DIRECTIONS OF GROUND-WATER FLOW AND LOCATIONS OF GROUND-WATER DIVIDES IN THE LOST RIVER WATERSHED NEAR ORLEANS, INDIANA

By E. Randall Bayless, Charles J. Taylor, and Mark S. Hopkins

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[Plates are in pocket]

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CONVERSION FACTORS, VERTICAL DATUM, AND WATER-QUALITY UNITS

Multiply	By	To obtain
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
mile (mi)	1.609	kilometer
mile per day (mi/d)	1.609	kilometer per day
foot per mile (ft/mi)	0.1894	meter per kilometer
square mile (mi^2)	2.59	square kilometer
pound (lb)	0.4536	kilogram
gallon (gal)	3.787	liter
cubic feet per second (ft^3/s)	28.32	liter per second

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929—a 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.

Abbreviated metric units used in this report: Chemical concentrations and some masses and volumes are given in metric units. Chemical concentration is given in milligrams per liter (mg/L), a unit expressing a unit of concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water. In places, mass is given as kilograms (kg), and volume is given in liters (L).

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ABSTRACT

The Mitchell Plain, a physiographic unit in south central Indiana, is a classic example of karst topography. The town of Orleans, Ind., which is in the Mitchell Plain, is a site of frequent flooding. Factors that enhance the potential for flooding in Orleans may include (1) location of the town in a karst valley, (2) a high runoff-rainfall relation for a loess- and residuum-covered area that drains into an occluded sinkhole near the center of Orleans, and (3) an overtaxed subsurface-drainage system during periods of intense rainfall. The U.S. Geological Survey, in cooperation with the U.S. Army Corps of Engineers, conducted a study during October 1993–April 1994 to improve an understanding of the hydrology of the Lost River Watershed near Orleans.

A composite ground-water potentiometric-surface map was constructed by use of static water levels from about 175 well-driller's records on file with the Indiana Department of Natural Resources. Synoptic water-level measurements were made at 11 of the 175 wells to evaluate the assumption that these water levels provided an accurate representation of the ground-water-level surface. The mean difference at the 11 synoptic sites was 8.3 ft; the total drop in water-table altitude across the study area is about 180 ft. The composite ground-water level-surface map was used as a basis for identifying subsurface-drainage divides and directions of ground-water flow.

Eight dye-tracing tests were done from November 15, 1993, through March 3, 1994, to examine the accuracy of ground-water divides delineated on the composite ground-water level-surface map. Dye was injected at seven swallow holes and one storm-infiltration well. Most of the tests were done during high-flow conditions–periods following substantial rainfall when the dry bed of Lost River was inundated. Five dye clouds emerged at Orangeville Rise, approximately 4.5 mi southwest of Orleans, and two dye clouds emerged at Hamer Cave Spring at Spring Mill State Park, 4.5 mi northeast of

Orleans. In the eighth test, dye injected into a shallow storm-infiltration well apparently did not enter the conduit-flow-dominated part of the karst aquifer; instead, it moved through a shallow, perched ground-water-flow system to resurge in seeps and springs discharging to an intermittent tributary in the upstream area of the Lost River Watershed.

Dye-trace observations made during this study were coevaluated with similar information from previous studies and indicate that (1) ground-water divides inferred from the composite ground-water level-surface map are accurate, (2) topographic divides south of Orleans coincide with ground-water drainage divides, and (3) subsurface piracy has created noncoincident surface- and ground-water divides in the area northeast of Orleans.

Three drainage areas, each having distinctive karst-drainage characteristics and affecting the drainage to and from Orleans, were identified. For purposes of this report, the three drainage areas are referred to as the sinkhole-drainage belt, the Flood Creek Watershed, and the Orleans karst valley. The sinkhole-drainage belt is an internally drained basin. Some ground water from the sinkhole-drainage belt may be channeled through the conduits that drain Orleans. The Flood Creek Watershed is a residuum- and loess-covered area that has few non-occluded sinkholes, has limited subsurface storage capacity, and can produce large amounts of storm runoff. The Orleans karst valley is a well-developed karst system that represents a former trunk to Lost River. Orleans is located near the axis of the karst valley.

INTRODUCTION

The Mitchell Plain, a physiographic unit in south-central Indiana, is a classic example of karst topography (Schneider, 1966). Karst topography forms in humid subtropical and tropical climates where carbonate bedrock is near land surface. The interaction between infiltrating precipitation that contains weak, natural acids and the near-surface carbonate bedrock creates features that typify karst topography and drainage systems—disappearing streams, sinkholes, caves, and springs. The hydrologic system in areas of karst topography can be difficult to understand because surface- and subsurface-drainage systems are nearly inseparable.

Orleans, Ind., which is in the Mitchell Plain (fig. 1), is a site of frequent flooding (Malott, 1952). Several hydrologic and anthropogenic factors may contribute to the flooding. These factors include (1) location of the town in a karst valley, (2) a high runoff-rainfall relation for a loess- and residuum-covered area that drains into an occluded sink near the center of Orleans, and (4) an overtaxed subsurface-drainage system during periods of intense rainfall.

The U.S. Geological Survey (USGS) and the U.S. Army Corps of Engineers (USACE) cooperatively accomplished a series of separate but related tasks to improve the understanding of the subsurface drainage characteristics of the Lost River Watershed near Orleans. These tasks included (1) constructing a map of the composite ground-water-level surface of the study area, (2) injecting and recovering fluorescent dyes at karst features in the study area to delineate ground-water flow paths and drainage divides, (3) compiling a bibliography of references describing the study area, and (4) constructing a map of karst features. The composite ground-water-level surface and dye-trace information were the focus of this study. The karst-feature and bibliographic information were compiled to assist interpretation of the composite ground-water level-surface map and dye-trace results.

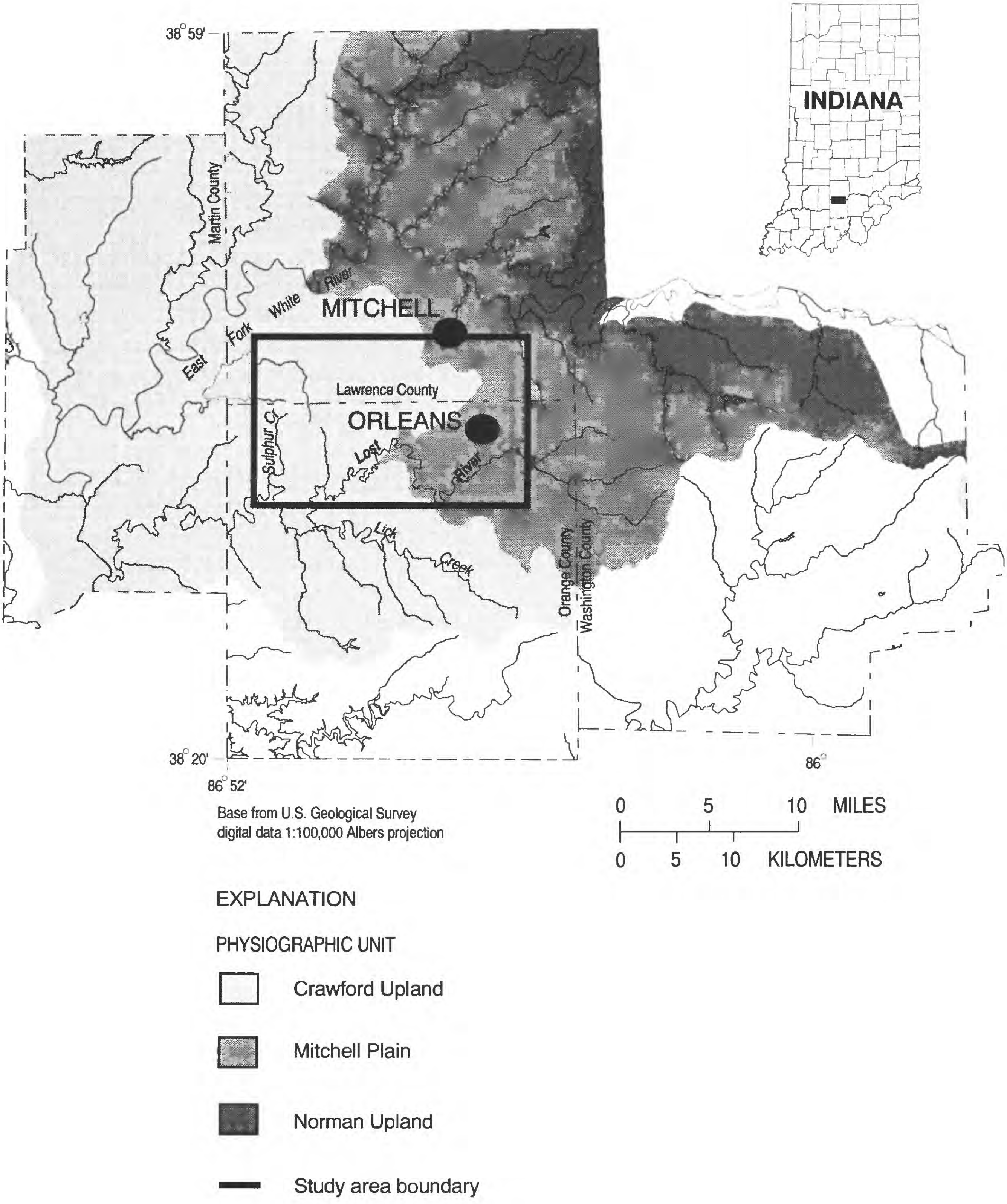

Figure 1. Regional hydrogeologic features, physiographic units, and location of the study area.

