Delineation of Ground-Water Basins and Recharge Areas for Municipal Water-Supply Springs in a Karst Aquifer System in the Elizabethtown Area, Northern Kentucky

By CHARLES J. TAYLOR

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CONVERSION FACTORS AND VERTICAL DATUM

CONVERSION FACTORS

Multiply	By	To obtain
acre	4,047.0000	square meter
cubic foot per second (ft^3/s)	2.83	liter per second
foot (ft)	0.3048	meter
foot per mile (ft/mi)	0.1894	meter per kilometer
foot per second (ft/s)	0.3048	meter per second
gallon (gal)	3.785	liter
million gallons per day (Mgal/d)	43.81	liter per second
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
thousand gallons per day (Kgal/d)	0.04381	liter per second

VERTICAL DATUM

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929—geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Delineation of Ground-Water Basins and Recharge Areas for Municipal Water-Supply Springs in a Karst Aquifer System in the Elizabethtown Area, Northern Kentucky

By Charles J. Taylor

Abstract

Ground-water basins and recharge areas for municipal water-supply springs for the Elizabethtown area, northern Kentucky, were delineated using a hydrogeologic-mapping approach, potentiometric map interpretation, and dye-tracing tests. Five distinct ground-water basins drained by major karst springs are present in the Elizabethtown area. These basins are composed of networks of hydraulically interconnected solution conduits and fractures. The boundaries of the basins for Elizabethtown and Dyers Springs—the primary sources of water for the city of Elizabethtown—were delineated by the positions of inferred ground-water divides on an existing potentiometric contour map. The results of dye-tracing tests, plotted as straight-line flowpaths, were used to confirm the presence and location of inferred ground-water divides and to adjust the position of the basin boundaries. Recharge areas of 4.8 and 2.7 square miles were delineated for Elizabethtown and Dyers Springs, respectively. Swallets that drain concentrated stormwater runoff from major highways are present in the recharge areas for both municipal-supply springs. Each spring is therefore potentially vulnerable to stormwater-runoff contaminants or accidental spills and releases of toxic or hazardous materials into certain highway drainage culverts.

INTRODUCTION

Springs are important sources of water supplies in the karst areas of Kentucky. A 1991 inventory reported that 25 different springs in 21 counties in Kentucky were used as public or semi-public water supplies (Kentucky Division of Water, 1991). Two springs in southeast Hardin County, Kentucky, Elizabethtown Spring (also known locally as City Spring) and Dyers Spring (Gaithers Station Spring), are used as the primary sources of municipal water for the City of Elizabethtown (fig. 1). About 1.4 Mgal/d is withdrawn from Elizabethtown Spring and about 567 Kgal/d is withdrawn from Dyers Spring during periods of highest consumptive use (Robert Best, Manager, Elizabethtown Water Plant, oral commun., 1995).

Conduit-dominated karst aquifers are widely recognized as being much more sensitive to ground-water contamination or degradation resulting from certain land-use practices than are typical granular and fractured-rock aquifers (Field, 1990). In recent years, considerable development of land for residential, industrial, and commercial uses has taken place in the Elizabethtown area, especially in and adjacent to sinkhole drainage areas known to be within the recharge areas of Elizabethtown or Dyers Springs.

Because of the concern for the increased potential for contamination and degradation of these two water-supply springs, the U. S. Geological Survey, in cooperation with the Kentucky Division of Water, Department of Environmental Protection, Natural Resources and Environmental Protection Cabinet, conducted an investigation to delineate the recharge areas of Elizabethtown and Dyers Springs and to gain a better understanding of the distribution and boundaries of the ground-water basins in the karst aquifer system

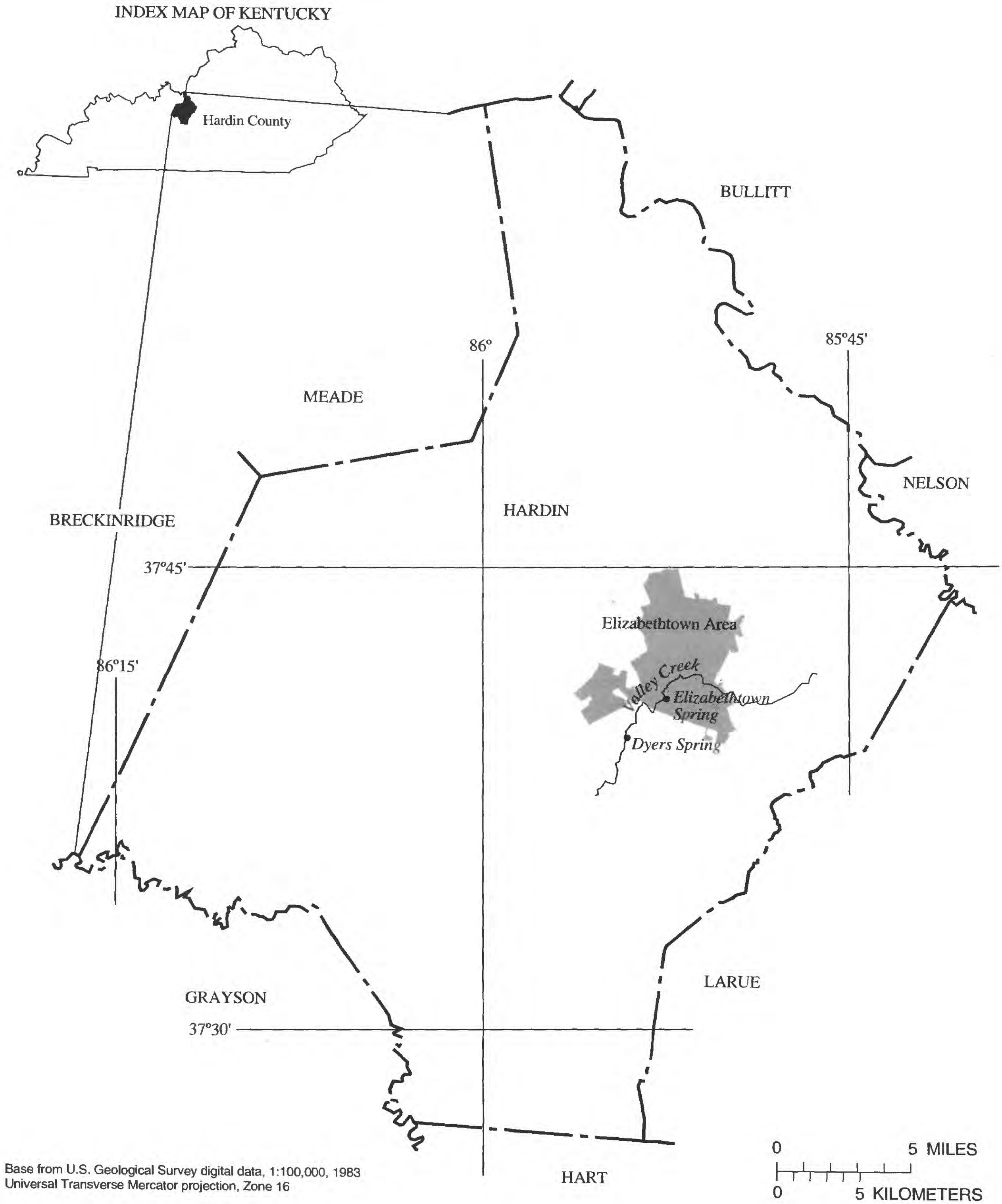


Figure 1. Location of study area and municipal water-supply springs, Elizabethtown area, northern Kentucky.

in the Elizabethtown area. This report presents the results of that investigation, which used a hydrogeologic-mapping approach that included potentiometric map interpretation and dye-tracing tests.

The information presented in this report is intended to aid water-supply managers and State regulators in developing a water-supply management and protection plan for Elizabethtown and Dyers Springs and to illustrate the use of hydrogeologic mapping methods to investigate the characteristics of karst aquifer systems.

Previous Studies

The stratigraphy and geologic structure of the Elizabethtown area are described on geologic quadrangle maps (1:24,000 scale) prepared by Kepferle (1963, 1966). A hydrologic atlas of the ground-water resources in a four-county area including Elizabethtown, Kentucky (Brown and Lambert, 1963), describes the lithologic and hydrogeologic properties of bedrock in the study area. Maps showing the altitude of the potentiometric surface of the shallow carbonate aquifer were prepared at a local scale of 1:24,000 by Mull and Lyverse (1984), at an intermediate scale of 1:50,000 by Lambert (1979), and at a regional scale of 1:250,000 by Plebuch and others (1985).

Lambert (1979), Mull and Lyverse (1984), and Mull and others (1988b) provide detailed information about the karst hydrology of the Elizabethtown area. Lambert (1979) describes the physiography and hydrogeology of southeastern Hardin and northeastern LaRue Counties, Kentucky, which includes the Elizabethtown area, and presents maps showing locations of major hydrologic features (springs and losing and gaining streams), spatial (geographic) variations in major-ion chemistry of water samples collected from wells and springs, and ground-water- level contours.

Mull and Lyverse (1984) describe the physical framework and hydrology of the karst aquifer system using hydrogeologic data obtained from geophysical logs of selected water wells, the results of aquifer (drawdown and recovery) tests, and discharge measurements of springs and surface streams. Discharge-rating curves for Elizabethtown and Dyers Springs were prepared using discharge measured during different hydrologic (flow) conditions. A map showing the altitude of the potentiometric surface prepared at 1:24,000 scale is included. The topographic and potentiometric contour lines depicted on this map illustrate the close correlation between topographic relief and the configuration of the potentiometric surface.

