*)-1.7)	e(0.8545 (ln Hard*)-1.702)	All Detects < Standards **(NOT)**
Cyanide, Free	57125	700	220,000	22	5.2	NO DATA
Demeton	8065483				0.1	NO DATA
Dieldrin	60571	0.000052	0.000054	0.24	0.056	All Data Non-detect **(NOT)**
Endrin	72208	0.76	0.81	0.086	0.036	All Data Non-detect **(NOT)**
gamma-BHC (Lindane)	58899	0.019	0.063	0.95		All Data Non-detect **(NOT)**
Guthion	86500				0.01	NO DATA
Heptachlor	76448	0.000079	0.000079	0.52	0.0038	Acute > DL > Chronic; All Non-detects
Heptachlor epoxide	1024573	0.000039	0.000039	0.52	0.0038	Acute > DL > Chronic; All Non-detects
Iron[6]	7439896			4,000	1,000	1/12 (8%) > Chronic **(NOT)**
Lead	7439921	15		e(1.273 (ln Hard*)-1.46)	e(1.273 (ln Hard*)-4.705)	All Detects < Standards **(NOT)**
Malathion	121755				0.1	All Data Non-detect **(NOT)**
Mercury	7439976	2	0.051	1.7	0.91	1 Detect < Standards **(NOT)**
Methoxychlor	72435	40			0.03	1/12 (8%) > Chronic **(NOT)**
Mirex	2385855				0.001	DL > Chronic; All Non-detects
Nickel	7440020	610	4,600	e(0.8460 (ln Hard*)+ 2.255)	e(0.8460 (ln Hard*)+ 0.0584)	All Detects < Standards **(NOT)**
Parathion	56382			0.065	0.013	NO DATA
Pentachlorophenol	87865	0.27	3	e(1.005(pH)-4.869)	e(1.005(pH)-5.134)	1 Detect < Standards **(NOT)**
pH		6.5-8.5		6.0 - 9.0		5.92 - 8.53; 1/12 (8%) < Standard **(NOT)**
Phthalate esters	N/A				3	NO DATA
Phenol	108952	21,000	1,700,000			NO DATA
PolychlorinatedBiphenyls (PCBs)	N/A	0.000064	0.000064		0.0014	Acute > DL > Chronic; All Non-detects
Selenium	7782492	170	4,200	20	5	All Detects < Standards **(NOT)**
Silver	7440224			e(1.72 (ln Hard*)-6.59)		All Data Non-detect **(NOT)**
Hydrogen Sulfide, Undissociated	7783064				2	NO DATA
Temperature				31.7 ° C		**NOT**
TDS and TSS	N/A	750,000		No adverse effects on aquatic life		
Toxaphene	8001352	0.00028	0.00028	0.73	0.0002	Acute > DL > Chronic; All Non-detects
Zinc	7440666	7,400	26,000	e(0.8473 (ln Hard*)+0.884)	e(0.8473 (ln Hard*)+0.884)	All Detects < Standards **(NOT)**
4,4'-DDT	50293	0.00022	0.00022	1.1	0.001	Acute > DL > Chronic; All Non-detects
E. Coli (Sec7-Primary Contact)		< 1		240 CFU (20% of samples)		5/6 > 240 CFU/100 mL **(IMPAIRED)**
Nutrient Issues as Narrative				Determined by WQB		NO3-N and TOC **(IMPAIRED)**

Figure 35. 305(b) Assessment Checklist for Nolynn Spring

View looking upstream toward spring (discharge point)

View looking downstream to swallet pool (insurgence point)

Figure 36. Skees Karst Window #1 Photographs

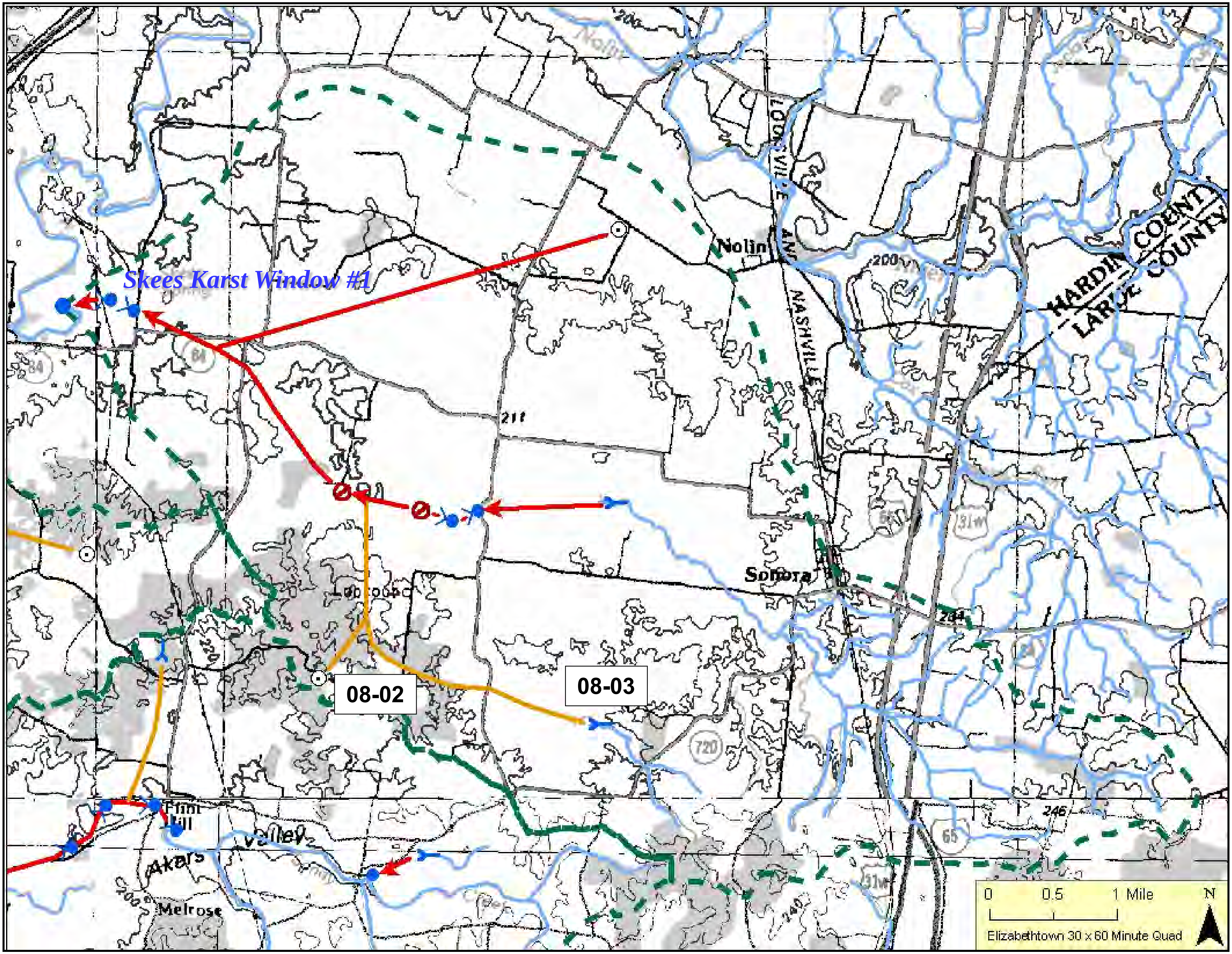


Figure 37. Waddell Spring Groundwater Basin Map (Showing Skees KW #1)

Skees KW1 (1398)	Hardin Co.					
401 KAR 10:031. Section 4, Section 6 & Section 7-Allowable instream concentrations of pollutants						Impairment Level ≤10%=Not 11-25%=Partial >25%=Impaired
Pollutant	CAS[1] Number	Water Quality Criteria µg/L[2]				
		Human Health:		Warm Water Aquatic Habitat[3]:		
		DWS[4]	Fish[5]	Acute	Chronic	
Aldrin	309002	0.000049	0.00005	3		All Data Non-detect **(NOT)**
Alkalinity (as $CaCO_3$)				Reduction >25%		**NOT**
alpha-Endosulfan	959988	62	89	0.22	0.056	All Data Non-detect **(NOT)**
Ammonia, un-ionized (mg/L) Y < 0.05 mg/L				Y=1.2(Ammonia-N)/(1+10pKa-pH)	pKa=0.0902+(2730/(273.2+T))	2 Detects; Y < 0.05 mg/L **(NOT)**
Arsenic	7440382	10		340	150	All Detects < Standards **(NOT)**
Beta-Endosulfan	33213659	62	89	0.22	0.056	All Data Non-detect **(NOT)**
Cadmium	7440439	5		e(1.0166 (ln Hard*)-3.924)	e(0.7409 (ln Hard*)-4.719)	Acute > DL > Chronic; All Non-detects
Chlordane	57749	0.0008	0.00081	2.4	0.0043	NO DATA
Chloride	16887006	250,000		1,200,000	600,000	All Detects < Standards **(NOT)**
Chloropyrifos	2921882			0.083	0.041	All Data Non-detect **(NOT)**
Chromium (III)	16065831			e(0.8190 (ln Hard*)+3.7256)	e(0.8190 (ln Hard*)+0.6848)	NO DATA
Chromium (VI)	18540299			16	11	NO DATA
Copper	7440508	1,300		e(0.9422 (ln Hard*)-1.7)	e(0.8545 (ln Hard*)-1.702)	All Detects < Standards **(NOT)**
Cyanide, Free	57125	700	220,000	22	5.2	NO DATA
Demeton	8065483				0.1	NO DATA
Dieldrin	60571	0.000052	0.000054	0.24	0.056	All Data Non-detect **(NOT)**
Endrin	72208	0.76	0.81	0.086	0.036	All Data Non-detect **(NOT)**
gamma-BHC (Lindane)	58899	0.019	0.063	0.95		All Data Non-detect **(NOT)**
Guthion	86500				0.01	NO DATA
Heptachlor	76448	0.000079	0.000079	0.52	0.0038	Acute > DL > Chronic; All Non-detects
Heptachlor epoxide	1024573	0.000039	0.000039	0.52	0.0038	Acute > DL > Chronic; All Non-detects
Iron[6]	7439896			4,000	1,000	All Detects < Standards **(NOT)**
Lead	7439921	15		e(1.273 (ln Hard*)-1.46)	e(1.273 (ln Hard*)-4.705)	All Detects < Standards **(NOT)**
Malathion	121755				0.1	All Data Non-detect **(NOT)**
Mercury	7439976	2	0.051	1.7	0.91	1 Detect < Standards **(NOT)**
Methoxychlor	72435	40			0.03	1/12 (8%) > Chronic **(NOT)**
Mirex	2385855				0.001	DL > Chronic; All Non-detects
Nickel	7440020	610	4,600	e(0.8460 (ln Hard*)+ 2.255)	e(0.8460 (ln Hard*)+ 0.0584)	All Detects < Standards **(NOT)**
Parathion	56382			0.065	0.013	NO DATA
Pentachlorophenol	87865	0.27	3	e(1.005(pH)-4.869)	e(1.005(pH)-5.134)	1 Detect < Standards **(NOT)**
pH		6.5-8.5		6.0 - 9.0		6.22 - 8.58 **(NOT)**
Phthalate esters	N/A				3	NO DATA
Phenol	108952	21,000	1,700,000			NO DATA
PolychlorinatedBiphenyls (PCBs)	N/A	0.000064	0.000064		0.0014	DL > Chronic; All Non-detects
Selenium	7782492	170	4,200	20	5	All Detects < Standards **(NOT)**
Silver	7440224			e(1.72 (ln Hard*)-6.59)		All Data Non-detect **(NOT)**
Hydrogen Sulfide, Undissociated	7783064				2	NO DATA
Temperature				31.7 ° C		**NOT**
TDS and TSS	N/A	750,000		No adverse effects on aquatic life		
Toxaphene	8001352	0.00028	0.00028	0.73	0.0002	Acute > DL > Chronic; All Non-detects
Zinc	7440666	7,400	26,000	e(0.8473 (ln Hard*)+0.884)	e(0.8473 (ln Hard*)+0.884)	All Detects < Standards **(NOT)**
4,4'-DDT	50293	0.00022	0.00022	1.1	0.001	Acute > DL > Chronic; All Non-detects
E. Coli (Sec7-Primary Contact)		< 1		240 CFU (20% of samples)		5/6 > 240 CFU/100 mL **(IMPAIRED)**
Nutrient Issues as Narrative				Determined by WQB		NO3-N and TOC **(IMPAIRED)**