Purpose and Scope

The purpose of this report is to describe general directions of ground-water flow and the approximate locations of ground-water divides near Orleans, Ind. In addition, this report includes information that may be helpful in interpreting the results of this study, including map locations of important karst features and an annotated compilation of pertinent bibliographic references.

Previous Investigations

Previous studies of importance to this study include those of Malott (1952), Murdock and Powell (1968), Bassett (1974), Bassett and Ruhe (1974), and Ruhe (1975). An extensive compilation of bibliographic references to previous investigations in the Lost River Watershed near Orleans is included at the back of this report ("Selected References" and "Appendix").

Malott (1952) summarized his observations of the Lost River drainage system and focused on the features of the Lost River and its intermittently dry bed (pl. 1). Malott described the role and relative importance of each of the swallow holes and ground-water discharge points along the river's course, including Flood Creek, the intermittent tributary that frequently floods Orleans. Malott surmised that Flood Creek, whose headwaters are about 3 mi east of Orleans, once flowed within the present-day city limits on its way southwest to its confluence with the dry bed. Malott documented flooding problems that dated to at least 1933 and attributed them to the inability of the terminal swallow hole to convey adequate amounts of storm drainage from the site. Storm drainage from Orleans likely combines with subsurface flow from the Pearson Creek drainage (Mt. Horeb Drain) and resurges at the Mathers stormwater rise.

Murdock and Powell (1968) delineated surface-water and ground-water divides in the Lost River system by means of topographic information and fluorescent dye-trace studies. Fluorescein dye was injected at low- to normal-flows. The 10 dye traces were used to define tentative ground-water divides between ground-water flow systems draining to the Orangeville Rise, the Rise of Lost River, Sulfur Creek, and Lick Creek (fig. 1; pl. 1); the Sulfur Creek and Lick Creek ground-water discharge points are outside the Lost River surface-drainage system. The Orangeville Rise ground-water basin was further divided into two subbasins (both described more fully in the section, "General Hydrology").

Bassett (1974) did four dye-tracing tests in the Lost River Watershed using rhodamine WT during relatively high flows. In three of the tests, dye was injected in the northwestern part of the drainage basin and emerged at the Orangeville Rise. In the fourth test, dye was injected at the sink of Mosquito Creek, approximately 3.7 mi northeast of Orleans, and emerged at Twin Caves. Bassett and Ruhe (1974) did quantitative dye-tracing tests from the Orleans Sewage Plant to the Orangeville Rise, measuring travel times of 46 and 26 hours for moderately low and moderately high flows, respectively.

Ruhe (1975) used a hydrologic balance to estimate storage ability of the Lost River Watershed. His study showed that storage was seasonally related to rates of evapotranspiration and that most of the storage capacity was in the karstic part of the watershed. Ruhe (1975) estimated that 10 to 17 percent of rainfall was discharged during summer, 79 to 86 percent was discharged during winter, and 21 to 46 percent was discharged during spring and fall. In addition, rainfall-runoff measurements by Ruhe (1975) indicated that Murdock and Powell's (1968) estimate of the area drained to the Orangeville Rise, 40.7 mi^2, probably is accurate.

Acknowledgments

The authors express their gratitude to members of the Orleans Rural Volunteer Fire Department for their assistance with the dye injections and to the people of Orleans for providing historical information and access to their property.

DESCRIPTION OF STUDY AREA

The study area includes surface-water and ground-water basins above the Orangeville Rise, as well as the fringes of adjacent ground-water basins where ground-water divides were not previously well defined (pl. 1). Ground-water basins include drainage to Sulphur Creek, Rise of Lost River, Hamer Cave, Twin Caves, and undetermined ground-water discharge points northwest of the study area.

Physiography and Geology

The study area is within the Mitchell Plain physiographic unit (Schneider, 1966; fig. 1). The Mitchell Plain is characterized by karst topography. Land surface in the Mitchell Plain slopes to the southwest at 20 to 30 ft/mi (Ruhe, 1975). Bedrock dips to the southwest at 40 ft/mi. The headwaters of the Lost River are in Washington County at an altitude of about 900 ft above sea level (ASL) (Malott, 1952). Surface altitudes in the drainage basin to Orangeville Rise range from 490 to 750 ft ASL. Surface altitudes are about 620 ft at Orleans and about 490 ft at the Orangeville Rise.

The Crawford Upland physiographic unit bounds the Lost River drainage basin on the south and west (Schnieder, 1966). The Crawford Upland is typified by high relief and well-integrated surface drainage. The surficial geology of the Crawford Upland is composed of siliciclastic rocks of Mississippian-age; these siliciclastic rocks overlie carbonate bedrock of Mississippian-age that forms the Mitchell Plain to the east. The Chester Escarpment is an abrupt topographic change of 100 to 200 ft and marks the boundary between the Mitchell Plain and the Crawford Upland. Some erosional remnants of the siliciclastic deposits are present in the study area; an example is Tom Rice Hill (pl. 1).

The Orleans area is underlain by the St. Louis and Ste. Genevieve limestones which together constitute a limestone sequence that is approximately 300-ft thick (Bassett and Ruhe, 1974). These formations consist of Mississippian deposits of the Blue River Group. Lower strata of the St. Louis limestone consist mainly of pellet-micritic limestone, calcareous shale, and silty dolomite. The upper St. Louis limestone is composed of micritic, pelletal, and skeletal limestone; some thin-bedded shale; and abundant thin beds and nodules of chert (Shaver and others, 1986). The Ste. Genevieve limestone is composed primarily of oolitic, skeletal, micritic, and detrital limestone. The area between the headwaters of the drainage basin and the Orangeville Rise is developed on the St. Louis limestone, but most of the sinkhole plain is developed on the Ste. Genevieve limestone.

The rugged sandstone ridges that form the Crawford Upland physiographic unit are developed on the Chester sandstone and the Mansfield sandstone; these deposits are of Late Mississippian and Early Pennsylvanian age, respectively (Malott, 1952).

Description of Aquifers

Virtually all ground-water withdrawals in the study area are from bedrock aquifers. The hydraulic characteristics of limestones in the study area have been altered greatly by dissolution of soluble beds of gypsum and widening of fractures and joints. The horizontal hydraulic conductivity of nonkarstic limestone generally ranges from 10^{-4} to 10^{-1} ft/d; but in a karst area, horizontal hydraulic conductivity can range from 10^{-1} to 10^{3} ft/d

(Freeze and Cherry, 1979). Wells completed in the St. Louis and Ste. Genevieve limestones generally yield sufficient water to supply domestic needs but cannot sustain large, continuous withdrawals.

The St. Louis and Ste. Genevieve limestones are mantled with 0 to 40 ft of silt-loam soils formed in loess or bedrock residuum. These soils are silt- and clay-rich deposits that do not contain enough coarse-grained material to constitute viable aquifers.

General Hydrology

When a karst system becomes well developed, the surface- and subsurface-drainage systems are well connected. In a well-developed karst system, streams are commonly unable to flow from headwaters to mouth without periodically disappearing into sinkhole or streambed swallow holes and reemerging at other karst features farther downgradient. In such a system, water moves through the subsurface as "conduit flow"—much like water flowing through a pipe—and its rate and volume relate to the hydraulic gradient and the size and interconnection of the solution cavities.

The position of subsurface-drainage divides also may depend on the hydraulic gradient and the orientation of widened joints, fractures, and bedding planes in the bedrock. As a result, subsurface-drainage divides may not correspond to topographic highs or surface-drainage boundaries. Furthermore, karst characteristics can develop differently at various depths; as a result, subsurface-drainage divides during high flows may not coincide with divides during low flows.