Mull and others (1988b) present the results of a series of qualitative and quantitative dye-tracing tests in the Elizabethtown area. Point-to-point subsurface flow connections are identified between certain sinkholes or sinking streams and each of the two water-supply springs. Dye-trace flowpaths are illustrated on a 1:24,000 scale map with potentiometric and topographic contour lines. In general, there is good agreement between the directions of ground-water flow indicated by the potentiometric contour lines and the plotted dye flowpaths. Dye-recovery (breakthrough) curves prepared from quantitative dye-tracing test results of Elizabethtown and Dyers Springs were used to evaluate solute transport characteristics, including traveltime, dilution, and dispersion properties. Smoot and others (1987) also discuss the relation between discharge and solute-transport characteristics of each spring.

Methods of Investigation

A hydrogeologic mapping approach was used to delineate karst ground-water basins and recharge areas of two municipal water-supply springs. Hydrogeologic mapping involves the identification of topographic, geologic, and hydrologic factors that affect ground-water occurrence and flow and is particularly applicable to investigations involving non-Darcian anisotropic aquifers (Bradbury and others, 1991). Combined use of field reconnaissance and mapping of karst drainage features, water-table or potentiometric-surface mapping, and dye-tracing has been successfully applied to delineate ground-water basins and the recharge areas of springs in different types of karst terranes (Thrailkill, 1985; Quinlan and Ewers, 1989; Bayless and others, 1994; Schindel and others, 1995).

During the present investigation, field reconnaissance of sinkholes, swallets (openings to subsurface conduits), sinking streams, and springs in the study area was done from August through December 1991. Reconnaissance was aided by inspection of geographic features visible on 1:1,000-scale aerial stereophotographs. Stratigraphic and geologic structural information was obtained from published 1:24,000-scale geologic quadrangle maps (Kepferle, 1963, 1966). The potentiometric surface map prepared by Mull and Lyverse (1984) was adopted for use as a (potentiometric) base map for delineating flowpaths and ground-water divides in the aquifer system base map. Changes in the general distribution and altitudes of hydraulic heads in the karst aquifer system since 1984, other than those associated with seasonal fluctuations in recharge, were assumed to be insignificant.

Because ground-water flow in the aquifer system occurs principally through solution conduits, and is therefore anisotropic and non-Darcian, interpretations about ground-water-flow directions based solely on potentiometric map interpretation are subject to error. In karst aquifer systems, discrete conduit-controlled ground-water flowpaths cannot be deduced from the configuration of the potentiometric surface alone. Dye-tracing tests by Mull and others (1988b), and additional dye-tracing tests done from October 1991 through March 1992 were used to obtain information about ground-water-flow directions in the karst aquifer system and confirm the location of ground-water divides indicated by the potentiometric base map. Dye tracing involves tagging or labeling a discrete quantity of ground water with a fluorescent dye (dye tracer) so that its flow in the subsurface can be tracked to a ground-water discharge point. Field and laboratory techniques described by Jones (1984), Quinlan (1986), and Mull and others (1988a) were used for dye-tracing tests conducted during this phase of the investigation. Non-toxic, fluorescent dyes were injected under moderate to high flow conditions at swallets in sinkhole depressions or in the channels of sinking streams. Where necessary, 300 to 500 gal of water were introduced into the swallet prior to the injection of dye from a tanker truck to initiate flow, and similar quantities of water were used to flush the dye into the subsurface drainage system. Passive dye detectors containing activated coconut charcoal or undyed cotton were used to monitor the resurgence of dye(s) at springs and surface streams.

Acknowledgments

Appreciation is expressed to Robert Best and Scott Fiepke, Elizabethtown Municipal Water Plant; Rick Gaines, Chief, Elizabethtown Fire Department; and Joe Ray, Ground Water Branch, Kentucky Division of Water; for assistance and support provided during the investigation. Gratitude also is expressed to numerous private landowners in Elizabethtown, Kentucky, for granting access to private property and providing information about the locations of sinkholes and springs in the area.

DESCRIPTION OF STUDY AREA

Elizabethtown and Dyers Springs are natural outlets for ground water discharging from a karst aquifer system beneath a sinkhole plain south of the city of Elizabethtown and Valley Creek (fig. 1) (Mull and others, 1988b). A preliminary hydrogeologic mapping area of about 7 mi^2 of the sinkhole plain was designated for this investigation (fig. 2). Hydrologic boundaries that border the study area include Valley Creek and two of its larger tributaries, Cole and East Rhudes Creeks. A major topographic drainage divide formed by the dissected upland between Valley and East Rhudes Creeks borders the study area to the south.

The topography of the Elizabethtown area exhibits the characteristics of a fluviokarst—a landscape exhibiting features formed by surface and subsurface (or karst) drainage (Sweeting, 1973). Sinkholes, springs, and sinking streams are common in the area. These solutional landforms are superimposed on the floodplain of Valley Creek and on adjacent stream-dissected uplands. Unlike many other karst areas, much of the surface runoff is drained by a dendritic network of surface streams. Valley Creek is the local and subregional base level for all surface and shallow ground-water drainage. Topographic relief in the area generally is less than 100 ft. Altitudes range from about 780 to 840 ft above sea level on the uplands to about 680 to 720 ft above sea level on the Valley Creek flood plain.

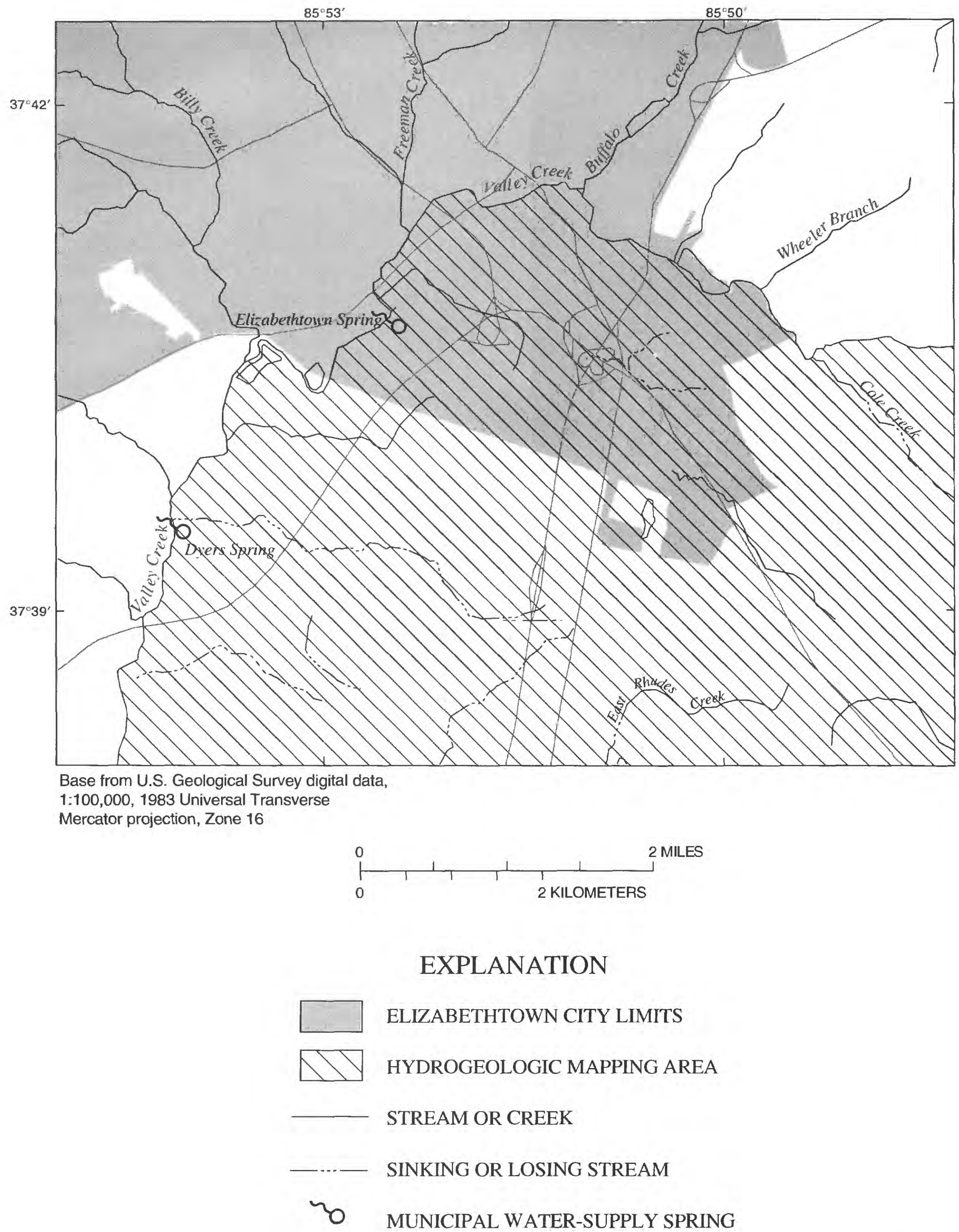


Figure 2. Location of hydrogeologic mapping area in Valley Creek karst plain, Elizabethtown area, northern Kentucky.

Karst Features

Three general types of sinkholes are present in the study area: (1) subsidence sinkholes, (2) cover-collapse sinkholes, and (3) karst windows. Subsidence sinkholes are usually broadly sloped closed depressions mantled with soil or alluvium. These solutional depressions form gradually as subsoil is piped into subsurface conduits and the overlying cover is progressively lowered. Cover-collapse sinkholes are usually steep-sided, funnel-shaped depressions in regolith or thinly bedded bedrock that form by sudden collapse of the cover over a developing subsurface cavity, when ground cover is sufficiently undermined by the development of an arch or cavity beneath the cover.