Figure 38. 305(b) Assessment Checklist for Skees Karst Window #1

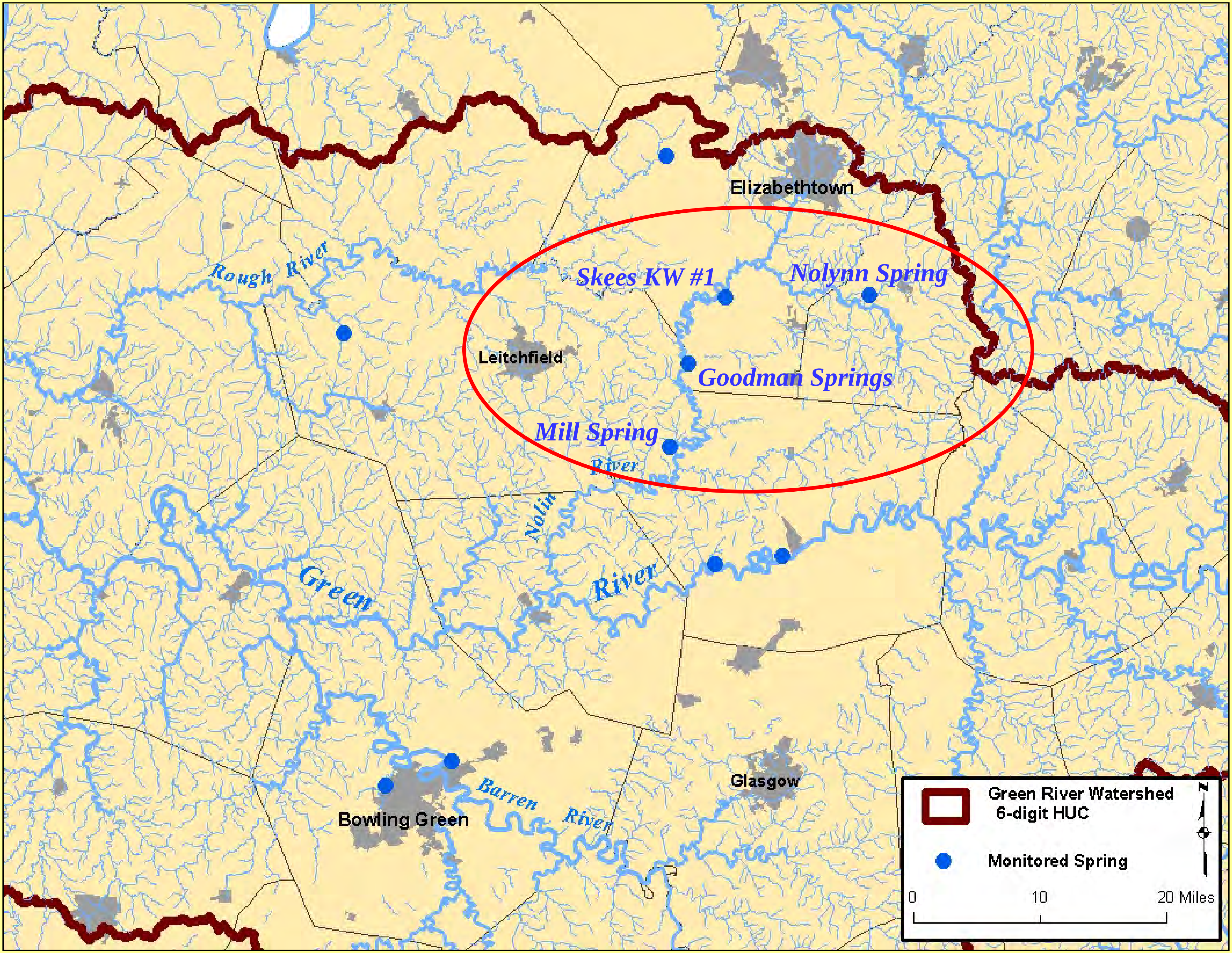


Figure 39. Study Area Springs Assessed for Macroinvertebrates

Taxa		Mill	Goodman	Skees	Nolynn
Oligochaeta	Unid. oligochaete	1 (1.7) 100	---------------	---------------	--------------
Gastropoda	*Elimia* sp.	19.6 (33.3) 66.4	1.3 (5.1) 173	13.7 (4.7) 52.9	16.3 (21.7) 94.9
Amphipoda	*Gammarus bousfeldi*	19.3 (32.7) 10.7	11 (41.8) 41.6	248.7 (85.2) 11.3	2 (2.6) 173
Isopoda	*Caecidotea* sp.	---------------	0.7 (2.5) 173	---------------	17.3 (23.1) 105.8
	Lirceus sp.	---------------	3.3 (12.7) 69.3	---------------	2.7 (3.5) 21.6
Ephemeroptera	*Baetis intercalaris*	---------------	---------------	---------------	2.3 (3.1) 173
	Diphetor hageni	---------------	1.7 (6.3) 173	26.3 (9.0) 8.8	--------------
	Stenonema femoratum	2 (3.3) 50	---------------	---------------	9 (12.0) 19.2
	Unid. Heptageniid immature	---------------	---------------	---------------	0.3 (0.4) 173
Trichoptera	*Ceratopsyche* sp.	---------------	---------------	---------------	0.3 (0.4) 173
	Cheumatopsyche sp.	0.3 (0.5) 173	---------------	---------------	--------------
	Polycentropus sp.	---------------	0.7 (2.5) 86.6	---------------	--------------
Diptera	*Chironomus* sp.	1.3 (2.2) 86.6	0.7 (2.5) 173	---------------	--------------
	Cricotopus/Orthocladius gp	---------------	------------------	---------------	0.3 (0.4) 173
	Dicrotendipes sp.	0.3 (0.5) 173	0.7 (2.5) 173	---------------	--------------
	Eukiefferiella sp.	---------------	---------------	---------------	0.3 (0.4) 173
	Microtendipes pedellus gp.	1 (1.6) 100	---------------	---------------	--------------
	Paraleptophlebia sp.	---------------	0.3 (1.3) 173	---------------	--------------
	Parametriocnemus sp.	-----------------	---------------	---------------	2.3 (3.1) 173
	Paratendipes albimanus	2.3 (3.9) 49.5	---------------	---------------	--------------
	Phaenopsectra punctipes gp.	0.7 (1.1) 173	---------------	---------------	--------------
	Polypedilum fallax	4.3 (7.3) 58.1	1 (3.8) 100	0.7 (2.3) 173	3.7 (4.9) 103.2
	Polypedilum flavum	2 (3.3) 132	---------------	---------------	--------------
	Polypedilum sp.	1.6 (2.8) 173	1.3 (5.1) 173	---------------	0.7 (0.9) 173
	Rheotanytarsus exiguus gp.	1.3 (2.2) 86	------------------	2 (0.7) 173	1 (1.3) 173
	Sublettea sp.	-----------------	0.3 (1.3) 173		--------------
	Thienemannimyia gp.	-----------------	---------------	0.3 (0.1) 173	0.7 (0.9) 86.6
	Xylotopus par	-----------------	0.3 (1.3) 173		6 (8.0) 145.3
	Unid. Chironomid immature	0.3 (0.5) 173	---------------	---------------	--------------
	Unid . Chironomid pupae	1.3 (2.2) 173	0.7 (2.5) 173		1.7 (2.2) 173
	Simulium sp.	-----------------	---------------	---------------	8 (10.6) 106.8
Total Individuals		175	78	870	225
Total Taxa Richness		15	15	6	18

Figure 40. Macroinvertebrate Taxa List [mean/plate (%relative abundance)/ CV]

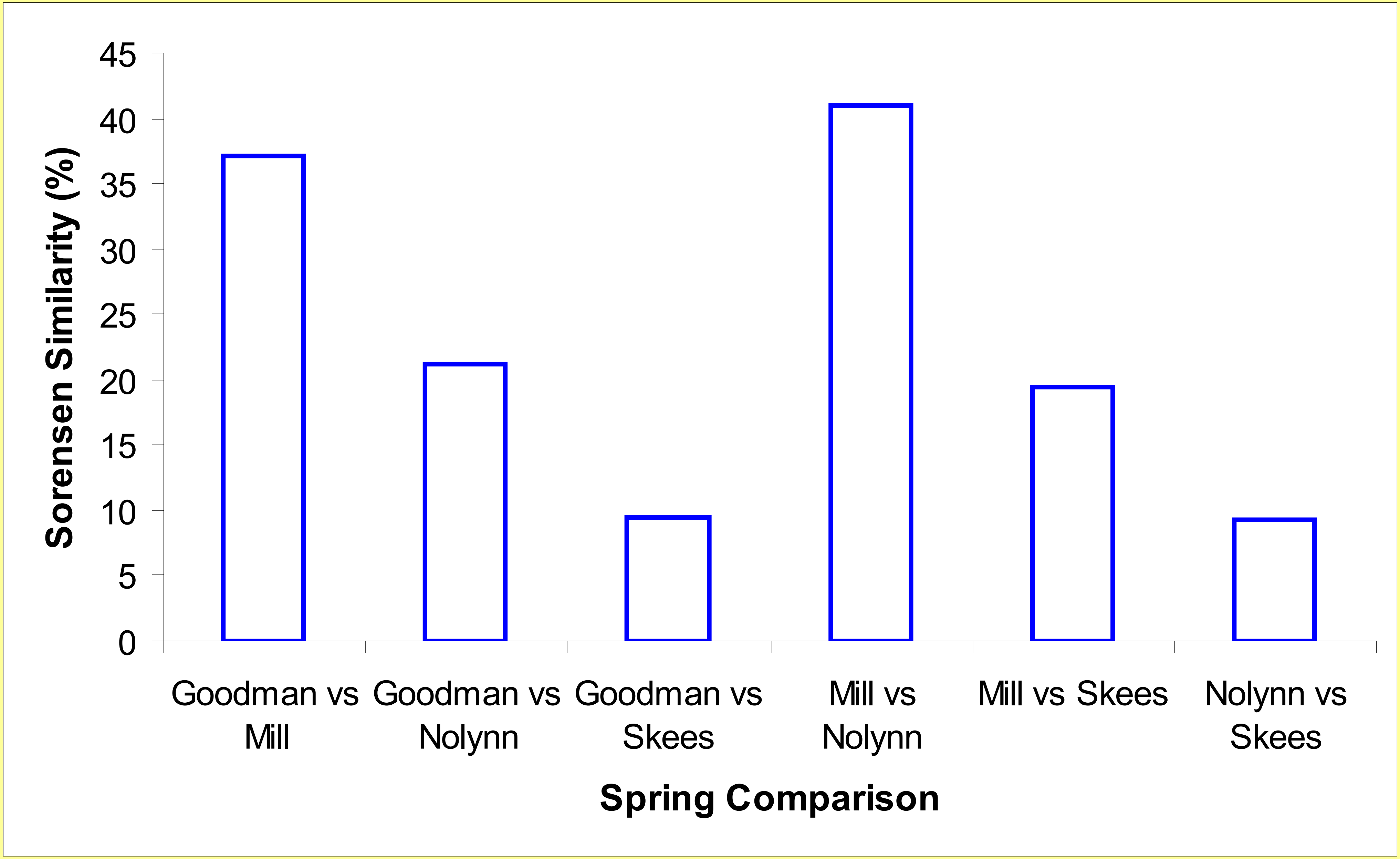


Figure 41. Sorensen Similarity (%) Spring Macroinvertebrate Community Comparisons