The Lost River surface-water-drainage basin has an area of about 163 mi^2 above its confluence with Lick Creek (Murdock and Powell, 1968). Most streams whose headwaters are in the eastern part of the watershed are diverted to subterranean routes when they reach the central part of the watershed because of its well-developed karst (pl. 1).

Murdock and Powell (1968) divided the Lost River Watershed into six ground-water subbasins on the basis of hydrologic and geomorphic characteristics. Most of the study area described in this report is contained in two subbasins that drain to Indiana's second largest spring, the Orangeville Rise, at Orangeville, Ind. The western subbasin drains 9.4 mi^2 of the Crawford Upland, and the eastern subbasin drains 31.3 mi^2 of sinkhole plain. Orleans overlies the eastern subsurface subbasin.

METHODS

This section describes the methods used to (1) construct a map of the composite ground-water-level surface and to quantify the accuracy of that map, (2) inject and detect fluorescent dyes, (3) analyze for the presence or absence of dyes in recovered detectors, and (4) provide quality assurance for the injection, recovery, and analysis of samples.

Water-Level Measurement and Construction of a Composite Ground-Water Level-Surface Map

A composite ground-water level-surface map for bedrock wells was constructed from static water levels reported on 175 well-driller's records. Well-driller's records were obtained from the Indiana Department of Natural Resources and from private companies operating in the study area. Wells in the study area usually are completed in dissolution-modified voids or in well-fractured sections of the limestone. Water-surface altitudes shown on 1:24,000 topographic maps for sinkholes, intermittent streams, and rivers were not used for constructing the composite ground-water level-surface map because the low permeability of soils that line many of these features may cause perched conditions that do not accurately reflect the hydraulic head at these locations. Because jointing and dissolution modification of the limestone aquifers is pervasive in the study area and karst characteristics are generally well developed, the wells were considered to be hydraulically connected to the aquifer system. Water-level altitudes indicated on the composite ground-water-level surface probably do not represent levels that would be measured in nonjointed zones of the bedrock. Water-level altitudes reported on the well-driller's records that spanned at least a 20-year period were not limited to any particular season.

Dye Injection and Collection, Analysis for Presence of Dye, and Quality Assurance

Standard techniques for the use of fluorescent dyes as ground-water tracers were used during this investigation (Jones, 1984a, b; Quinlan, 1986; Mull and others, 1988). The nontoxic fluorescent dyes used for the dye-tracing tests were sodium fluorescein (Color Index [C.I.] Acid Yellow 96), diphenyl brilliant flavine 7FGG (C.I. Direct Yellow 96), rhodamine WT (C.I. Acid Red 388), Tinopal[1] 5BMX optical brightener (C.I. Fluorescent Brightener 28). Fluorescein, direct yellow, and optical brightener are supplied as soluble powders and usually are dissolved in water to prepare a dye solution suitable for injection. Rhodamine WT is supplied as a 20-percent liquid concentrate from the manufacturer and usually is diluted with water to a concentration suitable for injection. The amount of dye injected at a particular site was determined according to guidelines suggested by Quinlan (1986) that consider (1) the straight-line distance to the farthest anticipated discharge point and (2) the flow conditions during the dye-tracing test.

For most dye injections done during this investigation, drainage into a swallow hole was induced with water hauled to the site in a 2,000-gal tanker truck. Approximately 200 to 500 gal of water was introduced into the swallow hole immediately before the planned dye injection to initiate flow and to provide a wetting front that would minimize loss of dye by absorption to dry sediment and aquifer material. In some cases, the preinjection water also improved drainage through partially blocked swallow holes by flushing accumulated sediment and debris. Preinjection water also was used to estimate the swallow hole's drainage capacity and ability to accept dye. If the swallow hole drained freely (no significant back up), then the dye solution was poured directly into the runoff entering the swallow hole opening. If preinjection water backed up substantially, the site was abandoned. After the injection of the dye, an additional 200 to 500 gal of water was used to push the dye farther into the aquifer system.

Point-to-point subsurface flow connections were established by use of passive dye detectors to monitor the discharge point of injected dyes. Passive dye detectors were constructed of either undyed cotton or activated coconut charcoal encased in a fiberglass screen. Fluorescent dyes emerging at ground-water discharge points were absorbed onto either the cotton or charcoal detectors. Fluorescein and rhodamine WT were absorbed and concentrated into charcoal detectors. Direct yellow and optical brightener were absorbed only into cotton detectors. Because the dyes have different absorptive affinities and because analytical techniques permit identification of more than one dye on a single detector, some tests traced two or more dyes—injected at different sites—without interference.

Dye detectors were placed at known or suspected ground-water-discharge points described in the literature and identified during field reconnaissance. Typical ground-water discharge points included ephemeral rises, storm rises, springs, ephemeral reaches of the Lost River, and cave streams. Dye detectors were immersed in the main current to ensure detection of a passing dye pulse.

[1]Any use of trade, product, or firm names is for descriptive purposes only and does not constitute endorsement by the U.S. Government.

Detectors were attached to specially constructed brick or concrete anchors that suspended the detectors above the bottom sediment. After dye injection, detectors were collected and replaced at intervals of 2 to 4 days. The replacement interval depended on the anticipated time of emergence and the hydrologic conditions that existed during the dye-tracing test. Detectors were changed more frequently after periods of heavy rainfall and excess runoff to prevent buildup of suspended sediment on the detectors. Deposition of suspended sediment on the detectors diminishes their ability to absorb dye.

Recovered charcoal and cotton dye detectors were rinsed vigorously under a stream of tap water to remove silt and accumulated debris. Detectors were labeled and placed in a vented, darkened cabinet to dry. The presence of direct yellow and optical brightener on cotton dye detectors was determined by visual examination of the detector under short-wave ultraviolet radiation in a darkened room. Dye-free cotton detectors appeared dark purplish-black under ultraviolet radiation. Presence of direct yellow on the detector was indicated by a canary-yellow fluorescence. Presence of optical brightener was indicated by a characteristic blue-white fluorescence. A distinctive chalk-white fluorescence was observed if both dyes were present.

Analysis of charcoal dye detectors required chemical processing to expel absorbed fluorescein and/or rhodamine WT from the charcoal. Approximately 20 mg of charcoal was removed from each recovered fiberglass packet and placed in an individually labeled 40 mL glass vial. The charcoal in each vial was covered with 20 to 30 mL of elutant and placed in a dark cabinet for 1 to 4 hours. The elutant was composed of ammonium hydroxide (NH_4OH) and isopropyl alcohol (2-propanol). Where fluorescein was used as the tracer, the elutant in each vial was examined in a dark room under a focused beam of white light, as described by Quinlan (1986). Presence of fluorescein was indicated by a characteristic green fluorescence. Visual identification of fluorescein in the elutant indicates dye concentrations of 3.0 mg/L or greater. If fluorescein was not detected visually, then a 10-mL aliquot of elutant was extracted from the vial and was examined by use of a scanning spectrofluorophotometer.

Spectrofluorophotometers identify fluorescent dyes in water or elutant on the basis of a characteristic spectrum that is emitted when a sample containing dye is excited by light of a particular wavelength. Unlike fluorescein, rhodamine WT was not visible at low concentrations by use of the beamed-light technique. As a result, the scanning spectrofluorophotometer was necessary for all identifications of rhodamine WT.

Specific procedures were followed during each stage of the dye-tracing studies to ensure the validity of the tracer results and provide quality-assurance and quality-control checks. Before a dye-tracing test was begun, ambient water conditions (high or low flow, turbidity) were evaluated to determine whether the amount of dye to be injected or the monitoring procedure to be used should be modified. In addition, background dye detectors were installed at dye-monitoring sites for 3 to 7 days before each injection. Background dye detectors were recovered and analyzed before injection to ensure that fluorescent solutes that might interfere with the interpretation of tracer-test results were not present. Background dye detectors were collected and replaced until no two consecutive positive detections of dye were found at any dye-monitoring site; then, the test was considered complete.

Several precautionary steps were taken to eliminate the potential for accidental contamination while preparing supplies, transporting and injecting dyes, and collecting and analyzing detectors. Dye detectors always were constructed in an area separate from that used for dye storage and mixing. Detectors always were handled before dye powders or solutions were handled. Dye detectors were stored in zip-locking plastic bags to prevent contact with fluorescent compounds. As dye detectors were recovered in the field, they were placed in individual zip-locking plastic bags, labeled with the name of the dye-monitoring site, the date the detectors were installed, and the date the detectors were retrieved.