Where solution occurs above an active ground-water conduit and part of the conduit is unroofed by development of a cover-collapse sinkhole, the subsurface stream may be exposed to view. This type of solutional feature is a karst window. Two karst windows are present in the study area (fig. 3): (1) the Gaithers karst window, about 1 mi east of Dyers Spring, and (2) the Cole Creek karst window on the east bank of Cole Creek about 0.75 mi southeast of Able Springs. Ground-water flows west through the Gaithers karst window (as indicated by the exposed part of the subsurface stream) and northwest through the Cole Creek karst window.

Swallets are tubular or fracture-like surficial openings that drain runoff into subsurface conduits and commonly are found in subsidence and cover-collapse sinkhole depressions. They also may be present on the crests and slopes of some hills and in the channels of sinking streams. Because swallets drain concentrated runoff directly into subsurface conduits, these solutional features are locations where the karst aquifer system is most vulnerable to the introduction of potential ground-water contaminants.

Sinkholes and swallets are not evenly distributed throughout the study area, but are located mostly in distinctive clusters (fig. 3). Sinkhole clusters form in ground-water recharge areas where fracture or dissolution porosity and permeability in the underlying bedrock is relatively great and karstification at or near the land surface is locally intensified. Undulating, sinkhole-like features are also present in parts of the area mantled by an insoluble shale-and-sandstone residuum. The presence of these features may be indicative of solutional openings at depth in the underlying limestones.

The influence of joints on sinkhole development is readily apparent. Sinkholes commonly exhibit an elongated or oval shape and may have pronounced linear gullying along opposite sidewalls. This morphology is diagnostic of the solutional depression being developed along the strike of a vertical fracture, such as a joint or fault. Distinctive sinkhole alignments also are present in the area. The alignments are formed as a consequence of intensified solution activity and sinkhole development along a joint, closely spaced joint set, or a fault trace. The most prominent sinkhole alignments trend northwest-southeast and approximately parallel the strikes of predominant joint sets mapped by Kepferle (1963, 1966) and the trends of two faults. On topographic contour maps of the area, some aligned sinkholes form sinuous bands that trend toward Valley Creek. These sinkholes probably mark former lines of surface streams whose flows were captured by the progressive development of subsurface drainage to solutional conduits.

The other sources of discrete recharge to the shallow karst aquifer are the sinking or losing streams. Subsurface conduits probably underdrain each of several known or suspected losing stream reaches (Lambert, 1979; Mull and Lyverse, 1984). Surface flow is lost by seepage through the streambed or by diversion to subsurface conduits by swallets in the alluvium or bedrock. Three sinking streams whose surface flows are terminated by drainage into one or more swallets may contribute significant amounts of recharge to one or more of the karst springs in the study area (fig. 3). The headwaters for each of these sinking streams are on or near the residuum-mantled upland and they sink into the subsurface not far from the point where the channels cross onto the limestone outcrop areas. Flow in each of the three streams is intermittent and extends along the entire length of their channels only after periods of intense or prolonged rainfall when stormwater flow exceeds the capacity of the streambed swallets. The upper reaches of Cole and East Rhudes Creeks usually are dry, and dry streambeds characterize the channels of the smaller tributaries draining to the

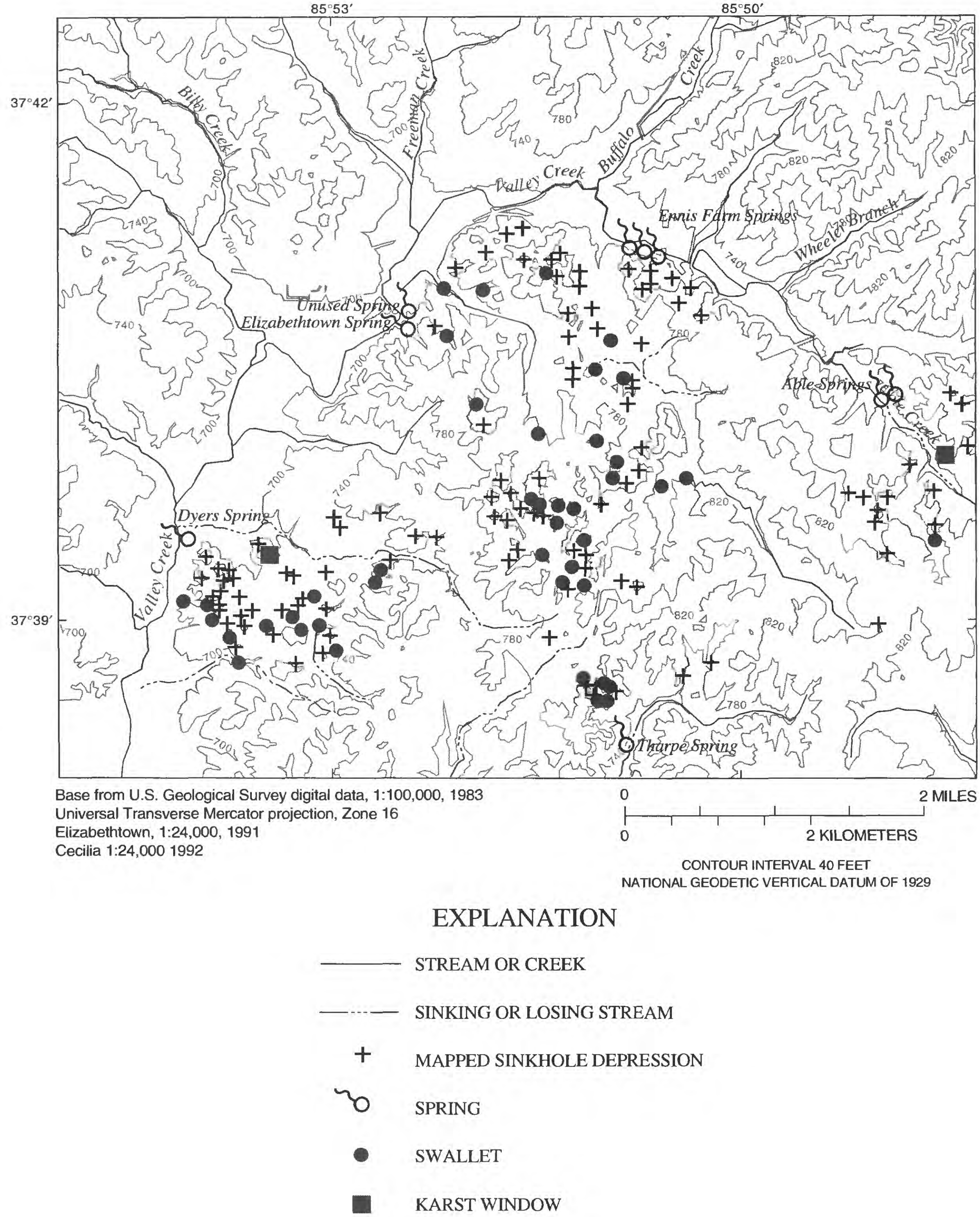


Figure 3. Distribution of springs, sinkholes, and other karst features, Elizabethtown area, northern Kentucky.

main stem of Valley Creek. Stream-discharge measurements indicate that about a 200-foot section of Valley Creek upstream from Elizabethtown Spring loses flow through solution-enlarged joints in bedrock exposed in the channel (Mull and Lyverse, 1984). However, the loss of streamflow here may be induced by withdrawals from municipal wells that supplement the municipal water supply from the two karst springs. A dye trace done by Mull and others (1988a) indicated that flow in the losing reach of Valley Creek is captured by municipal water-supply wells. No hydraulic connection between the losing stream reach of Valley Creek and either Elizabethtown or Dyers Springs was indicated by the results of this dye trace.

Springs

During the field reconnaissance, nine perennial karst springs were identified along the south side of Valley Creek and elsewhere in the study area. Elizabethtown and Dyers Springs are the two largest springs in terms of physical dimensions and discharge, and are the only springs in the area currently used to supply potable water. Elizabethtown Spring discharges directly to Valley Creek from a cave-like opening in the south bank of Valley Creek, although the water from the spring is impounded behind a dam constructed to facilitate water withdrawal. Under most hydrologic conditions, the spring discharge is by gravity flow and has a free surface with the atmosphere, however, under certain high-flow conditions, the spring discharge is under artesian pressure. Mull and Lyverse (1984) measured the discharge from Elizabethtown Spring as 2.6 ft/s on August 4, 1983, and 6.4 ft/s on April 21, 1983.

Dyers Spring (also known locally as Gaithers Spring) is about 1 mi south of Elizabethtown Spring. Water discharges from a conduit-like opening, usually under artesian pressure, at the bottom of a rise pit in the flood plain of Valley Creek. The rise pool formed by the spring discharge drains to Valley Creek through a meandering channel incised about 8 ft below land surface. Mull and Lyverse (1984) measured the discharge from Dyers Spring as 0.76 ft/s on August 4, 1983, and 4.5 ft/s on April 21, 1983.

Other karst springs in the study area include Unused Spring, Able Springs, Ennis Farm Springs, and Tharpe Spring. Unused Spring discharges directly to Valley Creek about 100 ft upstream (north) from Elizabethtown Spring. Ennis Farm Springs is a spring complex formed by three conduit-like springs and several seeps that issue from the base of a bluff along Valley Creek. Able Springs is a spring complex on Cole Creek that includes an alluviated rise pool in the center of the streambed, a second intermittent conduit-like spring in the streambank, and a number of small wet weather spring outlets along the bank. Tharpe Spring is a relatively small (about 1 to 2 ft in diameter) conduit-like perennial spring near the base of a narrow streamless valley in the south-central part of the study area. Flow from the spring outlet forms one branch of the headwaters for East Rhudes Creek.

Geology

The study area is mostly underlain by Mississippian-age limestones of the St. Louis and Ste. Genevieve Formations (fig. 4). The limestone bedding units in these two formations are highly fossiliferous, crystalline, and massive to tabularly bedded. Some limestones are dolomitic or siliceous and are interbedded with minor units of shale, dolostone, and chert. Bedded evaporites, mostly anhydrite and gypsum, also are reported present in the upper St. Louis Limestone but are not exposed at the surface (Kepferle, 1963, 1966).