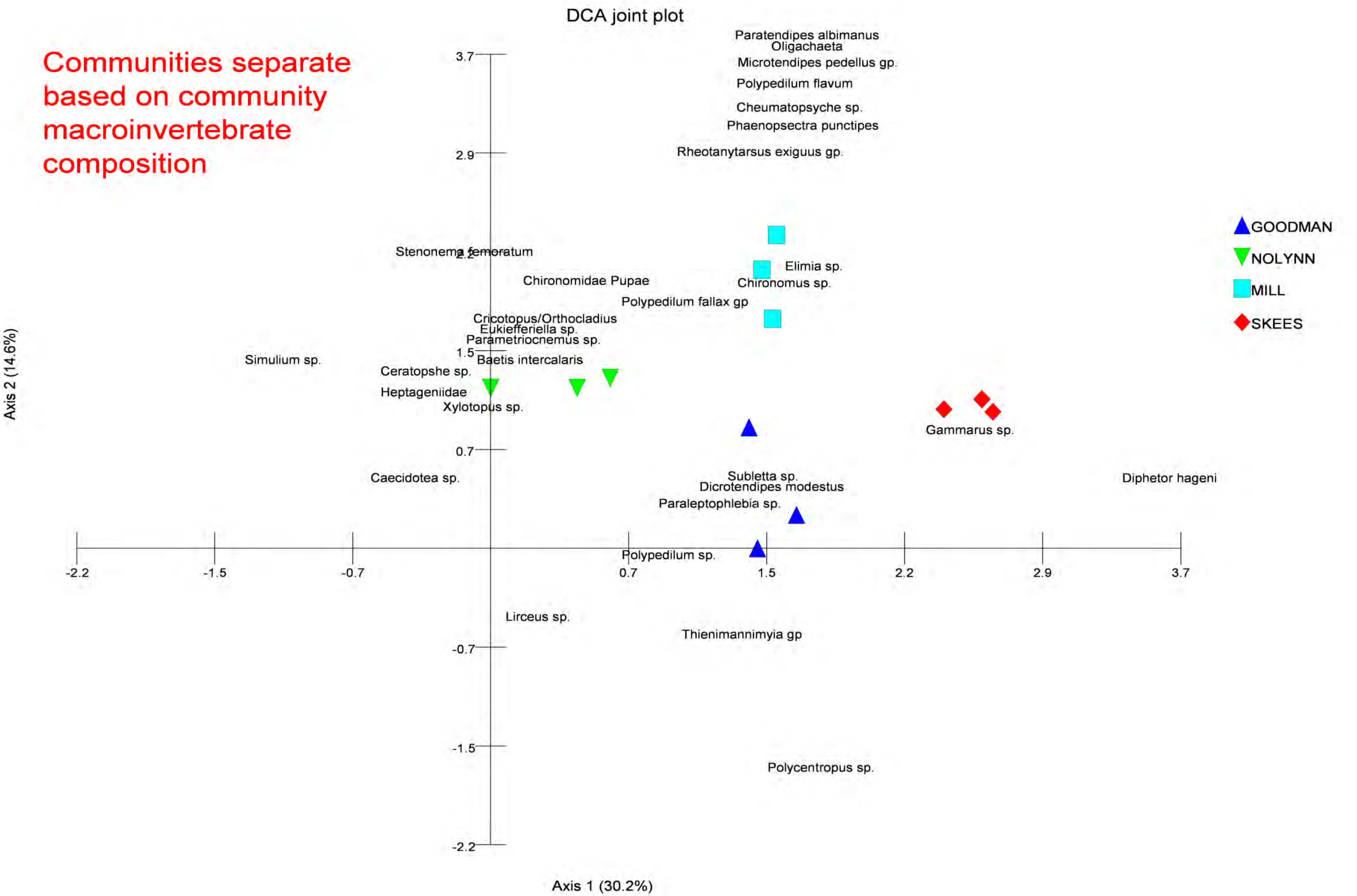


Figure 42. Detrended Correspondence Analysis (DCA) of Spring Macroinvertebrate Communities

