Groundwater Tracing in the Duschee Creek Karst Basin in Southeast Minnesota

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Photo of the Lanesboro Fish Hatchery Main Spring (overflow)
(Photo by E. Calvin Alexander, Jr.)

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SUMMARY

A series of dye traces, beginning with a 1985/87 project funded by the Legislative Commission on Minnesota Resources, have been used to study the hydrologic system of the area in and near the Duschee Creek watershed and the springs at the Department of Natural Resources Fish Hatchery at Lanesboro, Minnesota. These traces demonstrate that direct hydrologic connections exist to the Hatchery springs from at least one sinkhole and one stream swallet. Travel times to the springs are only 8-1/3 to 9-1/4 hours, corresponding to minimum leading edge velocities of 9.6 to 10.4 km per day (about 6 to 6-1/2 miles per day). Such rapid, direct connections threaten the water quality at the Hatchery in the event of an accidental spill, by deliberate waste disposal, or in runoff associated with large storm events.

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INTRODUCTION

The Duschee Creek watershed is located in Fillmore County, in the karst of southeastern Minnesota. A large fish hatchery is located near Lanesboro, in the Duschee Creek watershed. This hatchery, owned and operated by the Minnesota Department of Natural Resources (DNR), provides almost 40% of all trout stocked by the State in its lakes and streams (Stork, 1993). Therefore, the Lanesboro Hatchery is an important resource of the State, and contributes significantly to the State's direct and indirect revenues from recreational fishing.

All of the water used to hatch and raise the trout comes from two large springs. The water quality of those springs has been negatively impacted for many years by large recharge events, such as intense and/or prolonged rainfall events or by rapid snowmelt, particularly if accompanied by rain. Within hours, the spring water becomes turbid and remains so for at least a day, but usually longer, sometimes up to two weeks. Concern over the water quality at the Lanesboro Hatchery led to research studies beginning in 1985.

The first goal was to identify the source(s) of the sediment-laden waters which severely impacted the Hatchery springs after major recharge events. The anecdotal observations of the Hatchery personnel strongly implicated surface runoff from agricultural lands. This author hypothesized that surface waters running into one or more sinkholes were the source(s) of the problem. Concern was expressed that accidental spills or deliberate waste disposal in or near the critical sinkholes could pose a catastrophic threat to the Hatchery springs. The problem, therefore, became one of identifying the groundwater basin feeding the springs and then locating the sinkholes and/or stream sinks within that basin.

The initial working hypothesis was that the groundwater basin coincided with the surface water basin. The author expected that this hypothesis would be falsified and modified as the study progressed. The surface water basin is readily identified on the topographic maps and it provided a starting point. This study was begun by locating and dye tracing sinkholes and stream sinks within the Duschee Creek surface watershed. The study was later expanded to include dye traces from beyond the surface watershed boundaries.

Once positive results from dye traces were obtained, determining travel times between the critical sinkholes and the Hatchery springs was possible. Dye tracing can provide several types of travel time data, such as velocity of the leading edge of the dye and total length of time until the dye is flushed from the system. If a substance toxic to fish were spilled near a known sink, leading edge velocity data would tell the Hatchery personnel how much time they would have to prepare for the emergency. The length of time for complete flushing would indicate how long the emergency could last.