The geologic contact between the St. Louis and Ste. Genevieve Formations is gradational and is relatively difficult to identify in the field due to lithologic similarities and poor outcrop exposure. Kepferle (1963, 1966) mapped the formation contact as being 20 to 40 ft below the top of the Lost River Chert, a distinctive 5 to 10 ft thick zone of brecciated siliceous limestone and nodular chert in the lower Ste. Genevieve. A second distinctive chert bed, the Corydon Chert, 3 to 5 ft thick and characterized by spheroidal chert nodules, is present at or below land surface in the southern part of the study area (A.I. George, consultant, written commun., 1984). Several other relatively thin (1 to 3 ft thick) chert beds or zones also are present in this general stratigraphic level.

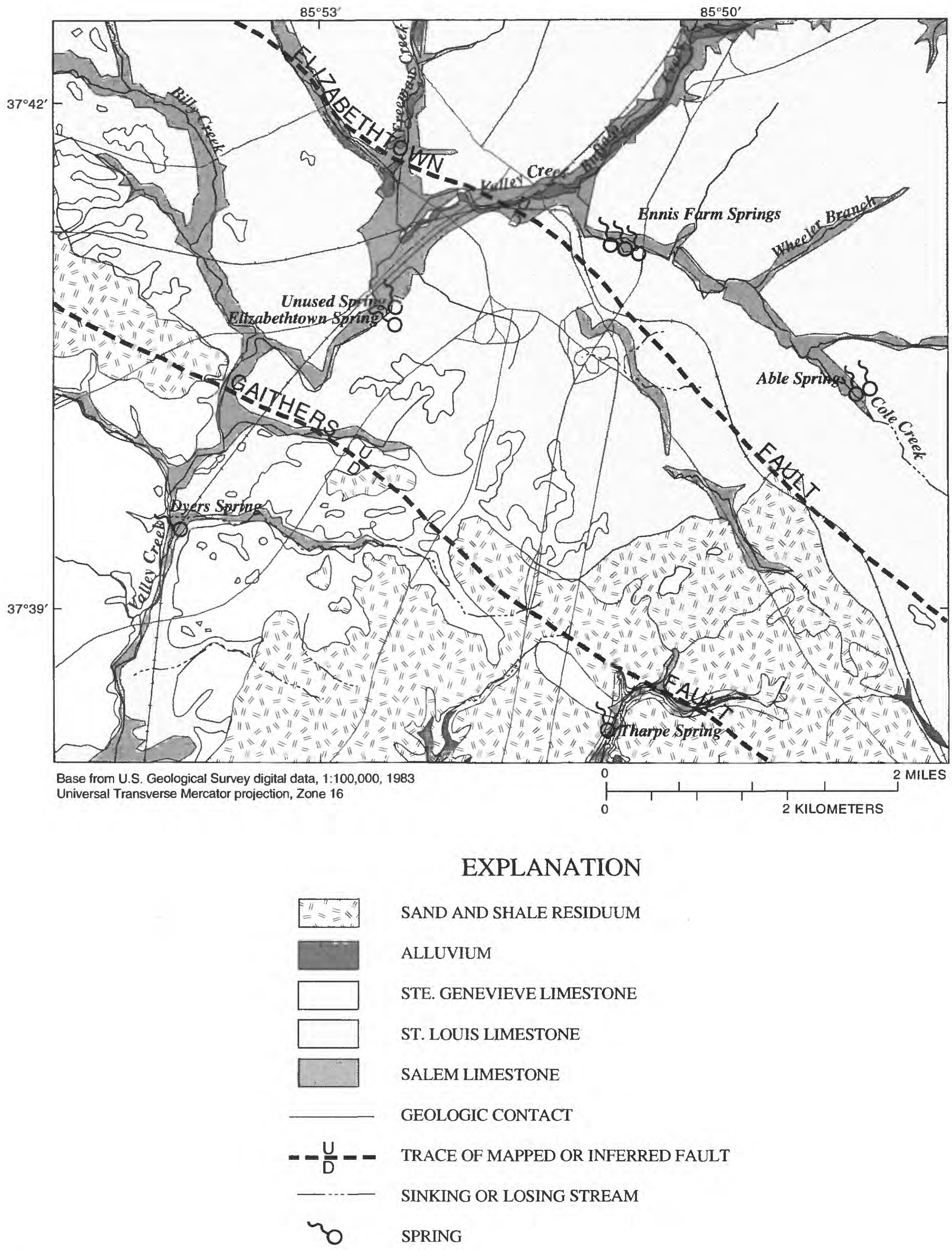


Figure 4. Surficial geology of Elizabethtown area, northern Kentucky.

The presence of chert beds in the stratigraphic section is hydrologically important, because they are relatively resistant rocks that resist karstification and are effectively leaky confining layers (Howard, 1968; Groves and Crawford, 1990).

Surficial deposits of alluvium, residuum, residual soil, and loess are present throughout parts of the area (Kepferle, 1963, 1966). Significant alluvial deposits are largely restricted to the Valley Creek floodplain in the southwest corner of the area, where they reach thicknesses of 15 to 40 ft (George, 1984). Mappable deposits of poorly sorted silt, sand, and lithic sandstone and shale fragments (sand and shale residuum) ranging 75 to 100 ft in thickness are present on much of the upland in the south-central part of the study area (Kepferle, 1963, 1966). The residuum is thought to be derived from erosion of mixed carbonate and siliciclastic rocks stratigraphically higher than the Ste. Genevieve, and may be slump sediment deposits filling former sinkholes that formed during an earlier period of karstification (Kepferle, 1966). Residual soils derived from weathering of limestone bedrock are composed mostly of reddish-colored clay loams with abundant chert and vary greatly in thickness.

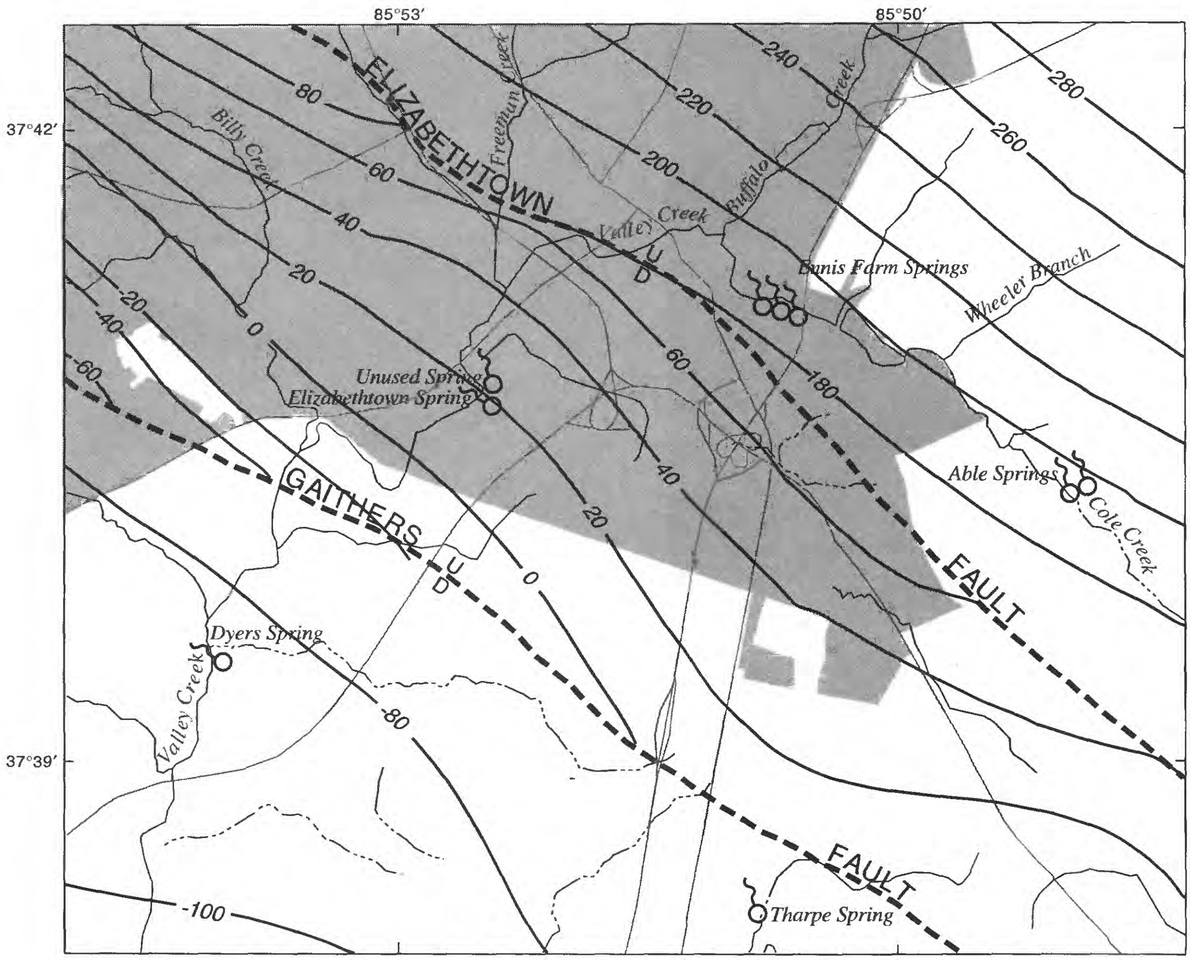
Bedrock strata in the area are broadly deformed and lie on the northern limb of a northeast-striking synclinal structure (Kepferle, 1963). The strike of the strata is about N70°W, and the strata dip to the southwest at about 100 to 150 ft/mi (fig. 5). Locally, the dip of bedrock strata are influenced by small-scale synclinal structures and by two mapped fault zones that cross the area from east to west, the Elizabethtown Fault (Kepferle, 1966) and the Gaithers Fault (Kepferle, 1963). Both are extensional faults with a downdropped block on the south side of the mapped fault trace. The total amount of vertical fault displacement across Gaithers Fault appears to be less than 50 ft and is 120 ft or less across the Elizabethtown Fault.