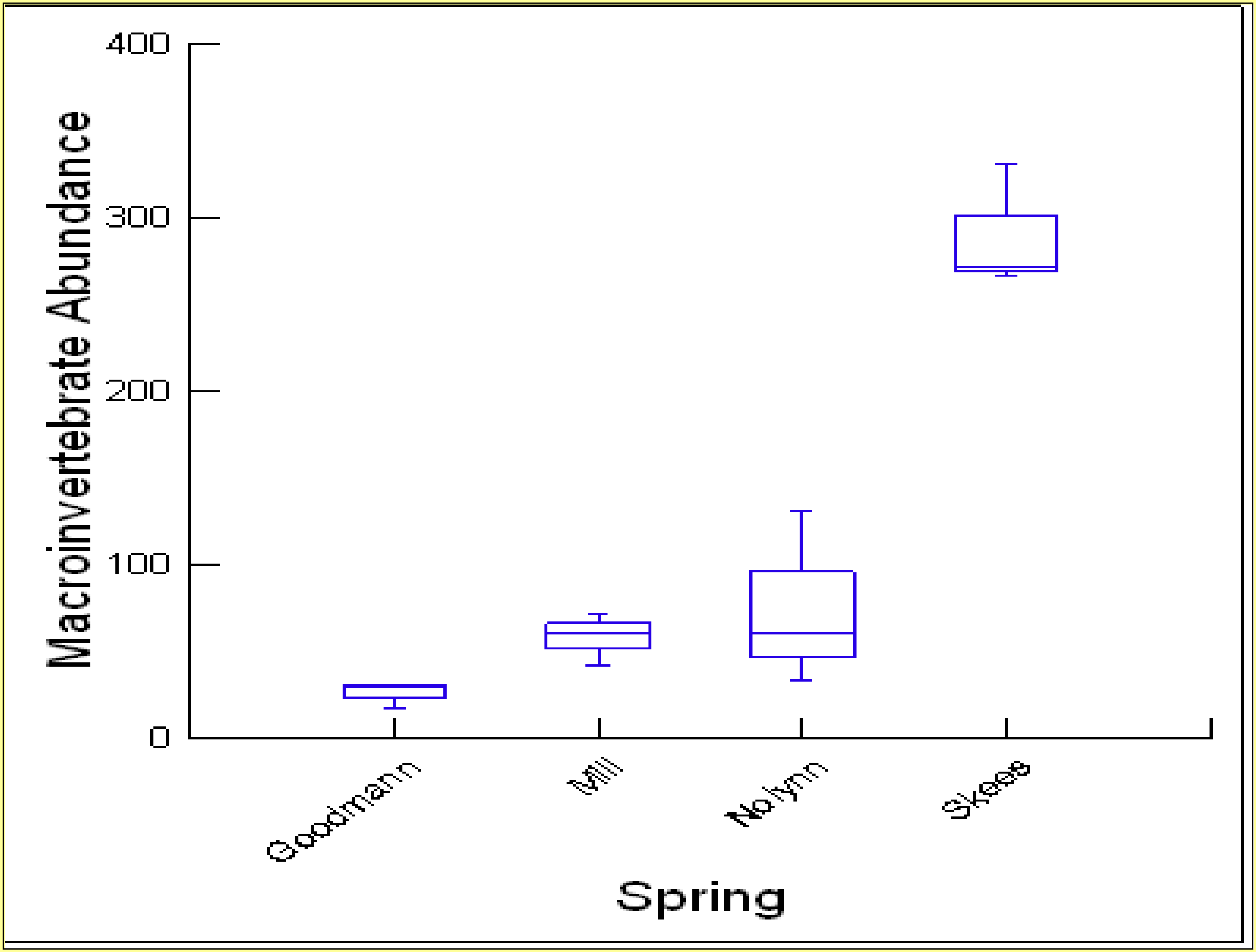


Figure 43. Macroinvertebrate Abundance at Evaluated Springs

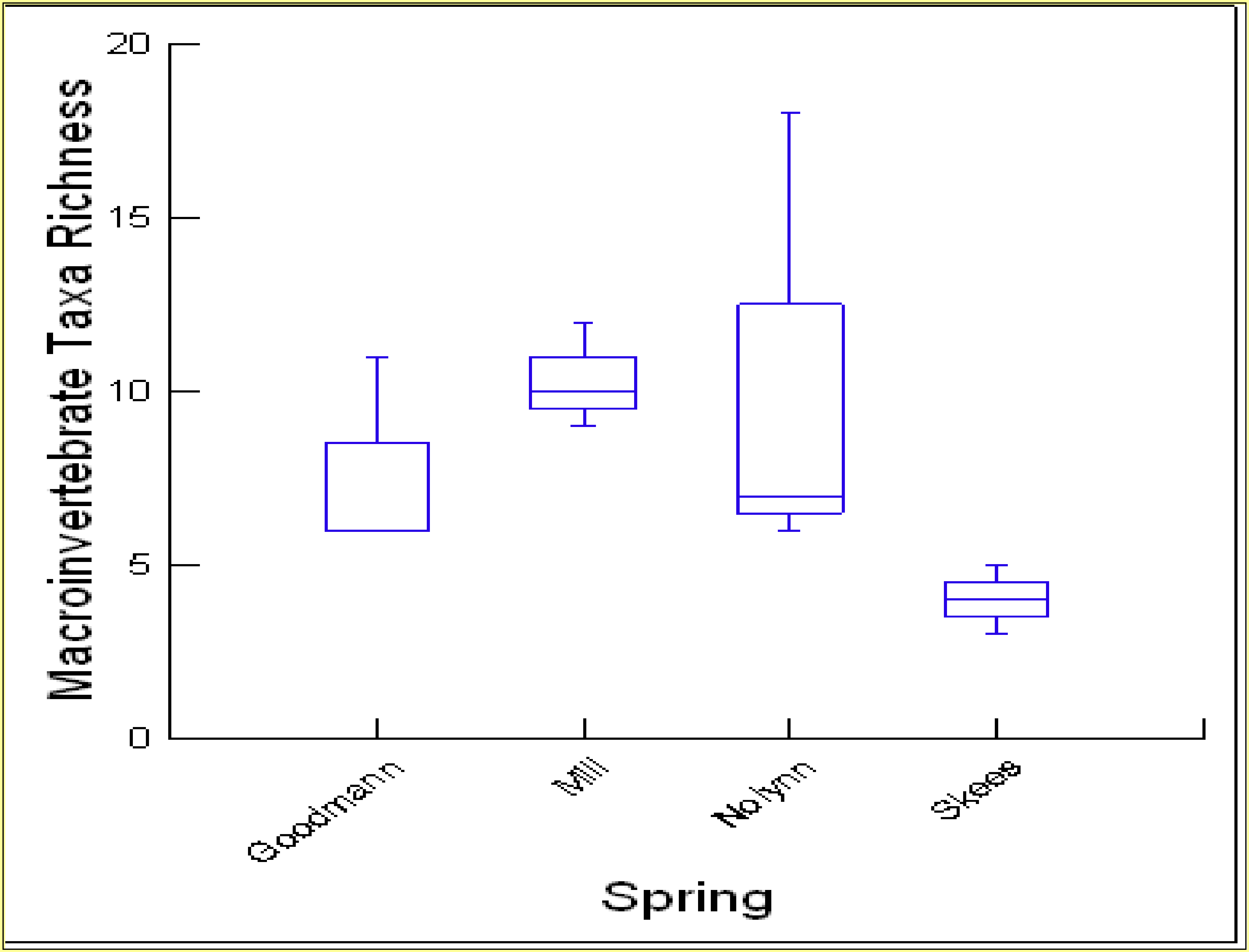


Figure 44. Macroinvertebrate Taxa Richness at Evaluated Springs

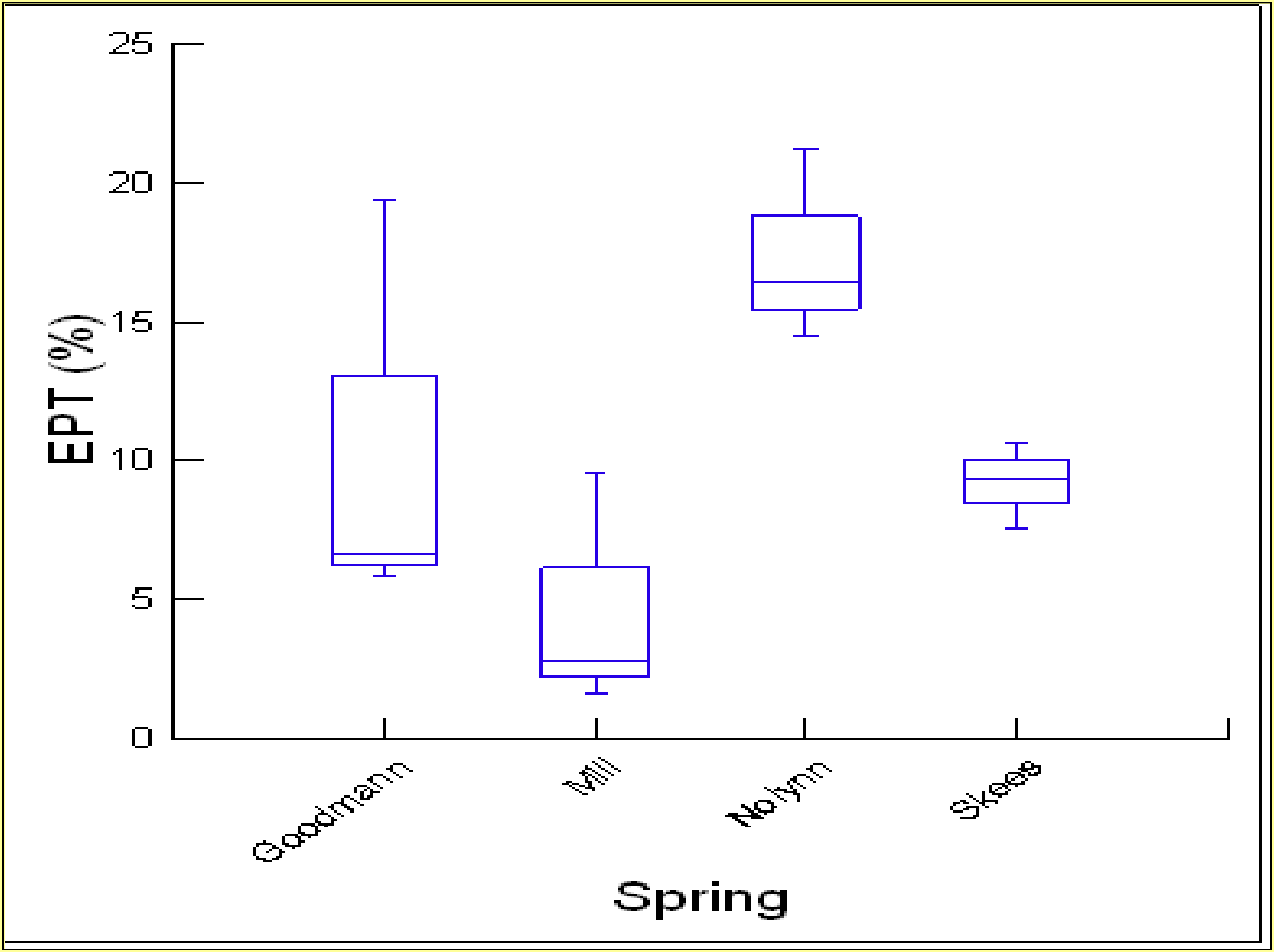


Figure 45. Percent (%) Ephemeroptera, Plecoptera and Trichoptera at Evaluated Springs