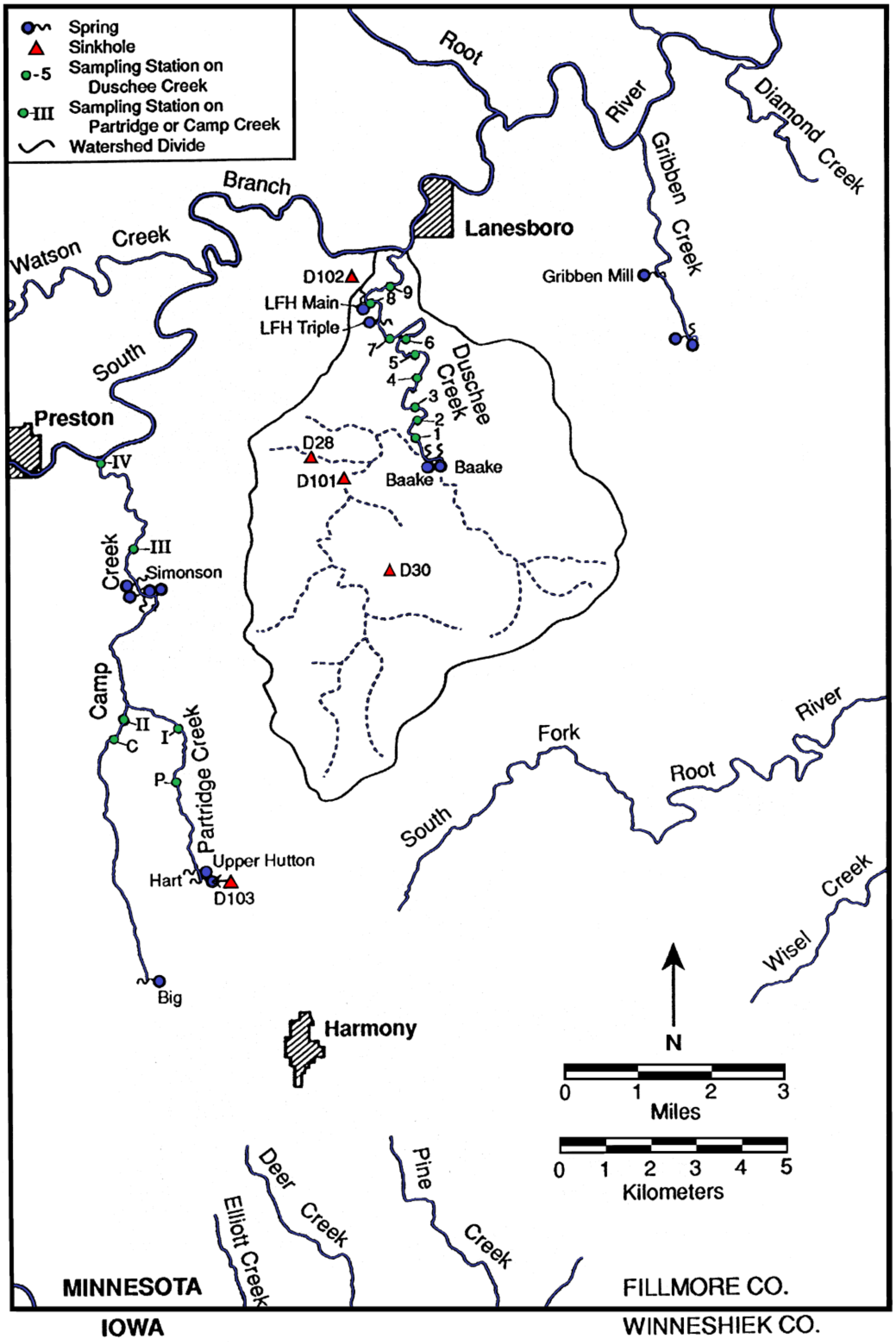
Nine dye traces from within the Duschee Creek study area were conducted to identify point sources which could have direct hydrologic connections to the Lanesboro Hatchery springs via the karst groundwater system. These traces have demonstrated characteristic flow times within the karst aquifer, and have begun to constrain the knowledge of the recharge area of the Hatchery springs.

STUDY AREA

The Duschee Creek basin is located in Fillmore County in southeastern Minnesota. The study area, shown in Figure 1, focuses on the surface watershed of Duschee Creek and surrounding areas. The Duschee Creek surface watershed encompasses approximately 59 square kilometers (22-3/4 square miles) and is outlined on Figure 1. In karst areas, the boundaries of a groundwater basin often do not coincide with those of a surface watershed. Therefore, the study area was defined to be the Duschee Creek surface watershed and surrounding areas.

Under most flow conditions Duschee Creek rises at various springs along its upper and middle reaches, but many of the smaller springs dry up during prolonged periods of dry weather. Tributaries to Duschee Creek which flow for only a short time during and after spring snowmelt and large precipitation events are shown in Figure 1 with a dotted line. Springs A373 and A381 rise in the southern end of the surface watershed and flow steadily year-round. The southwestern-most Duschee Creek tributary flows for approximately one mile below these springs (shown on Fig. 1 with a solid line) before it sinks into the creekbed in a losing reach. Between that sinking reach and Stream Swallet D101, Duschee Creek flows most of the year except during prolonged periods of dry weather (that reach is shown in Fig. 1 with a dot-and-dash line). The Bakke Springs rise year-round and flow steadily throughout dry periods. Duschee Creek is

Figure 1. Study area of the Duschee Creek karst basin.



a permanent stream below these springs.