Precautions also were taken to ensure that residual dye from a previous test would not be detected in a subsequent test. This was done by avoiding injection of the same dye during consecutive tests, especially if the same discharge point were anticipated. If a rainfall event of sufficient magnitude to flush residual dye from the aquifer system had occurred in the period between injections and background dye detectors indicated that no fluorescent compounds remained in the system, then repeated use of the same dye was allowed. Extra dye detectors were installed at certain critical dye-monitoring sites to ensure that the discharge point of dye was not missed and that tracer-test results were not misinterpreted.

GENERAL DESCRIPTION OF THE COMPOSITE GROUND–WATER–LEVEL SURFACE

The composite ground-water level-surface map (pl. 2) depicts the water-table surface interpreted from static water levels reported on well driller's records. The water table is highest in recharge areas and lowest at points where ground water discharges. In the area near Orleans, the highest water levels are located near the topographic divides (pl. 1 and 2). The water table slopes from higher water-level altitudes to major discharge points, including the ephemeral springs at Spring Mill State Park and Orangeville, the Rise of Lost River, and the dry bed and sustained-flow reaches of Lost River. Locally, the water table also slopes toward intermittent Mt. Horeb Drain and Dry Branch. Orleans is situated in the middle of a distinct water-level trough that is located approximately along a line connecting Twin Caves and Mathers stormwater rise.

USGS personnel synoptically measured water levels at 11 domestic wells in November 1993 to assess the accuracy of the composite ground-water-level surface as a representation of existing conditions. Financial constraints precluded use of a larger number of wells during the synoptic measurements. Statistical comparisons were made between water levels from the synoptic measurements and those reported on well-driller's logs. The mean difference between water levels measured in November 1993 and static water-levels reported on well-driller's records was 8.3 ft (table 1). The mean difference in eight wells was 8 ft or less, but the difference in the three remaining wells ranged from 24 to 29 ft. The three large differences could be attributed to various factors, such as well installation and driller measurement during a period of high flow or a period of heavy withdrawal at the well-owner's residence immediately before synoptic measurements.

Table 1. Data and summary statistics for reported and measured ground-water levels near Orleans, Indiana

[ASL, feet above sea level]

Measured (ASL)	Reported (ASL)	Difference (reported minus measured, in feet)
646	650	4
631	639	8
647	644	-3
625	620	-5
613	611	-2
612	613	1
621	650	29
594	593	-1
576	600	24
506	514	8
517	545	28

Summary statistics for the set of water levels	
Population:	11
Minimum difference:	1
Maximum difference:	29
Maximum difference:	29
Mean difference:	8.3
Mean absolute difference:	10.4
Standard deviation of difference:	10.6

DYE–TRACING TESTS

Eight dye-tracing tests were successfully completed during the period November 25, 1993, through March 3, 1994. The number of tests attempted was limited by the length of the study (approximately 4 months), the field conditions, the availability of suitable dye-injection sites, and the time required to restore dye concentrations to background levels. The eight dye traces delineated during this study, as well as traces from previous investigations (Bassett and Ruhe, 1973, 1974; Murdock and Powell, 1968) are shown on plate 2. Straight-line flow paths on plate 2 indicate the general direction but are not intended to represent the actual path of ground-water flow.

Field conditions were a limiting factor because southern Indiana experienced several periods of subfreezing daytime temperatures during January and February 1994. Freezing temperatures hampered retrieval of dye detectors, some of which froze in place and caused planned dye injections to be postponed because pumps on the water trucks could not function. On two occasions, flooding along the Lost River resulted in postponed injections and recovery of dye detectors.

Dye injections were made at seven swallow holes and one storm-infiltration well (table 2). Most of the tests were done during high flows (that is, periods following substantial rainfall when the dry bed of Lost River was inundated). Five dye

Table 2. Locations of dye-injection sites, dye-recovery sites, and dates of injection and recovery, Orleans area, Indiana

Dye trace number	Injection site name	Injection site latitude/longitude	Injection date	Principal dye-recovery site name[1]	Principal dye-recovery site latitude/longitude	Recovery date
1	Salkeld swallow hole	38°40′17″/86°26′14″	11-24-93	Orangeville Rise and Lost River	38°37′50″/86°33′27″	11-26-93
2	Soldier Moss swallow hole	38°42′41″/86°26′19″	11-24-93	Hamer Cave outlet	38°44′02″/86°25′30″	11-30-93
3	Industry Park sinkhole	38°38′56″/86°27′12″	12-23-93	Orangeville Rise	38°37′50″/86°33′27″	11-27-93
4	Ridgetop sinkhole	38°40′42″/86°24′30″	12-23-93	Orangeville Rise	38°37′50″/86°33′27″	12-27-93
5	County Line swallow hole	38°41′17″/86°27′16″	02-17-94	Orangeville Rise	38°37′50″/86°33′27″	02-21-94
6	Trashed sinkhole	38°41′40″/86°26′53″	02-17-94	Hamer Cave outlet	38°44′02″/86°25′30″	02-24-94
7	Rocky Bottom sinkhole	38°39′17″/86°22′14″	02-17-94	Orangeville Rise	38°37′50″/86°33′27″	02-21-94
8	Johnson stormwater well	38°40′17″/86°26′14″	02-17-94	Lost River	38°38′22″/86°24′18″	02-24-94

[1]Monitoring sites located downstream from principal dye-recovery sites and monitoring sites with no dye recovery (latitude/longitude) include: Orangeville Rise outlet channel (38°37′52″/86°33′29″), Lost River Rise (38°37′15″/86°33′43″), Whistling Cave outlet (38°44′10″/86°25′39″), Donaldson Cave outlet (38°43′49″/86°24′56″), Lost River (38°37′18″/86°33′25″), Lost River (38°37′18″/86°33′43″), Lost River (38°37′13″/86°33′47″), and Lost River (38°37′47″/86°25′14″).

clouds emerged at Orangeville Rise, approximately 4.5 mi southwest of Orleans, and two dye clouds emerged at Hamer Cave Spring at Spring Mill State Park, 4.5 mi northeast of Orleans. The eighth dye cloud, injected into a shallow storm-infiltration well, apparently did not enter the conduit-flow-dominated part of the karst aquifer; it moved instead through a shallow, perched ground-water-flow system to resurge in seeps and springs discharging to an intermittent tributary in the upstream part of the Lost River Watershed (pl. 2). The details and results of each of these dye-tracing tests are briefly described below.

Test 1. Test 1 was begun on November 24, 1993, at Salkeld swallow hole (table 2; pl. 2), which is 0.8 mi northeast of Orleans. This site is represented on the USGS Mitchell 7.5-minute topographic map as a small sinkhole depression that receives drainage from an intermittent stream to the east. The intermittent stream channel abruptly terminates at the sinkhole. The swallow hole is a crevice-like opening at the west end of the sinkhole. At the time of the dye injection, the swallow hole was flooded by stormwater runoff. The rate and volume of water entering the swallow hole could not be estimated because the channel is rocky and vegetated. About 300 gal of water was pumped into the pooled runoff over a period of 15 minutes to test the drainage capacity of the swallow hole. The additional surge of runoff did not noticeably increase the depth of pooled water at the swallow hole opening.

A solution of water and 4.0 lb of fluorescein dye were poured into the flooded swallow hole. Fluorescein was recovered November 26 and 30 at two sites, the Orangeville Rise and a downstream monitoring site on the Lost River. Fluorescein also was recovered November 26 on the Lost River approximately 0.5 mi upstream from the Lost River confluence with the channel from Orangeville Rise. No dyes were detected at any of the monitoring sites after November 30. The straight-line distance between the dye-injection site and the Orangeville Rise is approximately 7.5 mi. The general direction of ground-water flow between Salkeld swallow hole and Orangeville Rise is from northeast to southwest.

Test 2. Test 2 was begun on November 2, 1993, at a swallow hole in the bottom of a 6-ft-diameter regolith-collapse sinkhole approximately 1.6 mi northeast of Orleans (table 2; pl. 2). This sinkhole is in the area delineated by the USGS Mitchell 7.5-minute topographic map but, because of its small size, does not show on the map. A solution containing 3.5 lb of direct yellow dye was poured into the swallow hole and flushed with water. The dye was recovered November 30, 1993, from the stream that discharges at Hamer Cave. The straight-line distance between the dye-injection site and the mouth of Hamer Cave is approximately 1.6 mi. The general direction of ground-water flow between injection and detection sites for test 2 is from south to north.

Test 3. Test 3 was begun December 23, 1993, at a collapse sinkhole south of Orleans (table 2; pl. 2). Dimensions of the sinkhole are 20 ft by 30 ft. A solution containing 3.0 lb of direct yellow dye was poured into a soil-choked swallow hole near the edge of the sinkhole as flow was simultaneously induced with water from the tanker truck. During the dye injection, the sound of cascading water could be heard entering the main cavity beneath land surface. Dye was recovered on December 27, 1993, on cotton detectors collected at the Orangeville Rise. No dye was recovered on dye detectors placed in the Rise of Lost River. The straight-line distance between the dye-injection site and Orangeville Rise is approximately 6 mi. The general direction of ground-water flow between injection and detection sites for test 3 is from northeast to southwest.