Three prominent joints sets also are mapped on the Elizabethtown and Cecilia geologic quadrangles (Kepferle, 1963, 1966). The predominant joint set strikes at about N40°W, approximately parallel to the trend of the two mapped fault traces. A secondary joint set strikes at about N50°E, at approximately right angles to the predominant joint set. Bedding-plane (horizontal) fractures formed by stress relief are abundant throughout the geologic section, and are particularly well developed between adjacent limestone beds.

Description of Aquifer System

Ground water is stored in the alluvium along the Valley Creek flood plain and in the thicker deposits of the sand and siltstone residuum in the area. However, the most significant aquifer system is in the karsted Mississippian limestones. Ground-water flow in the limestones is dominated by movement through interconnected pipe-like solutional openings (solution conduits) and fractures. In the strictest sense, ground water is present only in conduits and fractures in the saturated zone but because of direct hydraulic connection, conduits and fractures in the unsaturated (or vadose) zone are an integral part of the aquifer system. The solution conduits generally increase in size and order in the downstream direction and are integrated into individual ground-water basins drained by one or more major karst springs. The aquifer system is recharged by the diffuse infiltration of precipitation through soil cover and entry of concentrated runoff into sinkholes and sinking surface streams. Ground water flows through each subsurface basin in response to hydraulic gradients controlled by topographic relief and the slope of the solutional conduits themselves. The potentiometric surface map prepared by Mull and Lyverse (1984) indicates that subregional ground-water flow is toward Valley Creek or its major tributaries, Coles and East Rhudes Creeks.

The potentiometric surface generally is less than 100 ft below land surface and the karst aquifer system exhibits relatively elastic hydraulic behavior (Mull and Lyverse, 1984) in that ground-water levels initially rise when the aquifer system is stressed by stormwater recharge but return relatively quickly to baseflow levels. This property reflects the relatively high hydraulic conductivity and low storativity associated with solution conduits and conduit-dominated subsurface drainage.



Base from U.S. Geological Survey digital data, 1:100,000, 1983 Universal Transverse Mercator projection, Zone 16

0 2 MILES

0 2 KILOMETERS

EXPLANATION

ELIZABETHTOWN

— 200 — STRUCTURAL BEDROCK CONTOUR -- Drawn on top of Lost River Chart and/or New Albany Shale. Contour interval is 20 feet. Datum is sea level (source: Kepferle, 1963, 1966)

U/D TRACE OF MAPPED OR INFERRED FAULT

SINKING OR LOSING STREAM

SPRING

Figure 5. Structural contours of bedrock strata, Elizabethtown area, northwestern Kentucky.

DELINEATION OF GROUND-WATER BASINS

Dye-Tracing Tests

Dye-tracing tests reported by Mull and others (1988b) and those done during this investigation (tables 1 and 2) were used to identify point-to-point hydraulic connections and ground-water flow directions between specific sinkhole or swallet recharge sites and springs. Straight-line dye flowpaths are plotted on the potentiometric base map in figure 6 to illustrate the results of dye-tracing tests. The dye flowpaths do not represent aquifer flow lines in the traditional (Darcian) sense, nor do they delineate the actual trends of solutional conduits in the subsurface. Rather, each plotted dye flowpath represents the demonstrated hydraulic connection and general direction of ground-water flow between the dye-injection and dye-recovery site(s).

Four dye flowpaths on the map indicate previous dye-tracing tests reported by Mull and others (1988b) that resulted in dye recoveries at Elizabethtown Spring (table 1). All dye injections for these tests were made at sinkholes or sinking streams in the sinkhole plain about 1.5 mi east of the spring. One dye-injection site is a swallet that is the terminus for a sinking stream that drains the upland near the east-central part of the study area (fig. 6, dye flowpath M2). A second dye-injection site (fig. 6, dye flowpath M5) is a swallet formed by a cave entrance beneath the major highway interchange at Interstate Highway 65 and the Western Kentucky Parkway.

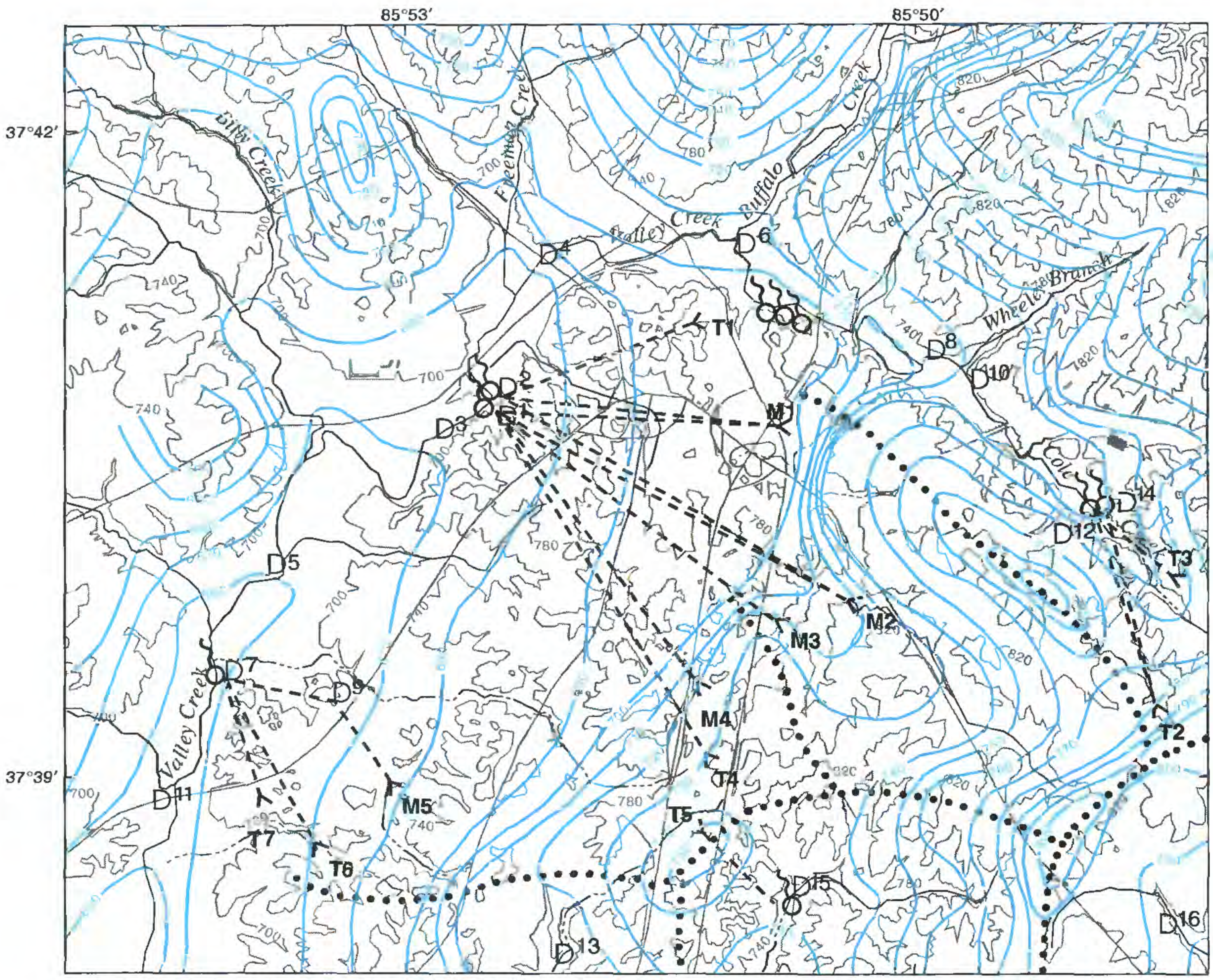
Table 1. Results of dye-tracing tests, Elizabethtown, northern Kentucky, February 1985 to February 1986

[Dye tracing tests were done by Mull and others, 1988]

Dye-injection site	Injection date	Dye-recovery site	Straight-line distance (miles)
M1: Swallet at Interstate Highway 65 at Western Kentucky Parkway Interchange	3-07-85	Elizabethtown, Unused Spring	1.44
M2: Sinking stream	9-11-85	Elizabethtown, Unused Spring	2.16
M3: Sinkhole	2-11-85	Elizabethtown Spring	1.74
M4: Sinkhole	2-03-86	Elizabethtown Spring	1.76
M5: Sinking stream	2-28-85	Gaithers Karst Window	.55
		Dyers Spring	1.02

Table 2. Results of dye-tracing tests, Elizabethtown, northern Kentucky, October 1992 to March 1993

Dye-injection site	Injection date	Dye-recovery site	Straight-line distance (miles)
T1: Vaughn sinkhole	11-14-91	Unused city spring	0.98
T2: Buhl sinkhole	10-16-91	Able Spring	.93
T3: Cole Creek Karst Window (swallet)	12-17-91	Able Spring	.38
T4: Sinkhole at Interstate Highway 65 weighing station	12-19-91	Elizabethtown Spring	2.01
T5: Watts Swallet	12-19-91	Tharpe Spring	.42
T6: Strickler Creek Swallet (sinking stream)	1-06-92	Dyers Spring	.86
T7: Swallet at mile marker 133, Western Kentucky Parkway	1-06-92	Dyers Spring	.53



Base from U.S. Geological Survey digital data 1:100,000, 1983
Universal Transverse Mercator projection
Elizabethtown, 1:24,000, 1991
Cecilia, 1:24:000, 1992

0 — 2 MILES
0 — 2 KILOMETERS

CONTOUR INTERVAL 40 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

EXPLANATION

- 700 — WATER-LEVEL CONTOUR -- Contour interval is 10 feet. Datum is sea level. From Mull and Lyverse, 1984.
- ● ● ● ● ● INFERRED GROUND-WATER DIVIDE
- —·-·— SINKING OR LOSING STREAM
- - - - - M1 STRAIGHT-LINE DYE FLOW PATH FOR DYE TRACE REPORTED BY MULL AND OTHERS (1988)
- - - - - - T1 STRAIGHT-LINE DYE FLOW PATH FOR DYE TRACE CONDUCTED DURING THIS INVESTIGATION
- ≻ DYE-INJECTION SWALLET
- D3 DYE-DETECTOR (MONITORING) SITE USED DURING THIS INVESTIGATION
- SPRING

Figure 6. Relation of dye flowpaths to the contoured potentiometric surface, Elizabethtown area, northern Kentucky.