The largest springs in the study area are the two springs located at the Lanesboro Hatchery. These two springs will hereafter be referred to as LFH Main and LFH Triple Springs. The primary goal of this research was to evaluate the potential threat to the water quality in these two springs by identifying any sinks from which contaminants could directly travel to these springs.

Another important spring in the area is the Gribben Mill Spring. It is located on Gribben Creek, in the next surface watershed east of the Duschee Creek watershed (Fig. 1). This spring is an important source for water in Gribben Creek, which is one of several streams in Minnesota with a self-sustaining wild population of brown trout.

GEOLOGY, GEOMORPHOLOGY, AND HYDROGEOLOGY

The bedrock in southeastern Minnesota consists of nearly flat-lying Paleozoic sedimentary rocks, which were deposited in the Hollandale Embayment between the Transcontinental Arch and the Wisconsin Dome of the Canadian Shield. The rocks are comprised primarily of Cambrian, Ordovician, and Devonian sandstones, shales, limestones, and dolostones which record successive transgressive and regressive cycles of deposition. Scattered patches of pre-Wisconsin glacial drift cover the bedrock in parts of the region. The drift is localized as much of the original deposits have been removed by headward erosion in the stream valleys. Wisconsin and perhaps pre-Wisconsin loess mantles much of the landscape (Austin, 1972).

The area can be described as a stepped plateau which dips gently to the southwest with deeply incised valleys. In general, the more massively-bedded dolostones form the successive caprock layers.

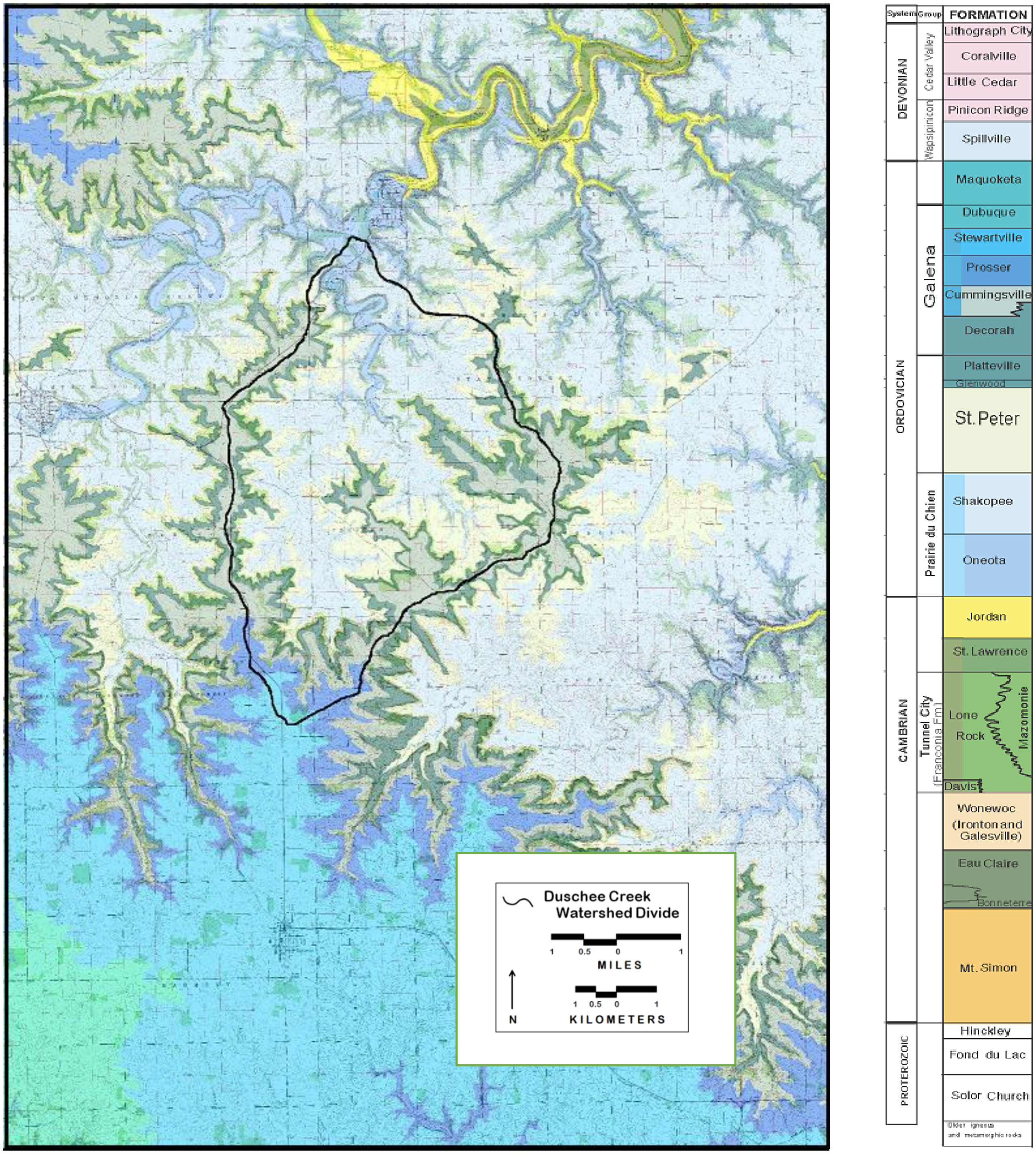
Most of the study area is characterized by gentle to steep slopes with thin soils on the hillsides. Somewhat thicker soils occur in the narrow valley bottoms; those soils are generally composed of alluvium and colluvium (Farnham, 1958).