Test 4. Test 4 was begun on December 23, 1993, at a regolith-collapse sinkhole about 2.5 mi east of Orleans (table 2; pl. 2). The sinkhole is 4 to 5 ft deep and filled with broken rock. A solution containing 4.0 lb of fluorescein was poured into a swallow hole on the north side of the sinkhole.

Dye was recovered December 27, 1993, on charcoal detectors at the Orangeville Rise and at two monitoring sites on the Lost River (downstream from the confluence with the Orangeville Rise discharge channel). Dye was not detected at the Rise of Lost River. Dye continued to resurge at the Orangeville Rise monitoring sites through January 7, 1994 — probably as dye was released from storage in the fractured upper bedrock at the injection site (Gruver and Krothe, 1991). The straight-line distance between the dye-injection site and Orangeville Rise is 8.6 mi. The general direction of ground-water flow between injection and detection sites for test 4 is from northeast to southwest.

Test 5. Test 5 was begun on February 17, 1994, at a swallow hole about 1.4 mi north of Orleans (pl. 2). The swallow hole was 3 ft by 1 ft and choked with soil. A solution containing 1.5 gal of rhodamine WT was injected by means of induced runoff into the swallow hole. The dye was recovered February 21, 1994, on charcoal dye detectors at Orangeville Rise. The straight-line distance between the dye-injection site and Orangeville Rise is about 6.8 mi. The general direction of ground-water flow between injection and detection sites for test 5 is from northeast to southwest.

Test 6. Test 6 was begun on February 17, 1994, at an irregularly shaped regolith-collapse sinkhole approximately 2.8 mi northeast of Orleans (table 2; pl. 2). The sinkhole is approximately 15 ft wide and 7 to 10 ft deep. The floor of the sinkhole is rocky, alluviated, and strewn with garbage. A 3-ft-deep runoff channel enters the sinkhole from the north. A solution containing 1.9 lb of direct yellow dye was poured into a stream of water directed from the tanker truck into the deepest part of the sinkhole. The dye was recovered on cotton detectors placed at the stream discharging from Hamer Cave. The dye was first recovered on February 24, 1994. The straight-line distance from the dye injection site to the Hamer Cave outlet is 3 mi. The general direction of ground-water flow between injection and detection sites for test 6 is from southeast to northwest.

Test 7. Test 7 was begun February 17, 1994, at a round, 15-ft-deep subsidence sinkhole approximately 2.0 mi southeast of Orleans (table 2; pl. 2). The sinkhole is near the crest of a ridge. The floor of the sinkhole is fairly flat and composed of broken slabs of weathered limestone. Several pieces of rock were removed from near the center of the sinkhole, and a 1-ft by 2-ft cavity was discovered. Approximately 200 gal of water from the tanker truck drained freely into the cavity. A solution containing 4.4 lb of fluorescein was poured into the cavity. An additional 700 gal of water was used to move the dye into the aquifer. Fluorescein was recovered on charcoal detectors collected February 21, 1994, at the Orangeville Rise. It was anticipated that dye also would emerge at the Rise of Lost River because the injection site was on a ground-water-drainage divide. No dye was recovered from the Rise of Lost River. The straight-line distance between the dye-injection site and Orangeville Rise is approximately 7.6 mi. The general direction of ground-water flow between injection and detection sites for test 7 is from northeast to southwest.

Test 8. Test 8 was begun on February 21, 1994, at a site 3.1 mi southeast of Orleans (table 2; pl. 2). The injection site was a stormwater-drainage well constructed in a shallow sinkhole depression in the headwaters of an intermittent stream valley. The well casing is constructed from 6-in.-diameter perforated polyvinyl chloride and is about 12 ft deep. When dye was injected, the well was draining runoff from a nearby stormwater culvert at an estimated rate of 0.1 ft^3/s. A slurry of approximately 8.0 lb of optical-brightener dye was mixed with water from the runoff channel and poured into a pool adjacent to the perforated well casing. Several buckets of water were poured around the casing to flush the dye into the well.

For this test, two additional dye monitoring sites were established on the Lost River. One site was just downstream from the tributary confluence, and the other was near the Johnson bridge (pl. 2). Optical brightener was recovered February 24, 1994, on cotton detectors collected from both of these monitoring sites. In addition, cotton detectors collected February 24, 1994, from two monitoring sites at the Rise of Lost River contained trace amounts of dye. These results indicate that dye moved through a shallow aquifer system to emerge from springs and seeps in the tributary valley. The dye then was transported farther downstream in the surface flow of the Lost River. Weak concentrations of dye detected in the Rise of Lost River indicate that the dye was diluted during transport to the Rise of Lost River or was substantially diverted into the shallow aquifer system and discharged to the Lost River. The straight-line distance between the dye-injection site and the tributary emergence is approximately 0.5 mi. The straight-line distance between injection site and the Rise of Lost River is about 9.5 mi. The general direction of ground-water flow between injection and detection sites for test 8 is from northeast to southwest.

DIRECTIONS OF GROUND–WATER FLOW AND LOCATIONS OF GROUND–WATER DIVIDES

Dye-trace information, the composite ground-water level-surface map, and topographic information were used in conjunction with previous studies to evaluate factors affecting stormwater drainage in the vicinity of Orleans. These factors include directions of ground-water flow and locations of ground-water divides.

Directions of Ground-Water Flow in Selected Areas

The distinction between surface-water and ground-water basins can be blurred in karst regions because surface- and subsurface-drainage systems can be directly connected. Conduits for ground-water flow developed in the karstic subsurface as an alternative to surface drainage. In some places, surface-water and ground-water divides are approximately identical, and ground-water conduits merely serve as a bypass to surface drainage. In other places, such as mature karst areas, the locations of ground-water divides and catchment areas generally do not coincide exactly with those of surface-drainage systems.

The relation between surface-water and ground-water systems is apparent from the geology, hydrogeology, and topography of three drainage areas near Orleans. The three drainage areas are referred to as (1) the "sinkhole-drainage belt," (2) the "Flood Creek Watershed," and (3) the "Orleans karst valley" (pl. 1). Each of the three drainage areas exemplifies a different stage of karst development, and each has some effect on drainage to and from Orleans. Understanding the characteristics of these three drainage areas is helpful in understanding the hydrology of the Lost River Watershed.

Sinkhole-Drainage Belt

The sinkhole-drainage belt is immediately southeast of the topographic divide that separates drainage to the Lost River from drainage to the East Fork White River (pl. 1; fig. 1). Area of the sinkhole-drainage belt is approximately 9.8 mi^2; altitude of the sinkhole-drainage belt ranges from 680 to 740 ft ASL.

With the exception of Mosquito Creek to the east, there is no organized surface drainage in the sinkhole-drainage belt. Runoff is drained internally by sinkhole depressions. Most sinkholes are open to the aquifer and drain freely. Mosquito Creek, located in the eastern part of the sinkhole belt, flows north across the surface approximately 2.2 mi before disappearing into an unnamed swallow hole. The subsurface route of Mosquito Creek has been traced to Twin Caves at Spring Mill State Park (Bassett and Ruhe, 1973). In this study, dye that was injected into swallow holes of the sinkhole-drainage belt (tests 2 and 6) emerged at Hamer Cave. Dye traces 4 and 5, which originate on and 0.75 mi south of the southern sinkhole-drainage belt boundary, terminate at the Orangeville Rise (pl. 2).

Flood Creek Watershed

The Flood Creek Watershed is immediately downgradient from the sinkhole-drainage belt. Area of the Flood Creek Watershed is approximately 8.1 mi^2. Altitude of land surface in the Flood Creek Watershed ranges from 630 to 680 ft ASL.

Karst development and the subsurface-drainage system does not appear to be as advanced in this drainage area as it is in the sinkhole-drainage belt or in the Orleans karst valley. Karst development may be inhibited in this area by geologic controls. One factor affecting the surface drainage and the stage of karst development is the presence of a glacially derived blanket of fine-grained material and bedrock residuum that inhibits infiltration of recharge. Recharge is required for bedrock dissolution and karst development. In addition, the upper St. Louis limestone is known to have horizons that contain abundant chert nodules (Palmer, 1976). Chert is composed of siliceous, rather than carbonate, material and is much more resistant to weathering. If the chert-rich horizons of the St. Louis limestone underlie the Flood Creek Watershed, then karst development may progress more slowly than elsewhere in the basin.