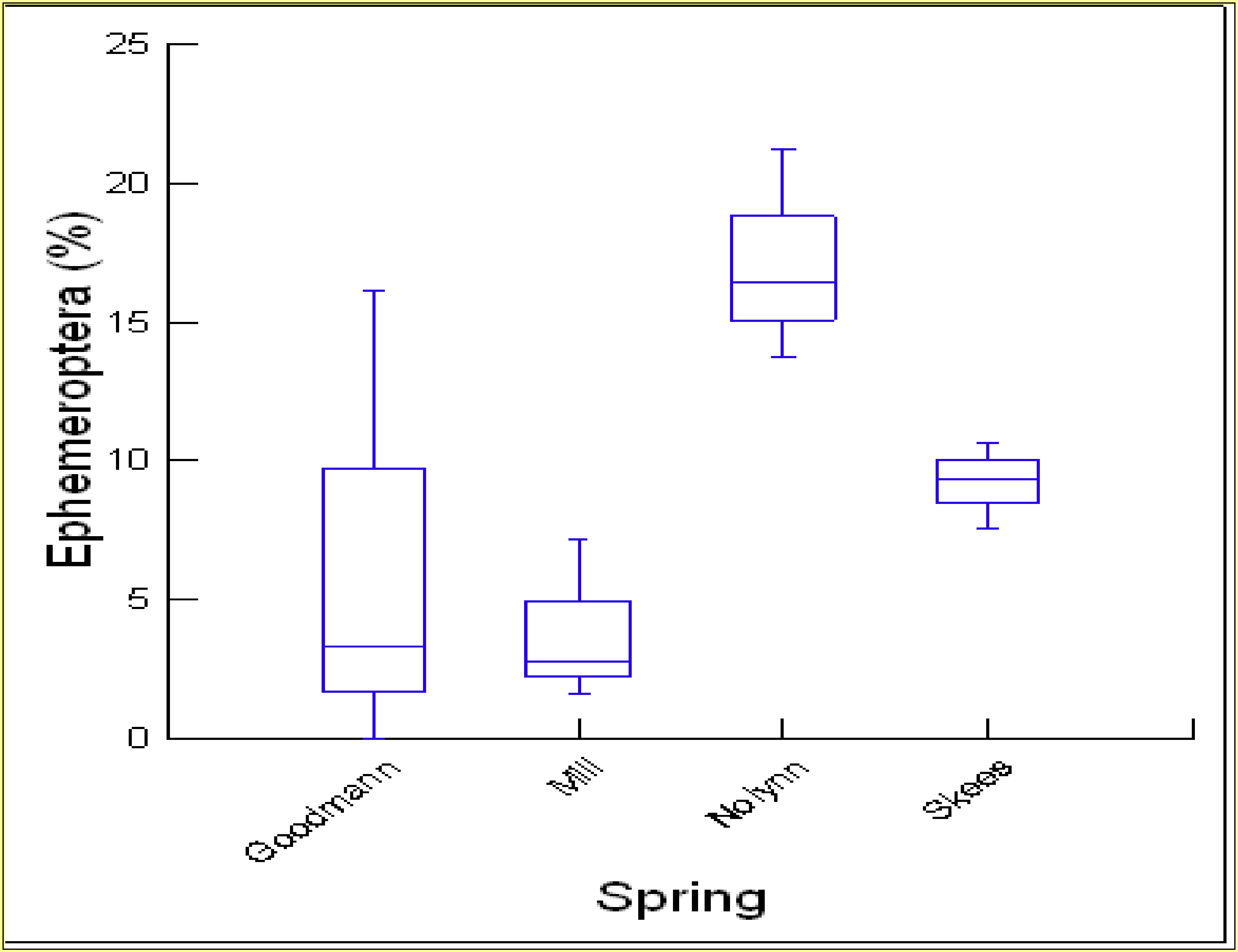


Figure 46. Percent (%) Ephemeroptera at Evaluated Springs

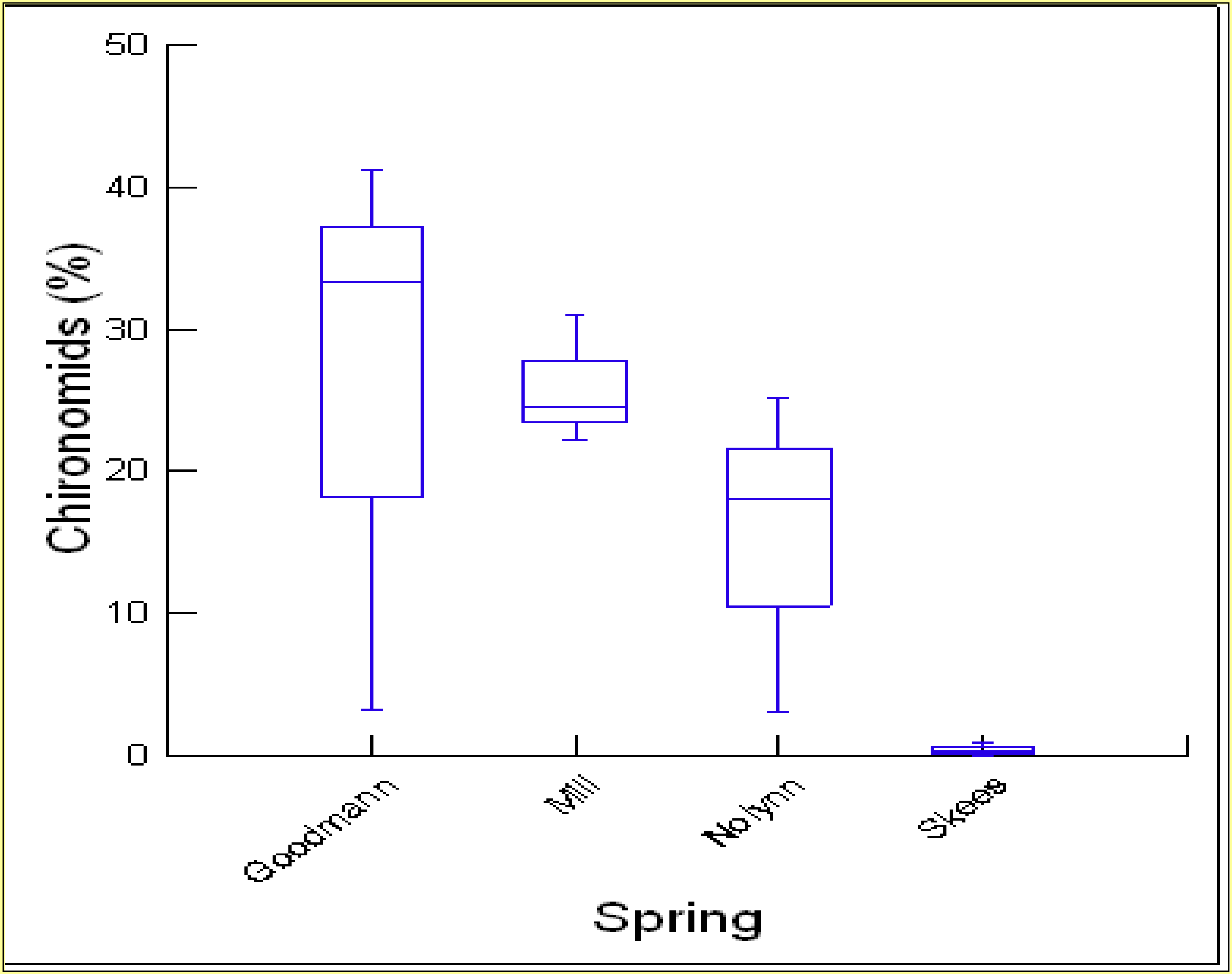


Figure 47. Percent (%) Chironomids at Evaluated Springs

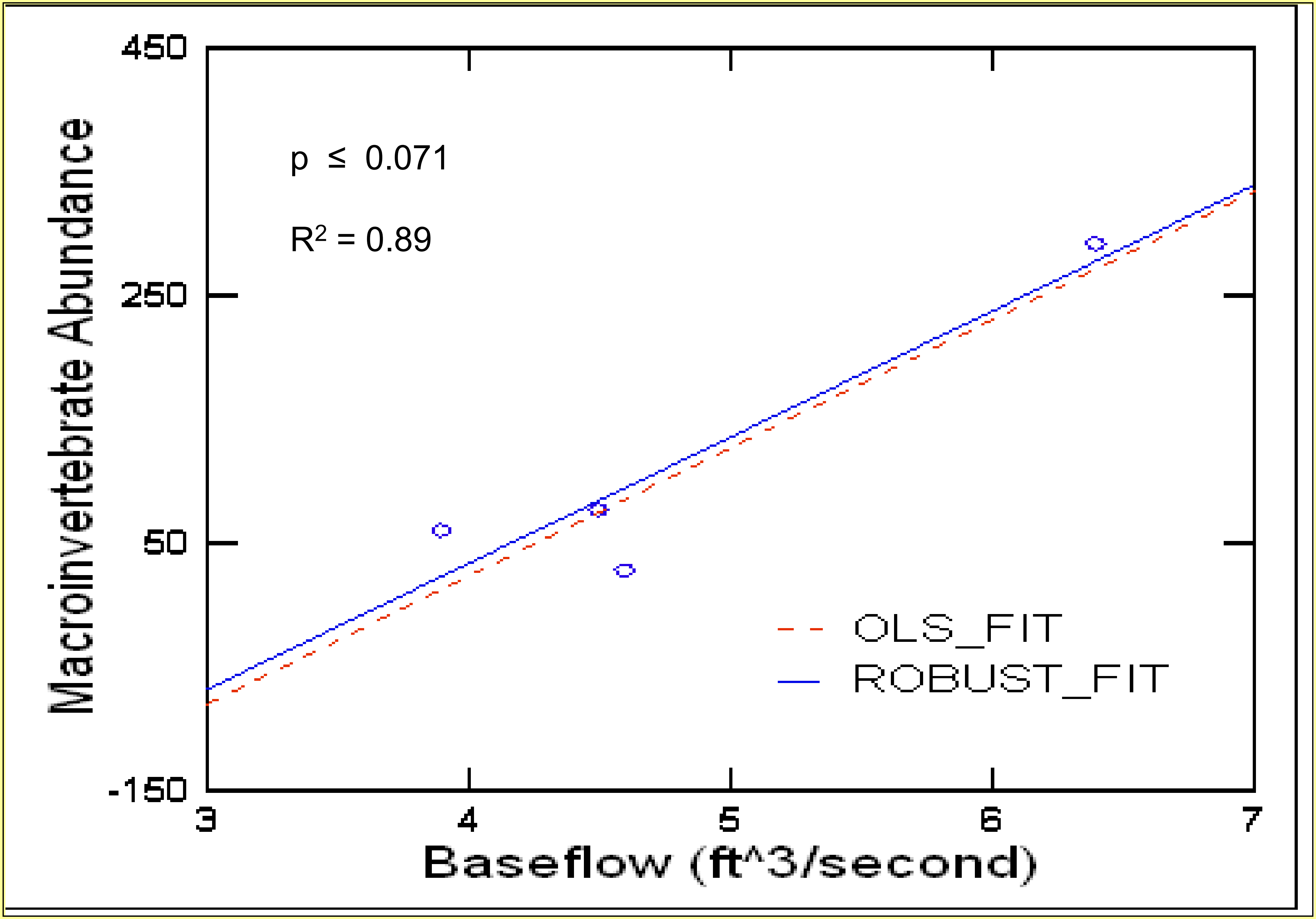


Figure 48. Relationship between Macroinvertebrate Abundance and Base Flow at Evaluated Springs

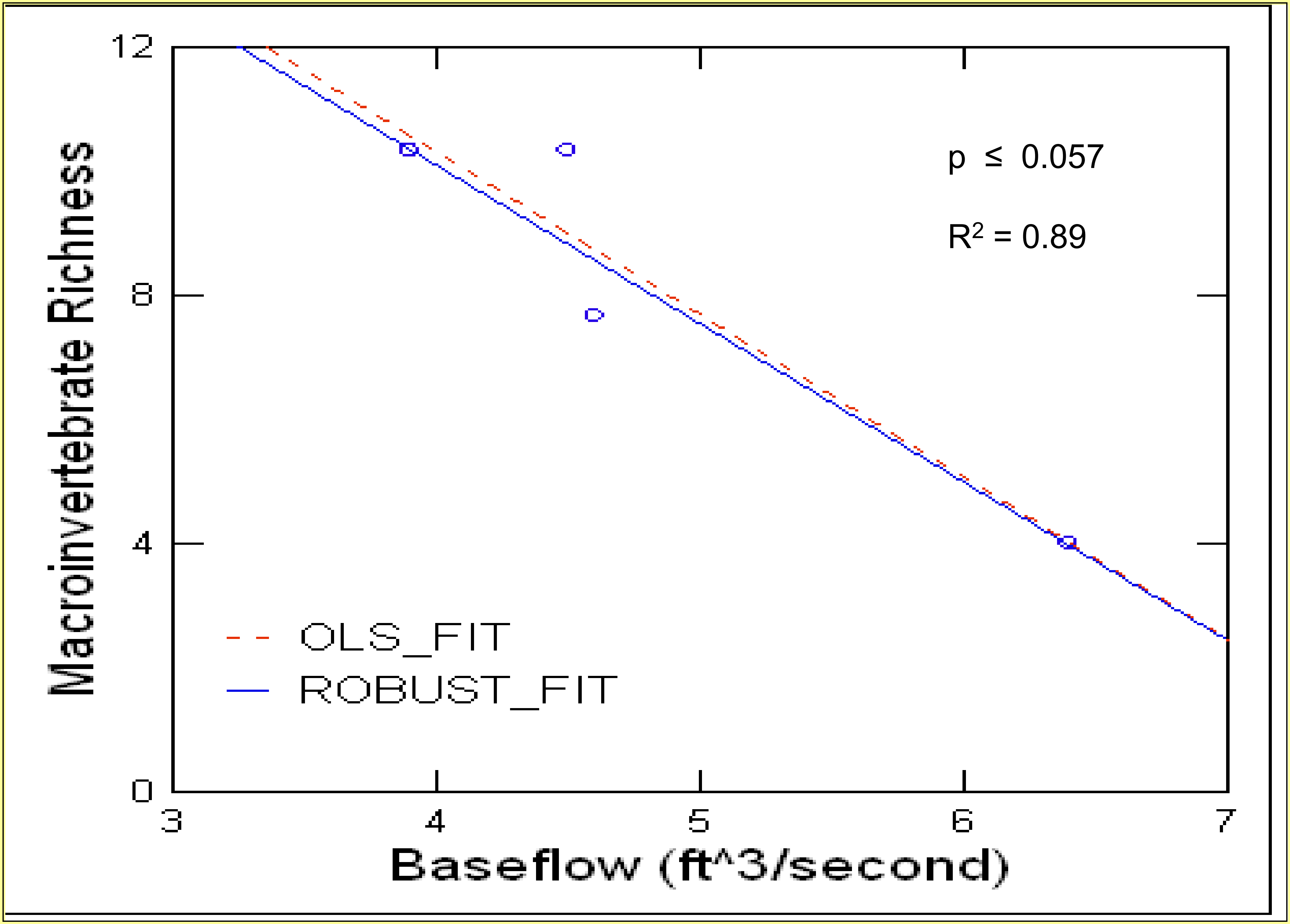


Figure 49. Relationship between Macroinvertebrate Richness and Base Flow at Evaluated Springs