A typical karst geomorphology is overprinted on the stepped plateau and is especially well developed in some areas in Fillmore County where the carbonates of the Galena Group are the first bedrock unit underlying the land surface. In such areas the density of sinkholes approaches tens to hundreds per square mile and the landscape becomes a classic sinkhole plain. The uplands which form the southern and western edges of the study area, particularly near Harmony, are such an area. Sinkholes occur more rarely in the lower carbonate strata of the Prairie du Chien Group which are the first bedrock units under most of the basin. However, some of the few sinkholes that have been identified in the lower section of this basin have a disproportionate influence on the water quality of the Hatchery springs. Figure 2 is a geology map of the Duschee Creek watershed and study area.

The Decorah shale is the most effective aquitard in the upper part of the stratigraphic section. The aquitard is breached where stream valley walls intersect the formation and there it crops out on the surface. Outcrops of the Decorah generally occur between the 366 m (1200-foot) and 335 m (1100-foot) elevation contours in the study area. The relatively low permeability of the shale causes springs and seeps to emerge just above the formation. Wet areas on the hillslopes make cultivation nearly impossible, so areas where such springs and seeps emerge are typically forested. These forested areas are shown on topographic maps as a green overlay. The Decorah shale is also penetrated by ungrouted wells and by abandoned wells. Therefore, the utility of the Decorah shale as a barrier to pollution of the deeper aquifers is, at best, limited to localized areas.

The river valleys of southeastern Minnesota form a classic

Figure 2. Geology of the study area.



Map and stratigraphic section updated, from: Runkel, et al., 2014.

dendritic pattern. Duschee Creek is a tributary to the South Branch of the Root River. The South Branch of the Root River is the local base level for the study area. The South Branch and other tributaries join the Root River, which flows about 84 km east to the Mississippi River. The deeply entrenched Mississippi is the regional base level. Many small creeks and some larger streams in southeastern Minnesota are losing in certain reaches, and/or completely disappear in a terminal sink, for part or all of the year.

LFH Main and Triple Springs emerge about 12 m above the contact between the Oneota dolostone and the Jordan sandstone. Although both are quite good aquifers in their own right, the hydraulic conductivities of the Oneota dolostone and the Jordan sandstone are substantially different, arising from differences in primary and secondary permeabilities. The Hatchery springs are probably contact springs, and simply rise hydraulically above the bedrock contact due to pressure head in the Jordan.