Drainage in the Flood Creek Watershed is mixed—surface-runoff occurs as sheetflow that is channelized during intense rains, but sinkhole drainage and diversion to swallow holes is also an active process. Most sinkholes in this area are shallow, and relief between sinks is low. In addition, most sinks are filled and occluded with silt, soil, and debris; few are well connected to the aquifer. As a result, intense and lengthy rains result in channelized runoff to occluded sinks and flooding of adjacent property. Orleans is located at the point where most of the surface drainage from the Flood Creek Watershed is diverted underground. Similar to the rest of the Flood Creek Watershed, the terminal sink of Flood Creek has a limited capacity and also can be a site of extensive flooding during intense rains.

Dye traces in the Flood Creek Watershed (dye traces 1, 4, and 5) indicate that the ground-water-flow direction is from the northeast to the southwest. All subsurface flow in the Flood Creek Watershed discharges to the Orangeville Rise.

Orleans Karst Valley

The Orleans karst valley represents the trunk of a former surface tributary to Lost River. The former line of surface drainage is delineated by the alignment and orientation of sinkholes between Orleans and the Mathers stormwater rise. The dendritic pattern produced by aligned sinkholes can be observed generally at altitudes of 600 to 630 ft (pl. 1).

The composite ground-water level-surface map indicates the existence of a major conduit near the axis of the karst valley. Composite ground-water-level contours in the vicinity of Orleans form a distinct trough that is oriented northeast-southwest and dips to the southwest. The water-level trough appears to connect drainage from Orleans with the Mathers stormwater rise. Results of dye-tracing test 1 indicated that flow from Salkeld swallow hole emerged not only at Orangeville Rise but also from the Mathers stormwater rise during high flows (pl. 1 and 2). Further evidence for a major conduit south and west of Orleans is indicated by the rapid flow-through time along dye traces 1, 4, and 5. On the basis of straight-line flow paths between the Orangeville Rise and the injection sites for dye-tracing tests 1, 4, and 5, ground-water velocities ranged from 2 to 4 mi/d. Similarly, velocities calculated by Bassett and Ruhe (1973, p. 81) from the Orleans Sewage Treatment Plant, along dye trace 12 (pl. 2), ranged from 3 to 6 mi/d. These velocities, which exceed the upper limit of hydraulic conductivities proposed by Freeze and Cherry (1979) for fractured limestone, also indicate the existence of a major ground-water conduit near Orleans.

Locations of Ground-Water Divides

A ground-water basin is defined generally as the area between the most distal sites of aquifer recharge and the ultimate discharge point of that water. Maps of composite ground-water-level surface and dye traces between sites of recharge and ground-water discharge can give information about the location of subsurface-drainage divides. The accuracy of divide locations determined from a composite ground-water level-surface map depends on the areal density and location of water levels available to construct the map. Similarly, the ability of dye-tracing studies to locate the most distal sites of aquifer recharge depends on the availability and accessibility of usable sinkholes. The approximate location of ground-water divides near Orleans and the extent and shape of the basins can be deduced from the concurrent evaluation of composite ground-water level-surface data and dye-trace information.

Four significant ground-water discharge points are in the study area: the Orangeville Rise, the Rise of Lost River, Hamer Cave, and Twin Caves. An important goal of this study was to locate the divides that separate drainage to each of these features. Ground-water drainage divides determined for high flows may not coincide with divides identified during low flows. In this study, it was assumed that the wells were not drilled during floods and that subsequently measured water levels that were used to construct the composite ground-water level-surface map are not representative of high flows. Results from this study did not indicate conflict between dye-trace information and divides located by means of the composite ground-water level-surface map.

Orangeville Rise–Rise of Lost River Ground-Water Divide

The ground-water divide that separates ground-water flows to the Orangeville Rise from ground-water flows to the Rise of Lost River is located along a northeast-southwest transect approximately 1.8 mi south of Orleans (pl. 1). Dye traces 3, 7, and 8, along with dye trace 13 (Murdock and Powell, 1968), tentatively identify the boundary between the Orangeville Rise and the Rise of Lost River ground-water basin (pl. 2). Refinement of the ground-water divide location would require additional dye-tracing tests in the area between the hypothetical straight-line flow paths shown on plate 2. Additional swallow holes suitable for injection in the area of the tentatively located drainage divide south and west of Orleans (pl. 1) could not be located. Some swallow holes found in the area between Orleans and the Orangeville Rise could be used to refine the subsurface-drainage divide. As with dye test 8, other high-flow clouds near the tentative ground-water divide may be diverted into the surface channel of the Lost River through shallow ground-water-flow paths. Examination of the land-surface topography, the map of the composite ground-water-level surface, and the dye traces indicate that the low-lying hills about 2.6 mi south of Orleans may represent the surface-water and ground-water divide between the two basins (pl. 1).

Orangeville Rise–Twin Caves Ground-Water Divide

The ground-water divide that separates ground-water flow to the Orangeville Rise from ground-water flow to the Twin Caves system is located along a southeast-northwest transect through the center of the sinkhole-drainage belt area. Location of the drainage divide can be inferred only from the composite ground-water level-surface map (pl. 2). Dye-tracing test 14 (Bassett and Ruhe, 1973), during which the disappearing Mosquito Creek resurged at Twin Caves, is the only trace information available (pl. 2). The ground-water discharge point of dye during test 6 was expected at Twin Caves but, instead, ground water flowed northwest to Hamer Cave (pl. 2). Suitable injection sites for future tracing tests in the sinkhole drainage-belt area northeast of Orleans were identified during field reconnaissance. East of Orleans, in the Flood Creek Watershed, swallow holes generally are occluded and poorly drained, and sites for dye-tracing tests that could refine the ground-water divide are scarce.

Orangeville Rise–Hamer Cave Ground-Water Divide

The ground-water divide that separates ground-water flow to the Orangeville Rise from ground-water flow to Hamer Cave is a continuation of the Orangeville Rise–Twin Caves subsurface-drainage divide (pl. 1). Dye traces 2 and 6, along with trace 18 (W.W. Engineering and Science, 1994), delineate the southern limit of drainage to Hamer Cave. Dye traces 4 and 5, along with trace 15 (Bassett and Ruhe, 1973), delineate the northern limit of ground-water flow to the Orangeville Rise. The ground-water divide separating ground-water flow to the Orangeville Rise from ground-water flow to Hamer Cave is about 4.8 mi north of Orleans. The location of the ground-water divide is tentative but, because the area is in the sinkhole-drainage belt, injection sites for future dye-tracing tests probably are numerous.

A series of low-lying hills about 3.2 mi northeast of Orleans identifies the location of the surface-water divide. A comparison of topographic, composite ground-water-level surface, and dye-trace information indicates that the surface-water divide may not coincide with the ground-water divide. Dye test 6 originates south of the surface-drainage divide but terminates at Hamer Cave. The results of dye-tracing test 6 possibly indicate that a network of ground-water conduits has extended the Orangeville Rise–Hamer Cave ground-water divide to the south of the surface-water divide. The composite ground-water level-surface map indicates that the injection site for test 6 is near the axis of a ground-water trough (pl. 2). This trough, which is similar to the ground-water trough that connects drainage from Orleans to downstream ground-water discharge points, probably indicates the presence of a major drainage conduit that conducts ground-water drainage from the sinkhole plain to ground-water discharge points at Spring Mill State Park. Headward expansion of a major conduit system may explain the ground-water divide that extends beyond the surface-water divide.

Northwestern Ground-Water Divides for the Orangeville Rise

Little dye-test information is available to determine the location of ground-water divides between Orangeville Rise and resurgences farther to the north and west of the Orangeville Rise ground-water basin. Dye traces 9 and 10 (Murdock and Powell, 1968), 15 and 16 (Bassett and Ruhe, 1973), and 17 (Bassett and Ruhe, 1974) (pl. 2) provide some information on the northern limit of the Orangeville Rise ground-water basin. Dye trace 9 resurged at Sulfur Creek, providing an indication of the location of the divide that separates ground-water flow to the Orangeville Rise from ground-water flow to the west (pl. 2). Drainage in the vicinity of Mitchell and farther north of Mitchell discharges ground water to Pless Cave and the Blue Springs Cave systems on East Fork White River (W.W. Engineering and Science, 1994).

SUMMARY

Dye-trace information was completed and a composite ground-water level-surface map was constructed to improve an understanding of the hydrogeology of the Lost River Watershed near Orleans. Additional information in this report includes a bibliography of references describing

previous hydrologic studies in the area and a map that delineates geomorphic boundaries and karst features. The results of the study suggest explanations for periodic flooding in Orleans and refine the delineation of ground-water divides that separate ground-water flows to the Orangeville Rise from ground-water flow to adjacent watersheds.