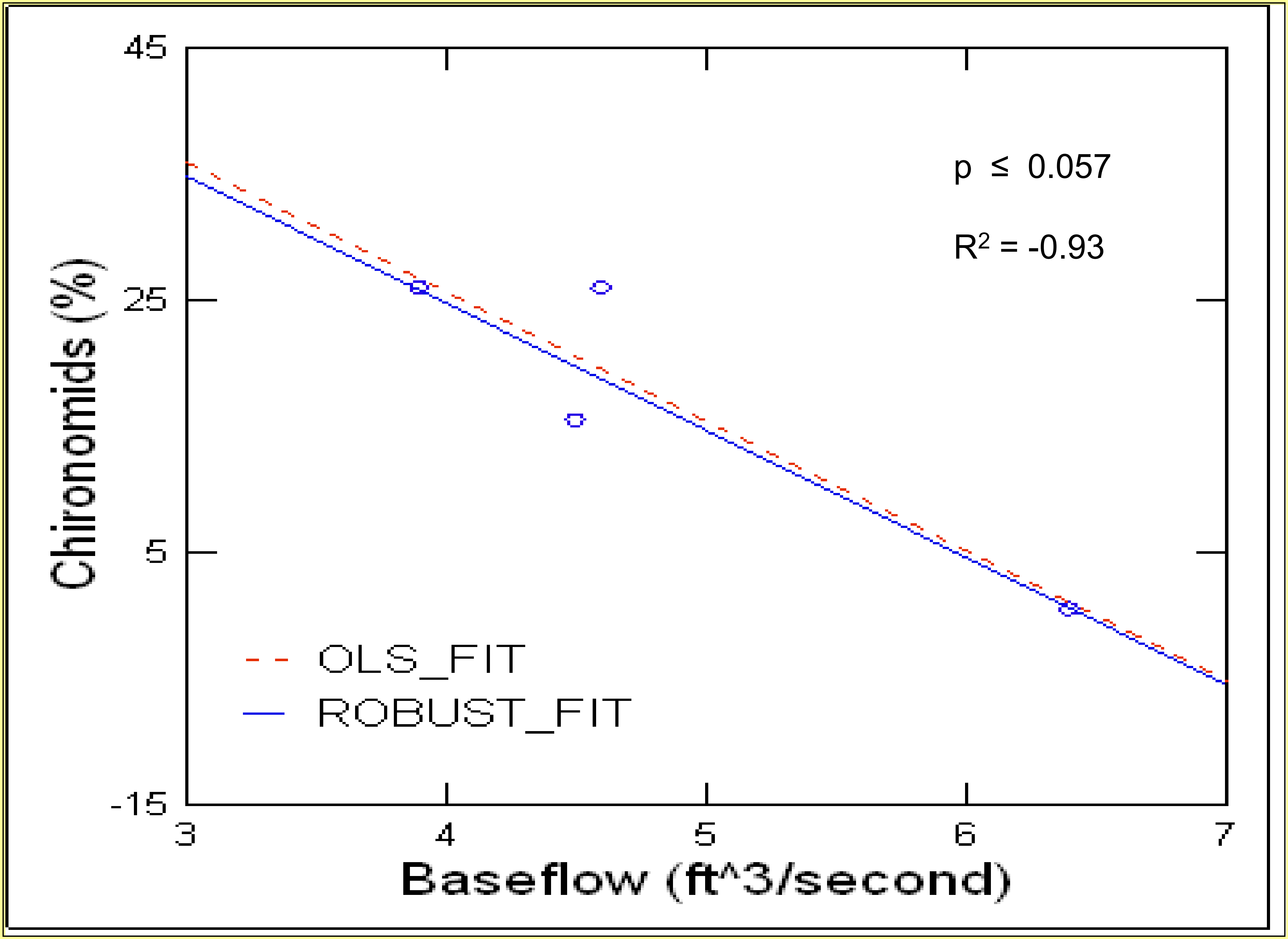


Figure 50. Relationship between %Chironomids and Base Flow at Evaluated Springs

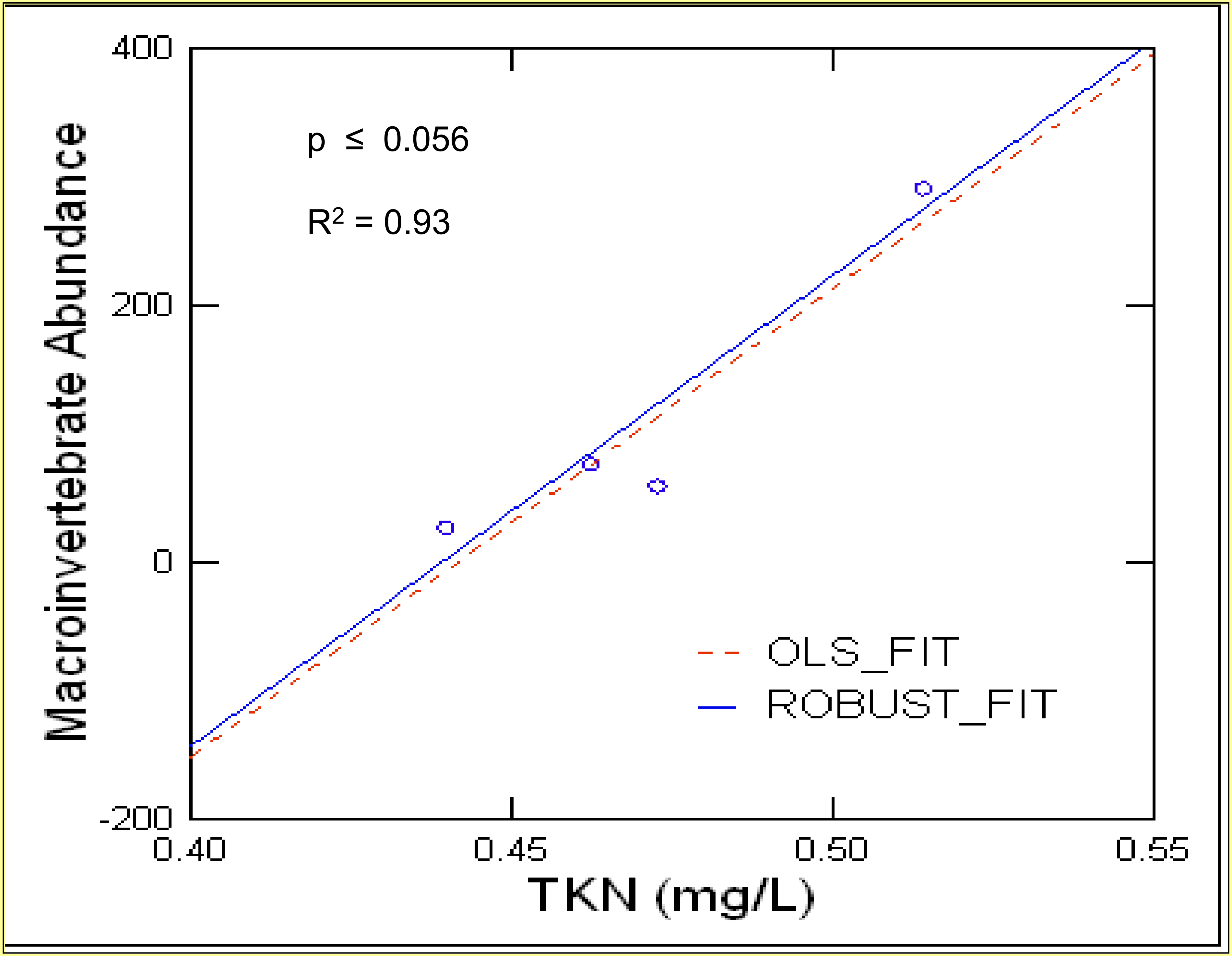


Figure 51. Relationship between Macroinvertebrate Abundance and TKN at Evaluated Springs

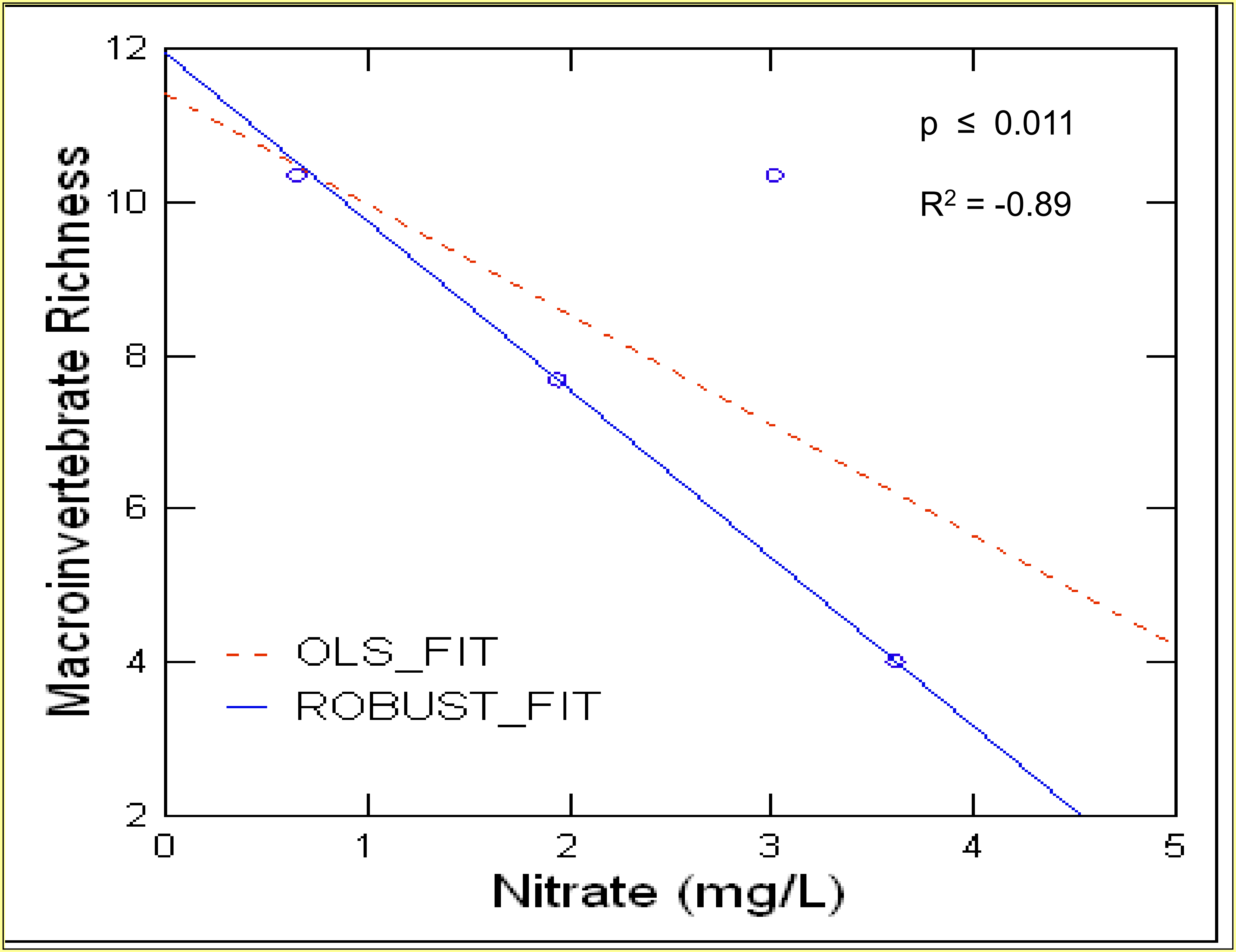


Figure 52. Relationship between Macroinvertebrate Richness and Nitrate (as N) at Evaluated Springs