Concern for the water quality of the Hatchery springs initiated this study. Background information about responses of the springs to climatologic events was provided by Hatchery personnel. Hanson (1986) noted that the spring waters turn turbid after heavy rains in the area of Harmony, Minnesota. The same phenomenon is not observed when it rains heavily only in the Lanesboro area. Other materials, such as leaves, twigs, and seeds commonly flush out of the springs, and are trapped within the Hatchery building on screens. Larger objects, such as corncobs, have reportedly come out of LFH Main Spring on rare occasions.

The ridge north of Harmony, which is literally pockmarked by sinkholes, is primarily agricultural land. It was possible that one or several of these sinkholes act as discrete input source(s). Several times per year small native aquatic organisms, such as stickelbacks and gamerus, are found on the screens in the Hatchery. This suggests that a direct connection to a nearby surface stream or farm pond may exist. Taken together, these hydrologic features suggest that the study area incorporates a well-developed karst hydrogeologic regime. These observations also suggest that a storm run-in component is the prime threat to the Hatchery spring water quality.

DISCHARGE DATA

Discharge data for the Hatchery springs and for Duschee Creek is very limited. Data for lower Duschee Creek (just above the Hatchery springs input) provided by Perry and others (1988) give mean discharge results for each of four calendar quarters, beginning Fall, 1986 as follows: (0.370 ± 0.075), (0.468 ± 0.184), (0.303 ± 0.098), and (0.402 ± 0.195) m^3/s, respectively. These values were derived from 35 measurements during 1986-87.

Table 1 lists additional discharge data supplied by Troelstrup (1987a). These measurements were taken during the first two days of Dye Trace #2, March 24 and 25, 1987. Discharge was measured at each of the nine stations on Duschee Creek, (Fig. 1) sampled in Dye Trace #2. Flowrates during the trace were at or slightly below normal for that time of year. These data suggest the possibility of a losing reach on the creek between Stations 3 and 4, involving a loss of 5% to 10% of the flow (Troelstrup, 1987b). The uncertainties of stream flow measurements, however, are at least that large and additional measurements would be needed to verify this suggestion.

Stream discharge was measured at stations 7 and 9 on Duschee Creek on April 16, 1989 at the beginning of Dye Trace #7 (Wheeler and Alexander, 1989). The discharge at Station 7 was 0.123 m^3/s, and the result at Station 9 was 0.363 m^3/s on that date.

Huber (1989), former Area DNR Hydrologist, stated that the average discharge of the Hatchery springs during the 1970s was

Table 1. Discharge data for the lower Duschee Creek, March 24 and 25, 1987.

Station on Duschee Creek	Name	KFD Number[1]	UTMs (NAD 83, Zone 15)		Location (township, range, section, quarters)	March, 1987	Number of Replicates	Mean Discharge (m^3/s)	Standard Deviation (m^3/s)
			Easting	Northing					
1	Duschee Creek Station 1 Dye Input	MN23:X00276	582,100	4,836,140	103N, 10W, 36, CDDC	24 25	2 2	0.224 0.268	0.048 0.004
2	Duschee Creek Station #2	MN23:X00277	582,216	4,836,440	103N, 10W, 36, CDAA	24 25	2 2	0.244 0.282	0.015 0.018
3	Duschee Creek Station #3	MN23:X00278	582,072	4,836,741	103N, 10W, 36, CAAC	24 25	2 2	0.237 0.259	0.022 0.033
4	Duschee Creek Station #4	MN23:X00279	582,266	4,837,387	103N, 10W, 36, ABCC	24 25	2 2	0.212 0.253	0.009 0.045
5	Duschee Creek Station #5	MN23:X00280	581,971	4,837,941	103N, 10W, 25, CDBD	24 25	2 2	0.263 0.316	0.020 0.003
6	Duschee Creek Station #6	MN23:X00281	581,847	4,838,272	103N, 10W, 25, CACB	24 25	2 2	0.260 0.291	0.029 0.028
7	Duschee Creek Station #7	MN23:X00282	581,561	4,838,285	103N, 10W, 25, CBCA	24 25	2 2	0.325 0.354	0.016 0.035
8	Duschee Creek Station #8	MN23:X00283	581,025	4,839,067	103N, 10W, 26, ABDA	24 25	0 2	Missing data 1.400	--- 0.000
9	Duschee Creek Station #9	MN23:X00284	581,490	4,839,418	103N, 10W, 24, CCCC	24 25	2 1	0.629 0.630	0.010 ---

[1] From: Gao, 2002.

approximately 0.309 m^3/s. He said that the value measured in October, 1988 was 0.300 m^3/s (Huber, 1989).