Several dye-tracing tests were done during the previous investigation at a swallet that drains a short sinking stream segment in the southwest part of the study area. Each test resulted in dye recovery at Dyers Spring (Mull and others, 1988b). The collective results of these tests are represented by single dye flowpath between the swallet and Dyers Spring (fig. 6, dye flowpath M5). The results of these tracing tests indicated that dye-laden ground-water from the injection site was conducted about 0.5 mi to the unroofed ground-water conduit exposed in the Gaithers karst window (Mull and others, 1988b). From there, dye-laden water flowed to Dyers Spring, about 0.75 mi to the west.

Seven additional dye-tracing tests were done during this investigation from October 1991 to March 1992. These tests were initiated at swallets in five sinkholes and two sinking streams in previously uninvestigated parts of the sinkhole plain. Two of these tests resulted in dye recovery at Dyers Spring, one test resulted in dye recovery at Elizabethtown Spring, and four dye-tracing tests resulted in dye recoveries at other karst springs in the study area (table 2).

Test 1

Optical brightener was injected on November 14, 1991, in a swallet near the bottom of a subsidence sinkhole at Vaughn Lane (Vaughn Lane sinkhole) in the northern part of the study area (fig. 6, dye flowpath T1). The injected dye was recovered on a cotton detector collected on November 21, 1991, at Unused City Spring. Two previous dye-tracing tests done by Mull and others (1988b) (fig. 6, dye flowpaths M1-2) indicated that Unused City Spring shared recharge with Elizabethtown Spring from certain sinkholes to the east, including the swallet at the intersection of I-65 and Western Kentucky Parkway. Dye was not detected at Elizabethtown Spring during this test, even though the amount of dye recovered by the detector at Unused City Spring indicated that a concentrated dye plume had discharged through the spring outlet. The result of this test therefore suggests the presence of a ground-water basin boundary where sinkhole recharge is drained only to Unused City Spring. The general direction of ground-water flow between the injection site and the spring for test 1 is to the southwest.

Test 2

Fluorescein dye was injected on October 16, 1991, in a cave-like swallet opening at the bottom of a 50-foot deep sinkhole (Buhl sinkhole) along Locust Grove Road in the east-central part of the study area (fig. 6, dye flowpath T2). Prior to initiation of this dye-tracing attempt, it was anticipated that the sinkhole might drain to Elizabethtown Spring, about 4 mi to the west. Therefore, the amount of dye injected was selected to enable a positive dye detection to be made at Elizabethtown Spring. Dye was visible in Coles Creek on October 24, 1991, 8 days following the injection. The visible dye plume was tracked about 2 mi upstream to its resurgence—a previously unknown alluviated rise-pool spring in the channel of Coles Creek. Later observations made during low-flow conditions confirmed that the rise pool is the headwater for Coles Creek. A second cave-like spring opening is about 25 ft to the east of the rise pool, which discharges into Cole Creek just downstream of the rise pool by way of small meandering stream. Dye also was visible in this second spring outlet and in several small high-level overflow outlets in the streambank. This spring complex is identified as Able Springs in this report. The general direction of ground-water flow between the injection site and Able Springs for test 2 is to the northeast.

Test 3

Fluorescein dye was injected on December 17, 1991, in a cave stream exposed in a small karst window on the east side of Coles Creek (fig. 6, dye flowpath T3). The dye was recovered on a charcoal detector collected on December 23, 1991, from the rise pool at Able Springs. However, dye was not recovered on the detector collected from the cave-like spring opening at Able Springs. When comparing the results of this test with those of test 2, the two spring outlets at Able Springs seem to be connected only under certain high-flow conditions, and when the water table declines below a certain altitude, flow in each spring originates from different conduit systems with separate recharge areas. The general direction of ground-water flow between the injection site and the rise pool at Able Springs indicated by test 3 is to the northwest.

Test 4

Fluorescein dye was injected on December 19, 1991, in a swallet at the bottom of a large cover-collapse sinkhole about 180 ft east of the truck weighing station on Interstate Highway 65 North (fig. 6, dye flowpath T4). The injection site is along a northwest-trending sinkhole alignment that marks the approximate position of the mapped trace of Gaithers Fault (fig. 5). The injected dye was detected on a charcoal detector collected from Elizabethtown Spring on December 23, 1991. The general direction of ground-water flow between the injection site and Elizabethtown Spring indicated by test 4 is to the northwest.

Test 5

Direct Yellow DY-96 dye was injected on December 19, 1991, at a swallet in a subsidence sinkhole adjacent to roadside culverts that drain part of State Highway 31E (fig. 6, dye flowpath T5). The dye was detected on a cotton detector collected on December 23, 1991, at Tharpe Spring. This spring is the perennial headwater for a branch of East Rhudes Creek. The general direction of ground-water flow between the injection site and Tharpe Spring indicated by test 5 is to the southeast, toward East Rhudes Creek.

Test 6

A fluorescein dye was injected on January 6, 1992, from a swallet in the channel of a losing, intermittent stream about 1 mi southeast of Dyers Spring (fig. 6, dye flowpath T6). The swallet is at the southernmost end of the northwest-southeast trending sinkhole alignment crossing the Western Kentucky Parkway. Dye was recovered on a charcoal detector collected at Dyers Spring on January 13, 1992, 9 days after the injection. The results of this dye-tracing test indicate a northwest direction of ground-water flow toward Valley Creek. The dye injected was not detected at the Gaithers karst window, indicating that ground-water flow from the injection site is not routed through the major ground-water conduit exposed there. Instead, the general direction of ground-water flow between the injection site and Dyers Spring indicated by test 6 is to the northwest.

Test 7

Tinopal 5BMX Optical Brightener was injected on January 6, 1992, into a swallet in a sinkhole downhill from the Western Kentucky Parkway at Mile Marker 133 (fig. 6, dye flowpath T7). The dye-injection site is the uppermost of several aligned open and partially alluviated swallets and cover-collapse sinkholes in a northwest-trending karst valley. The dye-injection site and the other sinkholes and swallets in the karst valley receive stormwater runoff from a culvert draining the highway roadbed. The karst valley and its attendant sinkholes are part of a larger sinkhole alignment that extends from Dyers Spring to the southeast for 1.0 mi. The injected dye was recovered on a cotton dye detector collected at Dyers Spring on January 10, 1992. The general direction of ground-water flow between the injection site and Dyers Spring indicated by test 7 is to the northwest, to Valley Creek. As in dye-tracing test 6, the dye injected during this test was not detected at the Gaithers karst window.

Ground-Water Flow Directions and Divides

The overall trend of development of solutional conduits and ground-water flow in many well-bedded and relatively flat-lying limestones is controlled by topographic relief and is usually perpendicular to the trend of a major entrenched surface stream (Palmer, 1991). This characterization can be applied to the karst aquifer system in the Elizabethtown area. As indicated by both dye flowpaths and the potentiometric surface, ground-water flow in the karst aquifer system is from upland recharge areas in the central and southern parts of the study area to the nearest entrenched stream—Valley Creek, Cole Creek, or East Rhudes Creek (fig. 6).

In the study area south of Valley Creek, the potentiometric surface slopes broadly from east to west. A large irregularly shaped potentiometric ridge is present to the east-southeast, defined by potentiometric contours at and above 710 ft above sea level (fig. 6). The apex of the potentiometric ridge is greater than 780 ft above sea level in the southeast corner of the study area. The potentiometric ridge is part of a larger regional ground-water divide mapped at 1:50,000-scale by Lambert (1979), and its overall trend is northeast-southwest. A series of smaller ground-water divides can be traced along the crest and down the western flank of the potentiometric ridge in the study area (fig. 6). These smaller divides seem to partition the aquifer system into areas where ground-water flow is to localized discharge zones along Valley Creek (to the west), Coles Creek (to the east), and East Rhudes Creek (to the south), and to an unnamed sinking stream near the center of the study area. One of the ground-water divides delineates the crest of a distinctive potentiometric mound that is approximately coincident with the mapped trace of the Elizabethtown Fault. The correlation of this potentiometric feature with the fault zone indicates that ground-water flow along or across the fault zone may be inhibited by low permeability conditions. Although permeability and infiltration commonly is great near the surface along most fault zones, permeability at depth commonly is reduced by the presence of clayey fault gouge, emplacement of hydrothermal vein minerals, or the effects of lithostatic pressures on fractured rock masses.