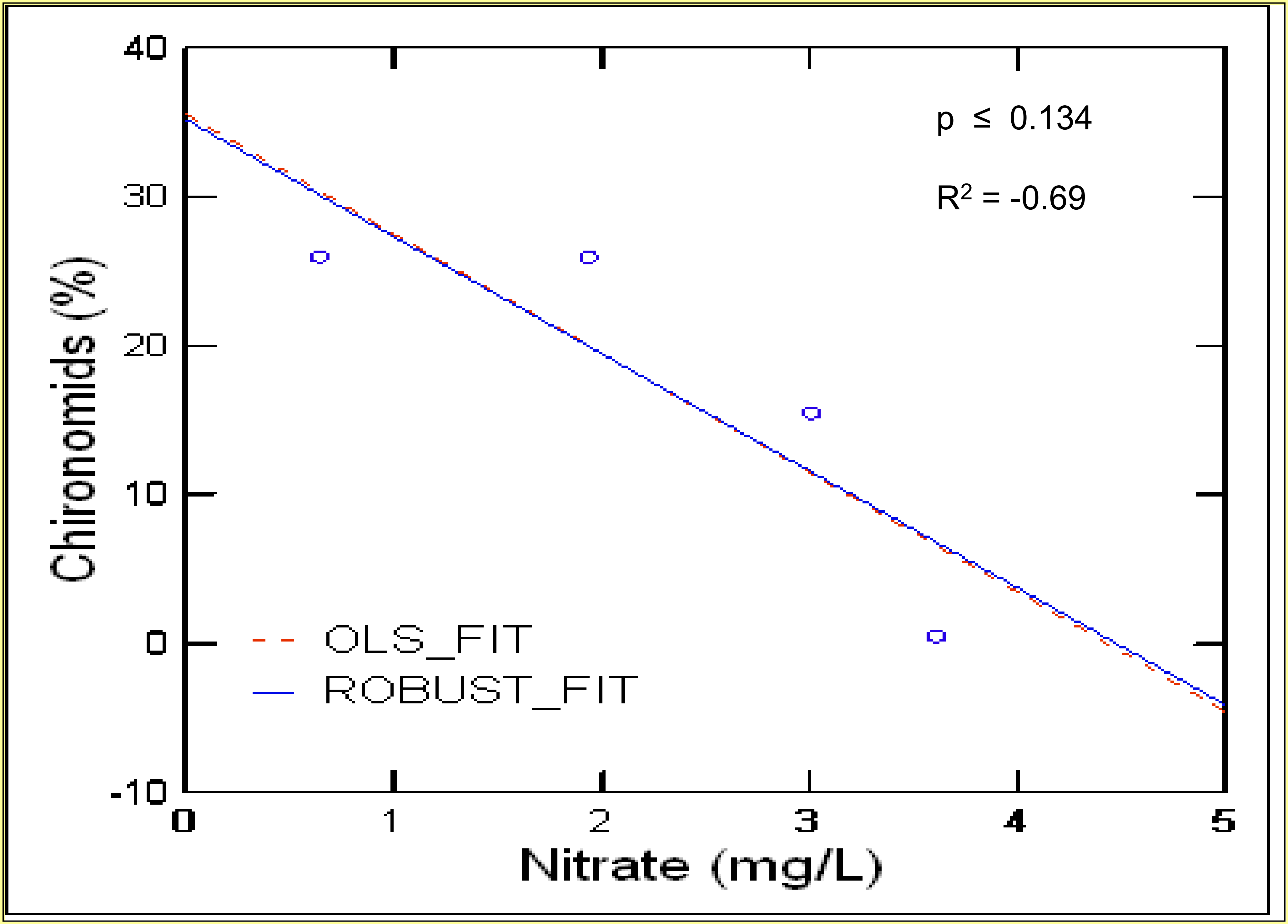


Figure 53. Relationship between %Chironomids and Nitrate (as N) at Evaluated Springs

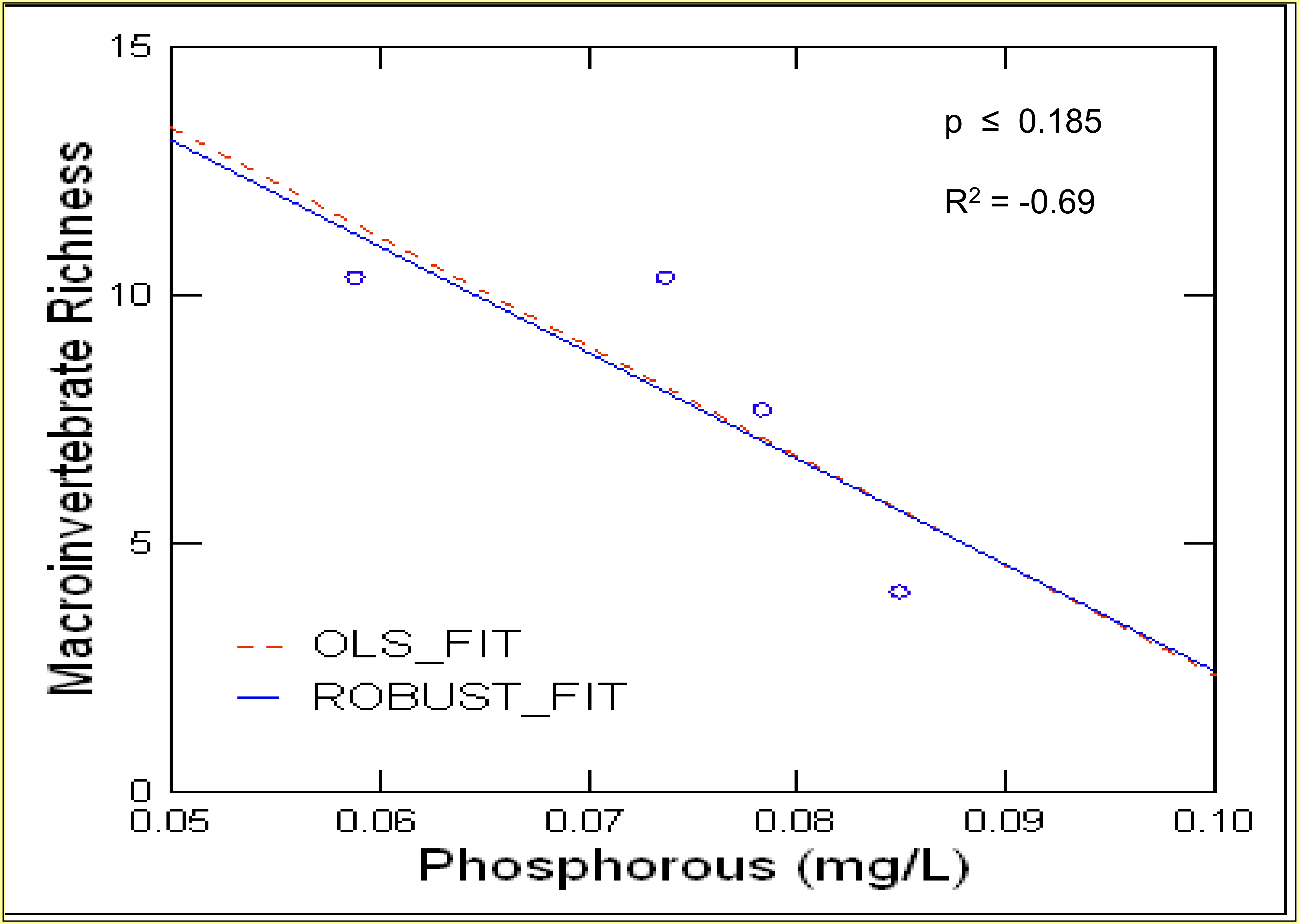


Figure 54. Relationship between Macroinvertebrate Richness and Total Phosphorus at Evaluated Springs

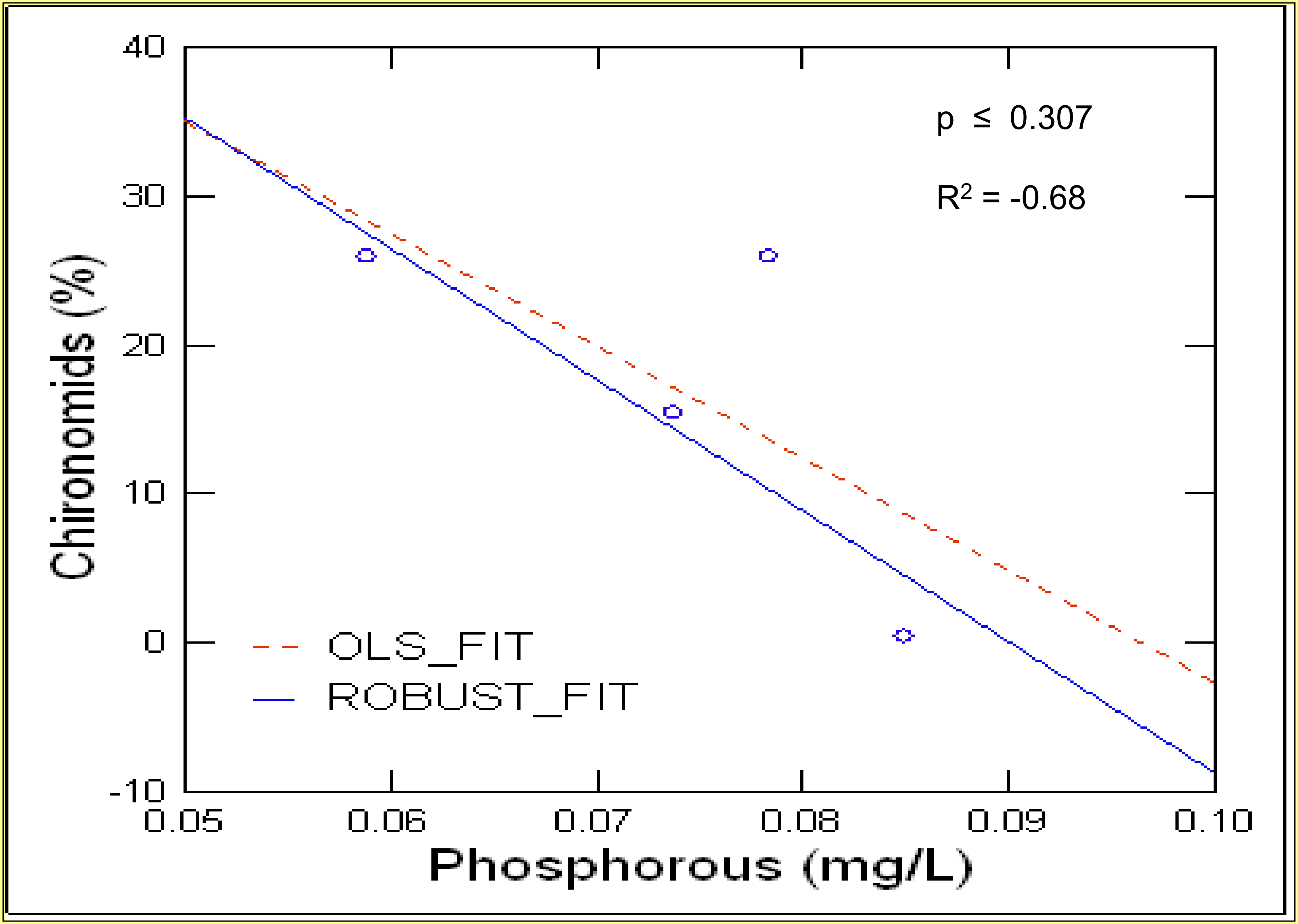


Figure 55. Relationship between %Chironomids and Total Phosphorus at Evaluated Springs