DYE TRACES

Methods:

The fluorescent dye, Rhodamine WT, was used in all traces in this study. It is a safe, non-toxic dye (Smart, 1984) which was specially formulated for water tracing studies (Smart and Laidlaw, 1977). Rhodamine WT is currently approved for tracing work by the U.S. Environmental Protection Agency (EPA). It has been used successfully for many years by agencies investigating surface and groundwater flow, such as the U.S. Geological Survey (USGS) (Hubbard and others, 1982; Kilpatrick and Taylor, 1986) the Minnesota Pollution Control Agency (MPCA), the DNR, and many other researchers. Rhodamine WT has been used particularly successfully by many karst researchers (Scanlan, 1968; Mohring, 1983; Jones, 1984; Vandike, 1985; Alexander and others, 1986; Alexander and Milske, 1986; Mohring and Alexander, 1986; Mull and others, 1988; Smart, 1988; Wheeler and others, 1988; Foster and others, 1992). The use of fluorescent dyes in southeastern Minnesota dates back at least to 1940 when S.P. Kingston (1943) of the Minnesota Department of Health (MDH) used fluorescein to investigate a water-born typhoid fever outbreak in Harmony.

When light of a particular wavelength strikes a fluorescent dye, the dye molecule adsorbs that light and then reemits the energy as light of a different, longer, wavelength. The concentration of dye in water can be measured by the intensity of re-emitted light, using a fluorometer. The fluorometer can detect levels of fluorescence produced by dye concentrations of less than 10 parts per trillion (10^{-12} g/g or ppt). When Rhodamine WT is in excess of about 10 parts per billion (10^{-9} g/g or ppb), which is 1000 times as concentrated as required for fluorometric detection, it becomes visible in the sample.

In all traces, the 20% solution (by weight) of Rhodamine WT supplied by its manufacturer, Krompton and Knowles, was used. The mass of dye used was measured, prior to each trace.

Background fluorescence is present in many natural waters, especially stream waters, due to organic compounds. The background fluorescence of the waters in the Hatchery springs is generally very low, usually equivalent to less than 20 ppt of Rhodamine WT. The background fluorescence of the water in streams is much more variable. The background in Duschee Creek ranged between 30 and 50 ppt in 1987; in April, 1988 it was between 180 and 200 ppt; and in June, 1988 it was 5 ppt. Prior to each dye trace, background samples were collected from each spring and stream.

During each trace, samples of water were periodically collected in 30 ml (8 dram) screw-cap vials. The fluorescent content of each vial was measured on a Turner Designs 10-005 Filter Fluorometer. Fluorescence of Rhodamine WT is temperature-dependent; therefore, all samples were equilibrated and maintained in a water bath during analysis. A set of standards was also placed in the water bath and analyzed at the beginning and ending of each batch.

The LFH Main Spring samples were collected from the spring overflow, which is immediately adjacent to the spring. The LFH Triple Spring samples, however, were collected from a settling basin because of better accessibilty. The settling basin is approximately 0.4 km from LFH Triple Spring, and the water is piped underground to the settling basin.

The fluorometric analysis is nondestructive and the vials were retained until the initial data analysis was complete. If any questions arose about a particular sample, that sample was reanalyzed. Positive results, indicating that dye was detected at one or more sampling stations, are reported as concentration versus time plots.

Table 2 lists the nine dye traces and summarizes the parameters of each. The following narrative describes each individual trace.

<u>Results of Individual Dye Traces</u>:

<u>Dye Trace #1</u>: The first trace was from a sinkhole about 3.4 km southwest of the Hatchery springs. The sinkhole is designated D28 (which is a short version of its identification number MN23:D0028) on the map figures. D28 is one of only a few sinkholes that have been found relatively close to the Hatchery springs. It is developed in the Prairie du Chien Group.
This sinkhole is located in a farm field to the side of a small, ephemeral tributary to Duschee Creek. The tributary is dry most of the year. However, during and shortly after intense rainfall

Table 2. Parameters of each trace.