Negative-relief potentiometric features—troughs—indicate the presence of convergent ground-water flow, and in the absence of a gaining surface stream can indicate the approximate locations of major ground-water conduits (Quinlan and Ewers, 1989). Ground-water discharge zones are indicated by the trough-like potentiometric contours that encircle Valley Creek and Coles Creek (fig. 6). A trough-like series of potentiometric contours also encircles the unnamed sinking stream near the center of the study area that is drained by the swallet at dye-injection site M2. These trough-like contours may reflect gaining flow to the lower reach of this stream, but may possibly reflect the presence of the subsurface conduit drained by the swallet. The shape of potentiometric contour lines near Valley Creek does not indicate potentiometric troughs that would reflect the presence of a major trunk conduit to either Elizabethtown or Dyers Spring. Well spacing may not be sufficiently close enough there to provide for detailed delineation of potentiometric features. However, the mapped potentiometric surface is relatively flat near Valley Creek, having altitudes of less than 710 ft above sea level. This indicates extensive, enhanced dissolution porosity and permeability in the karst aquifer system in this part of the area. This hydrogeologic characteristic is physically manifested by the presence of the conduits drained by Elizabethtown, Unused, and Dyers Springs, and by five other deeper hydrostratigraphic levels of large solutional conduits penetrated by municipal water wells drilled along Valley Creek (George, 1982).

Ground-water-flow directions indicated by plotted dye flowpaths are in good agreement with the configuration of the contoured potentiometric surface and the inferred positions of ground-water divides throughout the study area (fig. 6). The dye flowpaths illustrate convergent ground-water flow to Elizabethtown, Dyers, Unused, and Able Springs from recharge sources such as sinkholes, swallets, and sinking streams. Dye flowpaths plotted for tracing tests done from swallets M1 and M2 (fig. 6) indicate the presence of divergent flow between Elizabethtown and Unused Springs. Divergent flow commonly occurs where dissolution porosity is highly developed, such as near a ground-water discharge boundary, and represents piracy of subsurface flow between solution conduits. A predominant northwestern trend to the dye flowpaths is evident, inferring a similar overall trend to the major ground-water conduits. Fracture orientation may have played an important role in this apparent trend. Given the slope of the potentiometric surface, northwest-striking fractures would be oriented in the direction of the maximum hydraulic gradient, and could serve as favored routes for ground-water flow. The overall direction of flow through the aquifer system is approximately parallel with the geologic strike and with the axis of the regional syncline mapped by Kepferle (1963, 1966). However, geological controls such as bedrock structural dip and fracture orientation may not be as important to the development of ground-water-flow routes as the slope of the potentiometric surface. Dye flowpaths plotted for dye-tracing tests from swallet injection site T2 to Able Springs and from swallet injection site T5 to Tharpe Spring (fig. 6) indicate subsurface flow being contrary to the direction of geologic dip and toward the nearest entrenched surface stream.

Ground-Water Basin Boundaries

Ground-water divides inferred by the presence of positive-relief features on the mapped potentiometric surface indicate areas of relatively low dissolution porosity and permeability and sparse or poorly integrated solutional conduit development. Such hydrogeologic properties commonly exist at the margins or boundaries of karst ground-water basins (Thrailkill, 1985, Quinlan and Ewers, 1989). Ground-water basin boundaries can be inferred by the trends of ground-water divides. However, the presence and trends (positions) of the boundaries cannot be confirmed unless dye-tracing tests are available to provide direct evidence of subsurface flow connections and the diversion of ground-water flow directions across an inferred divide. Figure 7 illustrates the inferred ground-water basin boundaries for the two municipal water-supply springs in the Elizabethtown area. The boundaries are approximate and represent the total area of subsurface flow likely contributing recharge to Elizabethtown and Dyers Springs.

The Elizabethtown Spring Basin is bounded to the north and south by the two fault zones. As previously stated, the position of the Elizabethtown Fault trace is coincident with the large potentiometric mound that is delineated here as part of the inferred boundary of the spring basin. The effectiveness of the fault zone as a basin boundary seems to be confirmed not only by the potentiometric mound, but by the dye flowpath from swallet site T2 to Able Springs. In addition (though not illustrated in figures 6 or 7), a dye-tracing test was recently completed from a sinkhole site north of the Elizabethtown Fault that demonstrated a hydraulic connection to the Ennis Farm Springs, but not to Elizabethtown Spring (Dr. Nicholas Crawford, Western Kentucky University, oral commun., 1996). This dye-tracing test result also confirms a similar conclusion reached by Bentkowski (1991) on the basis of a water-quality study (the sinkhole injection site is the location of a former unpermitted hazardous waste deposal site). The boundary of the Elizabethtown Spring is well defined in the southeast by the large, northeast-trending subregional potentiometric ridge. Much of this part of the basin is in the area covered by thick deposits of the sand and shale residuum. Solutional karst features (sinkholes) are sparse in this area, swallets are absent, and surface stream drainage is more prominent. The Gaithers Fault delineates most of the southern basin boundary. Although potentiometric mounding is not significant there, dye-tracing tests done from swallets less than 0.5 mi apart on the north and south side of the mapped fault trace demonstrated that flow on the north side is to the Elizabethtown Spring Basin, and flow on the south side is to Tharpe Spring.

A significant internal complexity to the Elizabethtown Spring Basin is evident in the apparent splitting of dye-traced flow between Elizabethtown and Unused Springs from swallet injection sites M1 and M2 (figs. 6 and 7). As previously stated, this divergence of flow to the two separate spring outlets is a result of subsurface stream piracy following a linkage between conduits formerly draining to each individual spring. As a consequence, the two springs presently share recharge from an area that is delineated here as being in the northern part of the Elizabethtown Spring Basin. The exact geographic extent of the area of shared recharge has not been determined; however, the approximate boundaries of the area are constrained to the north between the dye flowpaths plotted from swallet injection sites T1 (which indicates flow only to Unused Spring) and M1, and to the south between the dye flowpaths plotted from swallet injection sites M3 (which indicates flow only to Elizabethtown Spring) and M2.

The boundaries of the Dyers Spring Basin are somewhat less well defined than that of the Elizabethtown Spring Basin (fig. 7). The Gaithers Fault zone is assumed to delineate the northern boundary. Surficial evidence of karstification becomes more sparse toward the northern half of the Dyers Spring Basin (refer to the sinkhole distribution pattern in figure 3). Much of the surface drainage there is conducted to an intermittent stream channel. Fingerlike deposits of the sand and shale residuum extend along and trend parallel to the Gaithers Station Fault zone (fig. 7). There is some evidence of potentiometric mounding along the fault zone on the north side of Valley Creek and in the far southeast corner of the study area. Much of the upgradient part of the Dyers Spring Basin is covered with residuum. The

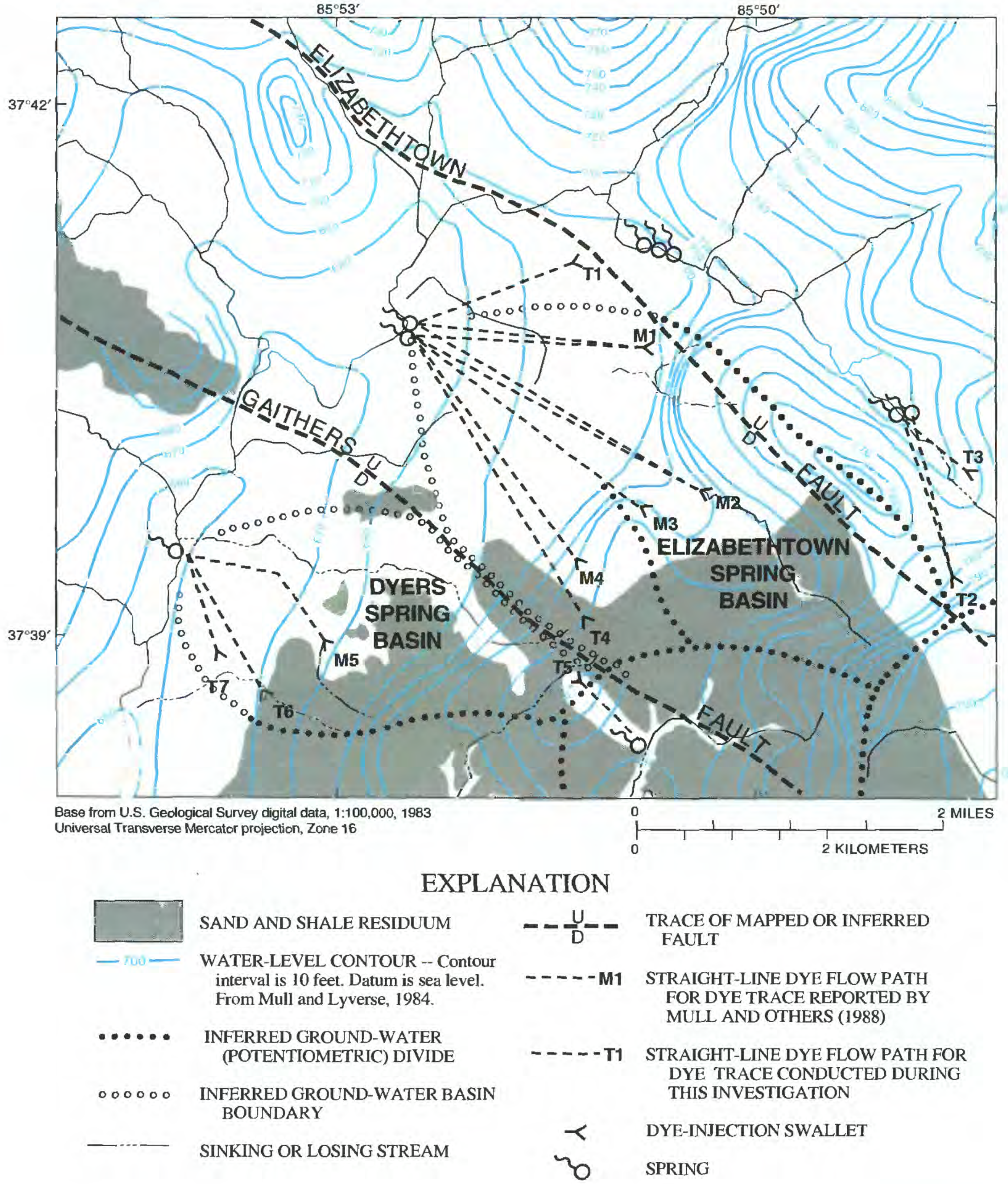


Figure 7. Ground-water basin boundaries and hydrogeologic controls in the karst aquifer system, Elizabethtown area, northern Kentucky.