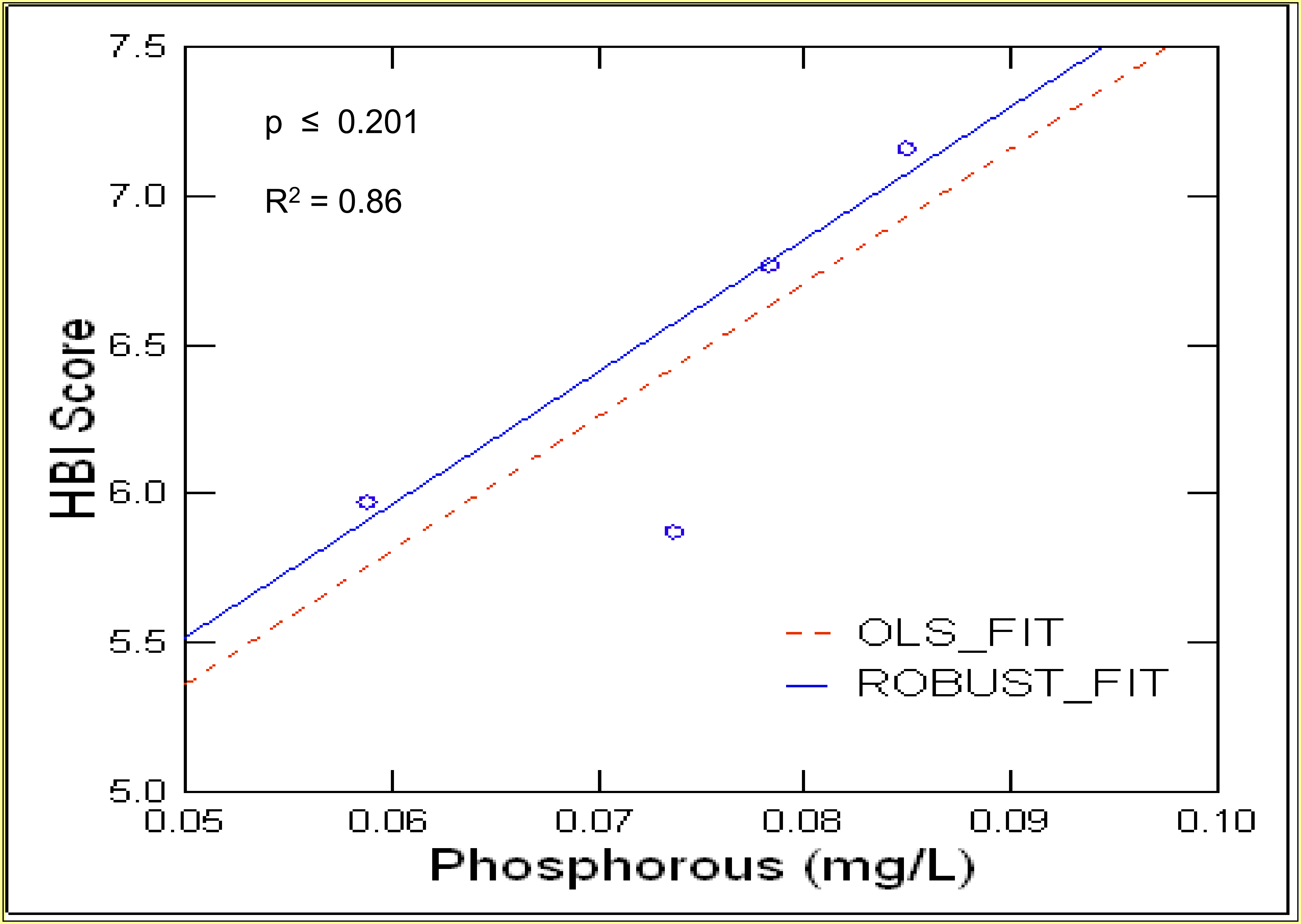


Figure 56. Relationship between HBI Score and Total Phosphorus at Evaluated Springs

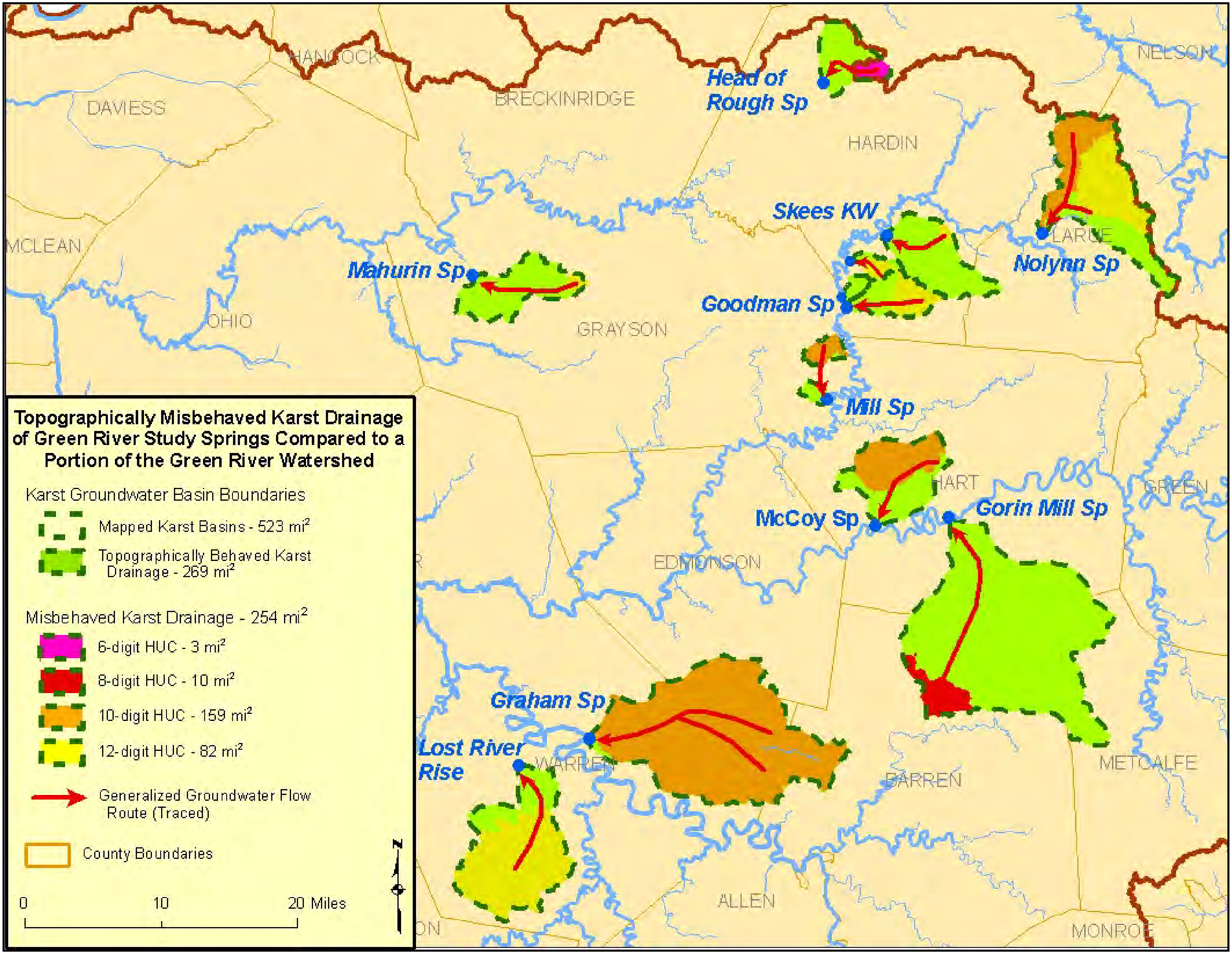


Figure 57. Karst Deviation and HUC Assessment Map

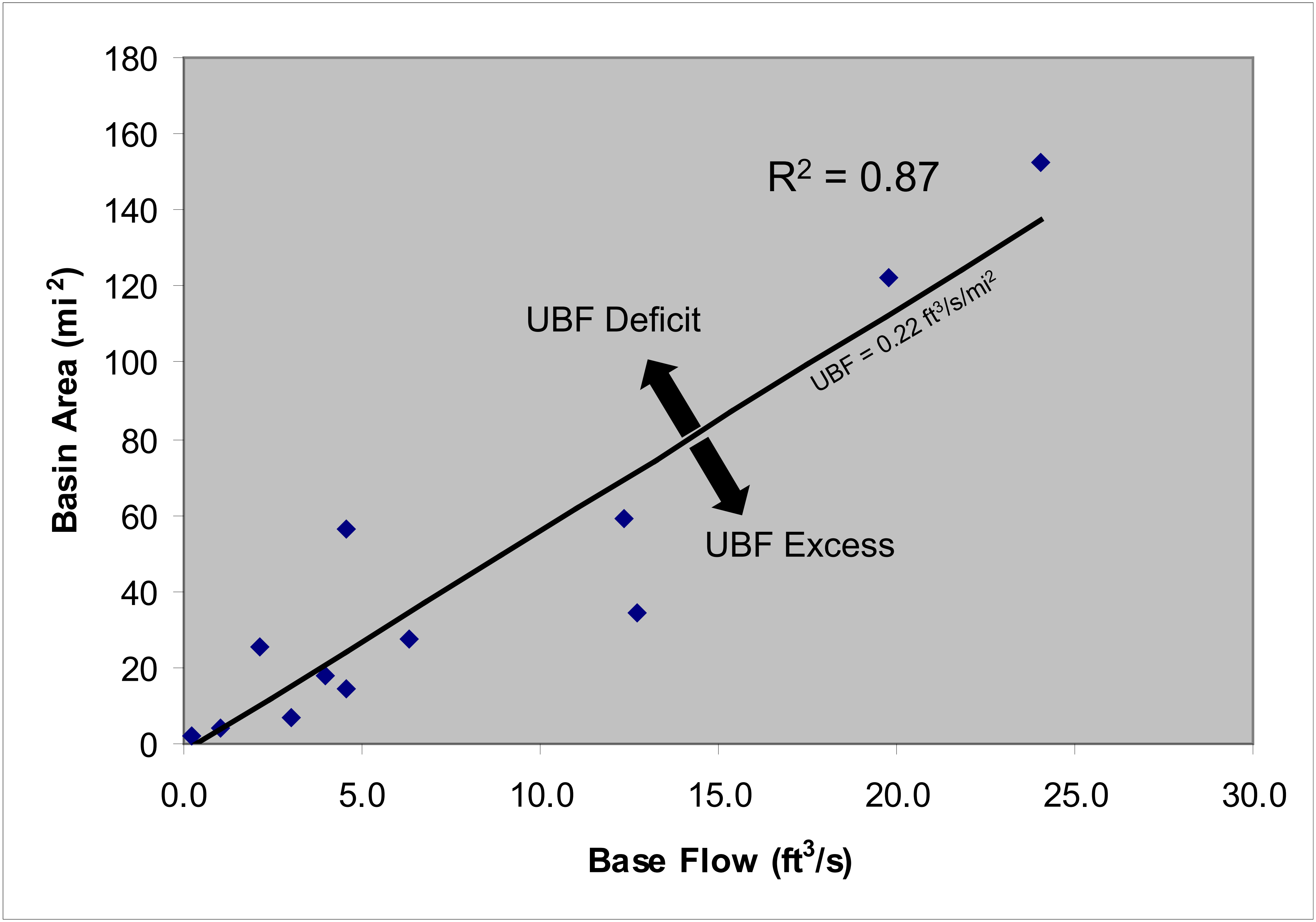


Figure 58. Spring Unit Base Flow Scatter Plot