For purposes of this report, the area surrounding Orleans was divided into three ground-water-drainage areas, each having distinct hydrologic characteristics and geomorphic appearance. In order of decreasing average altitude, the three drainage areas are the sinkhole-drainage belt, the Flood Creek Watershed, and the Orleans karst valley. The sinkhole-drainage belt is an internally drained area with numerous sinkholes and few surface channels. Dye-tracing tests indicate that ground-water within the sinkhole-drainage belt resurges at either the Orangeville Rise or Hamer Cave. In contrast with the geomorphic appearance and drainage characteristics of the sinkhole-drainage belt, the Flood Creek Watershed shows little evidence of karst development, and during intense storms most runoff becomes streamflow. Dye tests from available swallow holes in the Flood Creek Watershed indicate that most ground-water resurges at the Orangeville Rise, although during high streamflows, some ground water resurges at Mathers stormwater rise. The Orleans karst valley is drained primarily by a well-developed system of subsurface conduits.

Flooding in Orleans might be less severe if the surface water and ground water of the Flood Creek Watershed were in good hydraulic connection to the conduit system of the Orleans karst valley. Unfortunately, during heavy rains, Flood Creek flows into a sinkhole in Orleans that is choked with the same deposits that blanket most of the Flood Creek Watershed, and stormwater is inhibited from entering the subsurface. Engineering alternatives that might decrease the magnitude of flooding in Orleans are (1) construction of stormwater-detention structures to control the rate of flow and reduce the sediment load to Flood Creek Sink, and (2) an improvement of the hydraulic connection between the surface-drained Flood Creek Watershed and the conduit system of the Orleans karst valley.

In addition to examining the hydrology and possible sources of flooding in Orleans, results of this study (including dye-trace tests and construction of a composite ground-water level-surface map) were used to improve delineation of the ground-water divides in the area. In addition to the Orangeville Rise, parts of ground-water basins from which ground water resurges at Twin Caves, Hamer Cave, Rise of Lost River, Sulphur Creek, and East Fork White River also are represented in the study area. Results of dye-trace tests 1, 2, 4, 5, and 6 improved the accuracy of delineation of the Orangeville Rise–Twin Caves ground-water divide, and results of tests 3, 7, and 8 improved the accuracy of delineation of the Orangeville Rise–Rise of Lost River ground-water divide. Results of dye-tracing tests from previous studies also are shown on plate 2 and assist delineation of ground-water drainage divides to the north and west of Orleans.

Coexamination of dye-trace information and topography indicates that the low-lying hills south of Orleans may approximate the location of the Orangeville Rise–Rise of Lost River ground-water divide. A similar set of low-lying hills between Orleans and Spring Mill State Park may not be the location of the Orangeville Rise–Twin Caves ground-water divide; instead, it appears that the conduit system from Twin Caves extends beyond the line of hills. In all cases, results of the dye-trace tests and water levels shown in the composite ground-water-level surface were in agreement.

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Bassett, J.L., and Ruhe, R.V., ed., 1973, Fluvial geomorphology in karst terrain, *in* Morisawa, M., ed., 1973, Fluvial geomorphology, Proceedings: Binghamton, N.Y., 4th Annual Geomorphology Symposia Series, p. 74-89.

Drainage in the eastern, nonkarstic part of the basin parallels major lineaments and bedrock control. Dye traces indicate that no sinking stream resurged at both the Orangeville Rise and the Rise of Lost River. The area of the ground-water basin of Rise of Lost River is estimated to be about 85 mi^2 and that of the Orangeville Rise, about 48 mi^2. On the basis of the amount of dye injected during high flow at the Orleans Sewage Treatment Plant and the amount of dye recovered at the Orangeville Rise, Bassett and Ruhe estimated that about 70 percent of the dye passed through the system as a dye pulse; therefore, the system is "analogous to open pipe flow." Discharge at Orangeville Rise responded to rainfall in the basin within 4 hours during one measured storm. Discharge measurements for six dates during 1972-73 were used to check the ground-water basin divides as indicated by dye-trace tests. Discharge measurements agreed with results of dye-trace tests, except during one storm when a stormwater bypass at Dry Branch was identified as the cause of a discrepancy between ground-water basin divides located with discharge information and divides located with dye-trace tests. Ground-water emergences at stormwater rises in the dry bed probably occur when discharge at the Orangeville Rise reaches its upper limit, estimated to be 180 to 190 ft^3/s. A log-log relation between discharge and calcium concentration, as well as hydrochemical information, is described.

Bassett, J.L., and Ruhe, R.V, 1974, Geomorphology, hydrology, and soils in karst, southern Indiana–Field Conference, April 24-25, 1974: Bloomington, Ind., Indiana University, Water Resources Research Center, 54 p.

Four dye-tracing tests were done; results are presented in a composite map with 10 dye traces originally mapped by Murdock and Powell (1968). Data describing injection and sampling point altitudes, separation distance, hydraulic gradient, and travel time are presented. Injected dye slugs consisted of 1.8 gal of 20 percent rhodamine WT. Dye detections were confirmed with a filter fluorometer. Travel time from the Orleans Sewage Treatment Plant to the Orangeville Rise, previously traced qualitatively by Murdock and Powell, was 46 hours when discharge was 60 ft^3/s and 26 hours when discharge was 148 ft^3/s. Comparison of precipitation records measured at Bedford, Ind., with hydrographs measured at Orangeville showed a response time of less than 4 hours. The 85 mi^2 area that drains to the Rise of Lost River is identified as the "eastern integrated surface drainage," and the 48 mi^2 area that drains to the Orangeville Rise as the "western highland area." Correlation equations relating concentrations of primary chemical constituents and discharge were developed for 36 data sets collected at the Orangeville Rise.

A second project described in this report is a water-balance investigation at a single, variably saturated sinkhole on Mann Farm, Lawrence County, Ind., during which numerous measurements were made.

The third project described in this report is the use of soil properties to estimate the unsaturated-zone storage capacities. Calculations based on mean soil properties indicate that the storage capacity of the sinkhole plain is about 3,900 acre-ft/mi^2. In the eastern parts of the Lost River drainage basin, storage capacity is about 8,700 acre-ft/mi^2.

Gruver, B.L., and Krothe, N.C., 1991, Evidence for epikarst storage in a classic sinkhole plain, Mitchell Plain, Indiana—Proceedings of the American Geophysical Union 1991 Fall Meeting, Programs and Abstracts, December 9-13, 1991, San Francisco, California: San Francisco, Calif., American Geophysical Union, p. 206.

Oxygen and deuterium isotopes were used for hydrograph separation at the Orangeville Rise. A storm preceded by prolonged low flows caused increased discharges at the Orangeville Rise within 6 hours. Hydrograph separation for both situations showed that about 20 to 25 percent of the discharge could be attributed to rainfall. A large volume of water was flushed from epikarst storage.

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REFERENCES WITH ANNOTATIONS

Hoggatt, R.E., 1975, Drainage areas of Indiana streams: Indiana Department of Natural Resources, Division of Water, 231 p.

The drainage areas of surface-water subbasins are given. Subbasins that are in the Lost River Watershed are the Lost River above Carters Creek (35 mi^2), Lost River including Carters Creek (44.2 mi^2), Lost River at entrance into ground (99.3 mi^2), Lost River above Mt. Horeb Drain (141 mi^2), Mt. Horeb Drain at mouth (13.2 mi^2), Lost River above Dry Branch (162 mi^2), and Dry Branch at mouth (9.76 mi^2).

Krothe, N.C., and Libra, R.D., 1983, Sulfur isotopes and hydrochemical variations in spring waters of southern Indiana, USA: Journal of Hydrology, v. 61, p. 267-283.

Sulfur isotopes and general water chemistry were used to differentiate springs draining shallow, conduit-flow karst systems and deeper, regional diffuse-flow systems. The Orangeville Rise was identified as having characteristics of the former.

Malott, C.A., 1922, The physiography of Indiana, *in* Handbook of Indiana geology: Indiana Department of Conservation, Publication 21, pt. 2, p. 59-256.

This report, an early and brief overview of the Lost River area, includes several findings from work done by M.N. Elrod in the late 1800's. Elrod (1899) states that during certain storms (when water enters the fourth sink), resurging water bursts forth from the wet-weather rises and for a while leaves the intervening part of the dry bed with no flow. Several additional features are briefly described, including Wesley Chapel Gulf, Lost River Cave, Elrod Cave, the Orangeville Rise, the Orangeville Gulf, and the Rise of Lost River. The hydrology of the area is summarized, including observations about the connections between Carters Creek, Fultons Branch, Lick Creek, Stampers Creek, the Lost River, and the two major rises; these observations are consistent with currently understood drainage divides.