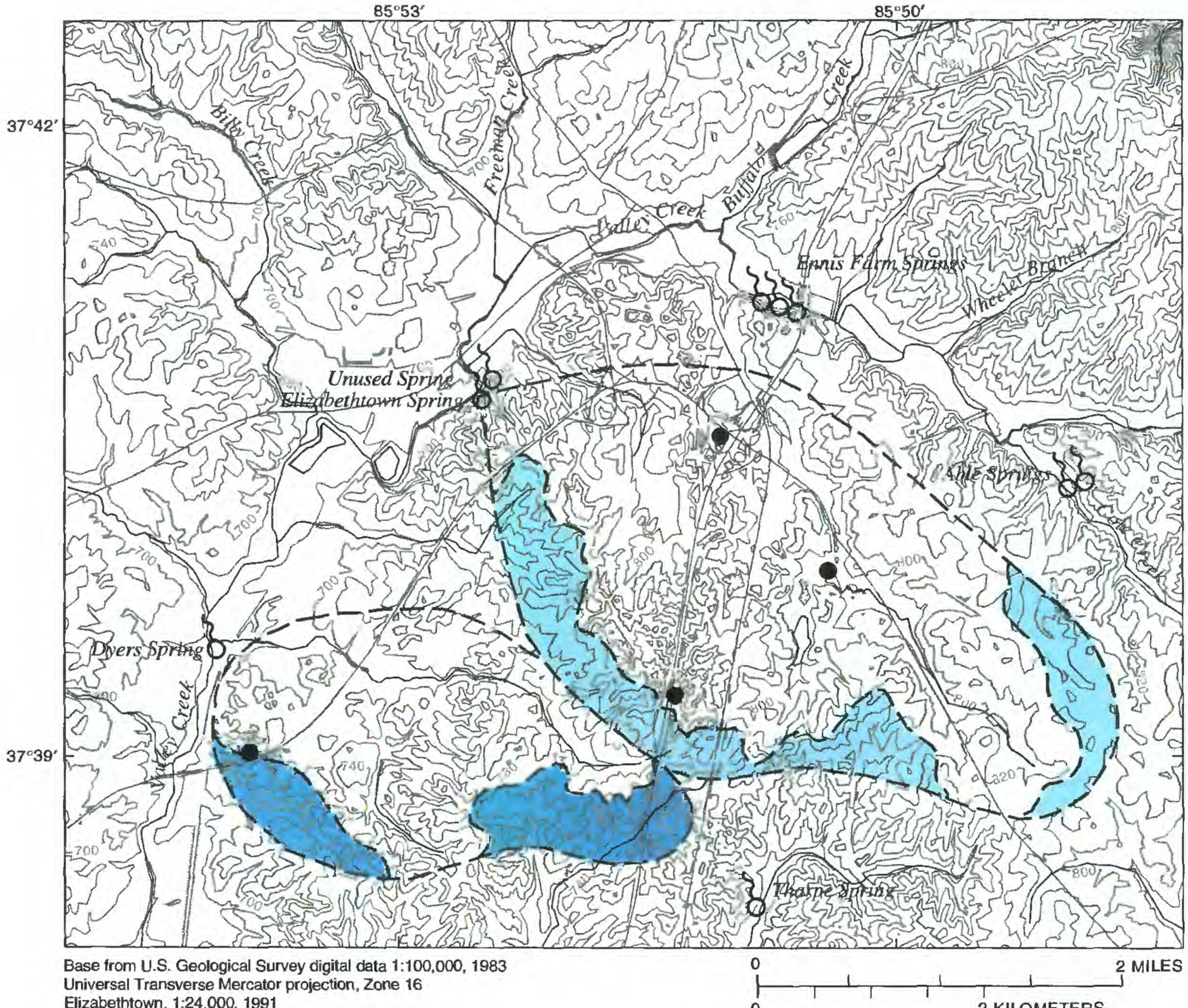
easternmost boundary of the spring basin is marked by a small localized potentiometric mound depicted by potentiometric contours greater than 740 ft above sea level (fig. 7). A dye-tracing test from swallet site T5 demonstrated that ground-water flow near the apex of the potentiometric mound is directed to Tharpe Spring to the southeast. The basin boundary of Dyers Spring to the south is rather poorly defined, but is interpreted to follow the curvature of the potentiometric surface. In much of this part of the study area, the limestone bedrock is overlain by thick deposits of residuum. Sinkhole alignments extend along gullies and former stream segments that have eroded through the residuum. Dye-injection swallets T6 and T7 (fig. 7) and M5, which drains a short sinking stream segment used during a dye tracing test by Mull and others (1988b) are present there along the margins of the residuum-mantled upland (fig. 7). The dyes injected at all three sites were recovered at Dyers Spring.

The sand and shale residuum is apparently effective in limiting karstification. Well-defined sinkholes are sparse in the areas covered by the residuum and swallets are absent, except near the margins of the deposits where the residuum is less than 15 ft thick. The sinking streams that contribute flow to Elizabethtown and Dyers Springs head in the areas covered by the residuum and are diverted into swallets that drain to subsurface conduits a short distance after flowing onto the limestone bedrock. Tharpe Spring and the cluster of sinkholes that provide recharge to it are developed along a former tributary valley of East Rhudes Creek where the thick residuum has been stripped by erosion. Lambert (1979) reports that wells dug or drilled in the residuum do not supply adequate yields for domestic water supplies; however, wells that penetrate into limestones underlying residuum-mantled areas do provide significant yields. Therefore, although the residuum is not a productive aquifer, it is an important leaky confining unit that stores and distributes recharge to the underlying karst aquifer system. The presence of the residuum in the upgradient parts of the Elizabethtown Spring and Dyers Spring Basins may account for the relatively consistent and high discharges from the springs (relative to other nearby springs) despite the rather small overall size of the basins.

DELINEATION OF RECHARGE AREAS FOR WATER-SUPPLY SPRINGS

The approximate boundaries of the recharge areas of Elizabethtown and Dyers Springs are shown in figure 8. The recharge area boundaries are delineated by the ground-water divides that enclose the karst ground-water basins previously shown in figure 7. However, each recharge area also encloses topographic divides where surface drainage is conducted to a sinkhole or sinking stream demonstrated by dye-tracing tests to be a discrete source of recharge for one of the two water-supply springs. Subareas delineated by stippled patterns in figure 8 indicate parts of each springs' recharge area where surface drainage (and possibly ground-water drainage) is discharged outside of the boundaries of the recharge area.

The total surface area of the Elizabethtown Spring Basin is estimated here at 4.8 mi^2, and the total surface area of the Dyers Spring Basin is estimated at 2.7 mi^2. Approximately two-thirds of the area in the Elizabethtown Spring Basin is developed for residential, commercial, and industrial land uses. This area includes almost all of the sinkholes drainage areas west of Interstate Highway 65 and much of the catchment of the unnamed sinking stream to the east. The remaining one-third of the area in the Elizabethtown Spring Basin, largely to the south and east, is relatively undeveloped forest or pasture land. The area in the Dyers Spring Basin is more rural and contains mostly sparsely developed residential and agricultural lands. Significantly, swallets that drain concentrated stormwater runoff from major highways are present in the basins of both water-supply springs. Each spring is therefore potentially vulnerable to stormwater contaminants or accidental spills and releases into certain highway drainage culverts.



Base from U.S. Geological Survey digital data 1:100,000, 1983
Universal Transverse Mercator projection, Zone 16
Elizabethtown, 1:24,000, 1991
Cecilia, 1:24,000, 1992

CONTOUR INTERVAL 20 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

EXPLANATION

AREAS WHERE TOPOGRAPHIC DIVIDES INDICATE SURFACE (AND POSSIBLY GROUND WATER) DRAINAGE IS DISCHARGED OUTSIDE OF INDICATED SPRING RECHARGE AREA

Dyers Spring

Elizabethtown Spring

INFERRED BOUNDARY OF RECHARGE AREA

SWALLET RECEIVING DIRECT RUNOFF FROM HIGHWAY DRAINAGE CULVERT

SPRING

Figure 8. Geographic boundaries of the recharge areas for Elizabethtown and Dyers Springs, Elizabethtown area, northern Kentucky.

CONCLUSIONS

The results of this hydrogeologic mapping investigation indicate that the recharge areas of Elizabethtown Spring and Dyers Spring are 4.8 and 2.7 mi^2, respectively. The approximate boundaries of the recharge areas are defined by a ground-water basin delineated for each spring on the basis of potentiometric map interpretation and dye-tracing tests. Important geologic controls that appear to have influenced the development of the karst aquifer system in the Elizabethtown area and the basin boundaries of the two municipal-supply springs include two fault zones, and extensive deposits of sand and shale residuum having relatively low permeability. Clusters of sinkholes and swallets in each spring's basin provide direct concentrated recharge to the solution conduits draining the basins. In both spring basins, sinking streams drain relatively unkarstified uplands and are diverted underground by swallets near the contact between the residuum deposits and the underlying limestones. Land use and development is more extensive in the Elizabethtown Spring Basin. However, both of the municipal-supply springs are potentially vulnerable to contaminants in concentrated stormwater runoff from major highways or accidental spills and releases into certain highway drainage culverts.

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