Malott, C.A., 1929, Three cavern pictures: Proceedings of the Indiana Academy of Science, v. 38, p. 201-206.

Wesley Chapel Gulf cavern and its relation to the Lost River and the Rise of Lost River are described briefly. The surface-water drainage area above the first swallowhole is about 60 mi^2. The surface-channel distance from the first swallow hole to the Rise of Lost River is 21 mi; but straight-line distance, a more likely path for subsurface flow, is about 8 mi.

Malott, C.A., 1932, Lost River at Wesley Chapel Gulf, Orange County, Indiana: Proceedings of the Indiana Academy of Sciences, v. 41, p. 285-316.

The locations of the four gulfs in the Lost River region—Orangeville Gulf, Tolliver Gulf, Crow Hollow Gulf (Rise of Stamper's Creek), and Wesley Chapel Gulf—are described. The report includes a brief discussion of the Lost River but is mostly a detailed account of Wesley Chapel Gulf explorations. A brief mention is made of the Charles T. Brown Cavern that connects Tolliver and Turner swallow holes; three levels were documented within a 45-ft section. The author also mentions northwest-southeast joint patterns.

Malott, C.A., 1945, Significant features of the Indiana karst: Proceedings of the Indiana Academy of Sciences, v. 54, p. 8-24.

General descriptions of typical karst features from southern and south-central Indiana are given.

Malott, C.A., 1949, Hudelson Cavern, a stormwater route of underground Lost River, Orange County, Indiana: Proceedings of the Indiana Academy of Sciences, v. 58, p. 236-243.

A detailed cave map gives dimensions and altitudes of most cavern passages. Biota in the cavern include white blind crawfish and blind fish. Hudelson Cavern was likely carved by rapidly moving storm-flow that precedes filling of Turner swallow hole.

Malott, C.A., 1952, The swallow-holes of Lost River, Orange County, Indiana: Proceedings of the Indiana Academy of Sciences, v. 61, p. 187-231.

This posthumous publication summarized Malott's 25 years of observations of the Lost River in Orange County, Ind. Malott describes the Lost River

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drainage basin as a three-tier system that consists of (1) an upland limestone plain whose water table is limited by the river-surface altitude, (2) a middle area with an extensive underground drainage system, and (3) a lower basin where the river is well entrenched and where base level responsible for the karst development in the upper and middle areas is established. The west-to-east development of the Mitchell Plain through geologic history is described in some detail. An early developing subterranean cutoff of the Lost River, originating at a sink southeast of Orleans (NE1/4, sec. 3, T. 2 N., R. 1 W) and passing through the Peacher Cave system before emerging at Mathers stormwater rise, is described. Subsequent discussion describes the merging of the underground Pearson Creek system (whose headwaters are near Mitchell, in Lawrence County) with the underground stream that sinks in Orleans and then emerges at Mathers stormwater rise; most of the flow from the rise is furnished by these two systems. A karst valley trending northeast-southwest is identified and appears to connect the Orleans drainage with the Peacher Cave–Mathers stormwater rise paleoflow system. These and most other significant karst features in the immediate vicinity of the dry bed are shown. Several of the more significant features and their role in transmitting stormwater drainage are described. Features described include Stein Swallow Hole, Turner Swallow Holes, Tolliver Swallow Hole, Wesley Chapel Gulf, Mathers stormwater rise, the Orangeville Rise, and the Rise of Lost River. Stein Swallow Hole can convey about 750 ft^3/s before overflow is shunted to the Turner Swallow Holes. When extended flooding exceeds the capacity of Turner Swallow Holes, also about 750 ft^3/s, an even larger amount of flow is shunted to Tolliver Swallow Hole. The water table is generally 20 to 25 ft and 30 to 35 ft below the dry bed at Stein and Turner Swallow Holes, respectively. The explored section of Tolliver Swallow Hole is 3 to 4 ft high, 10 to 25 ft wide, 565 ft long, and about 50 ft below the dry bed. These unique features are developed in the St. Louis limestone. Other less impressive and unnamed swallow holes and ground-water discharge points are also described. During a storm, ground water near Turner Swallow Holes was described as being muddy in a well screened at 35 ft, but clear at 80 ft. Orangeville Rise discharges as much as 2,000 ft/s during storms.

"Old Sulphur" is a name used by Malott to describe a stream whose headwaters are about 3 mi east of Orleans. The stream once was a surface tributary to the Lost River but now sinks into swallow holes in the former valley. This stream may be the same stream that is referred to as "Flood Creek" in Murdock and Powell (1968).

Murdock, S.H., and Powell, R.L., 1968, Subterranean drainage of Lost River, Orange County, Indiana: Proceedings of the Indiana Academy of Sciences, v. 77, p. 250-255.

Fluorescein (1 $lb/ft^3/s$) dye-trace tests were used to determine the extent of subbasins in the northern part of the Lost River Watershed. Information describing the 10 dye traces includes locations and altitudes of injection and recovery points; direction, gradient, travel time and distance between the injection and recovery points; surface-water flow rates and the mass of dye use in each dye-trace test. Dye-tracing tests were done at low flow to normal flow conditions.

Palmer, M.V., 1976, The Mitchell Plain of southern Indiana: The National Speleological Bulletin, v. 38, no. 4, p. 74-78.

This article is a synopsis of the geology upon which the Mitchell Plain physiographic unit is formed. A southeast-northwest geologic section through the Lost River Watershed illustrates the west-to-east development of karst topography. The role of relatively impermeable unconsolidated deposits in the eastern part of the basin is described.

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Powell, R.L., 1961, Caves of Indiana: Indiana Geological Survey Circular 8, 127 p.

This publication describes 398 caves in central and south-central Indiana. Some descriptions include a map and description of the basic cave hydrology. A base map, a discussion of the geologic setting, an explanation of the development of karst geomorphology, and a description of cave features and nomenclature are included.

Powell, R.L., 1987, The Orangeville Rise and Lost River, Indiana, *in* Geological Society of America Centennial Field Guide, North-Central Section, 1987, p. 375-380.

Thirteen dye traces in the Lost River Watershed, including those of Murdock and Powell (1968) and Bassett and Ruhe (1974) are shown in this report. Discharge at the Orangeville Rise is about 9 ft^3/s at low flow and about 185 to 200 ft^3/s at flood stage. The Orangeville Rise pit is at least 100 ft deep. The rise pit of the Rise of Lost River is at least 165 ft deep. Tolliver Swallow Hole and Wesley Chapel Gulf also are briefly described.

Powell, R.L., and Krothe, N.C., 1983, Field trips in Midwestern geology: Geological Society of America, v. 2, p.65-85.

This travel guide, from the Ohio River border of Indiana to Indianapolis, gives directions to many examples of the Mississippian rocks that are exposed in southern Indiana and to locations that typify the physiographic units in the area. The guide describes the hydrology of the Lost River drainage basin and gives directions to many of the classic karst features in the area, including the first and principal sinks of the Lost River, Sink of South Fork of Stampers Creek, Miles Cave, Tolliver Swallow Hole, and Wesley Chapel Gulf. The description for stop 32 includes a discussion of the clay-rich soils that overlay much of the non-karstic uplands. Topographic maps showing site locations are included.

Tweddale, J.B., 1987, The relationship of discharge to hydrochemical and sulfur isotope variations in spring waters of south-central Indiana: Bloomington, Ind., Indiana University, M.S. thesis, 165 p.

Six springs in south-central Indiana were studied from June 1986 through April 1987 for variations in sulfur isotope ratios and inorganic constituents. Results of samples from Pluto 1 and Trinity springs indicate that the wide variations in sulfur isotope ratios and chemistry are not related to discharge. Water chemistry of the White River Brine spring and the Orangeville Rise varies but it does not correlate to discharge. The variation in water quality is attributed to differences in flow path and depth of flow within the St. Louis limestone.

Wells, E.R., and Krothe, N.C., 1989, Seasonal fluctuation in ^{15}N of groundwater nitrate in a mantled karst aquifer due to macropore transport of fertilizer-derived nitrate: Journal of Hydrology, v. 112, p. 191-201.

The study area is the upper drainage basin of the Lost River. Isotopic evidence in this soil-mantled part of the basin indicates that a mix of both septic effluent (or animal waste) and fertilizer-derived nitrates are in the bedrock aquifer. Samples collected in May, after application, showed little increase in fertilizer-derived nitrogen, but 9 of 20 wells sampled after application in September contained isotopic fractions indicative of a relatively large fertilizer-derived component. The transport of nitrogen is believed to be facilitated by macropore flow through the otherwise low-permeability surficial deposits.