Trace No.	Dye Input		Dye Input Sites (township, range, section, quarters)	KFD Number[1]	Dye Input Site UTMs (NAD 83, Zone 15)		Dye Mass	Positive Detection Site(s)
	Date (dd mm yyyy)	Time (hh:mm)			Easting	Northing		
1	21 Nov 1986	16:10	Solberg Sinkhole 23D28 (T102N, R10W, Sec 2, BCBA)	MN23:D00028	579,989	4,835,658	2.9 kg	LFH springs
2	24 Mar 1987	11:25	Duschee Creek Station 1 (T103N, R10W, Sec 36, CDDC)	MN23:X00276	582,100	4,836,140	1.4 kg	Duschee Creek Stations 2-9
3	24 Jun 1987	9:40	Solberg Sinkhole 23D28 (T102N, R10W, Sec 2, BCBA)	MN23:D00028	579,989	4,835,658	2.6 kg	LFH springs
4	31 Oct 1987	9:15	Simonson Sinkhole 23D30 (T102N, R10W, Sec 12, CCD)	MN23:D00030	581,670	4,833,069	4.9 kg	(none)
5	9 Apr 1988	10:27	Partridge Creek Dye Input 23X244 (aka, Point P) (T102N, R10W, Sec 28, CDCD)	MN23:X00244	577,254	4,828,111	609 g	Partridge & Camp Stations I, III, & IV (downstream only)
	9 Apr 1988	12:22	Camp Creek Dye Input 23X318 (aka, Point C) (T102N, R10W, Sec 29, BDCC)	MN23:X00318	575,489	4,828,889	632 g	Camp Creek Stations II, III, & IV (downstream only)
6	20 Jun 1988	14:30	Sinkhole 23D5737 (aka, D103) (T102N, R10W, Sec 4, AAA)	MN23:D05737	578,221	4,826,385	620 g	Hart spring
7	15 Apr 1989	10:02	Robbers Bend Sinkhole 23D8732 (aka, D102) (T103N, R10W, Sec 23, DCC)	MN23:D08732	580,694	4,839,495	206 g	(none)
8	15 Oct 1991	8:00	Kulsrud Sink 23B62 (aka, 23D101) (T102N, R10W, Sec 2, CAAA)	MN23:B62	580,564	4,835,276	3 kg	LFH springs
9	17 Jun 1992	11:00	Kulsrud Sink 23B62 (aka, 23D101) (T102N, R10W, Sec 2, CAAA)	MN23:B62	580,564	4,835,276	2.4 kg	LFH springs

[1] From: Gao (2002)

events, or during rapid snowmelt, large amounts of runoff flow across the area in the immediate vicinity of the sinkhole. During such runoff periods, some flow was diverted directly underground via this sinkhole (Solberg, 1987).

The dye was flushed underground with 6430 l of water. Water samples were collected hourly through 22:00 November 21 at LFH Main Spring. Those samples had no trace of dye. The earliest sample collected the next morning was taken at 05:45 by Hatchery personnel. By that time the dye was visible in the spring water. Samples were collected frequently on November 22 and 23, 1986. A few samples were collected daily during the next five days. A limited number of samples were collected at LFH Triple Spring on November 22.

Figure 3 is a log/log plot of the dye concentration versus time. Because no samples were taken through the night of November 21-22, when dye first began to emerge is not known. Its arrival time can only be constrained as greater than 5 hours, 50 minutes but less than 13 hours, 35 minutes. Figure 3 demonstrates that the dye emerged in at least three separate peaks.

The location of D28 and a schematic connection between the sinkhole and the Hatchery springs are shown in Figure 4. The exact underground flowpath(s) taken to reach the springs are unknown; therefore, only a straight-line connection can be shown although the water almost certainly did not flow in a straight line.

Figure 3. Dye Trace #1 log/log breakthrough curve at LFH Main Spring. Log dye concentration is on the vertical axis, and log time is the horizontal axis.

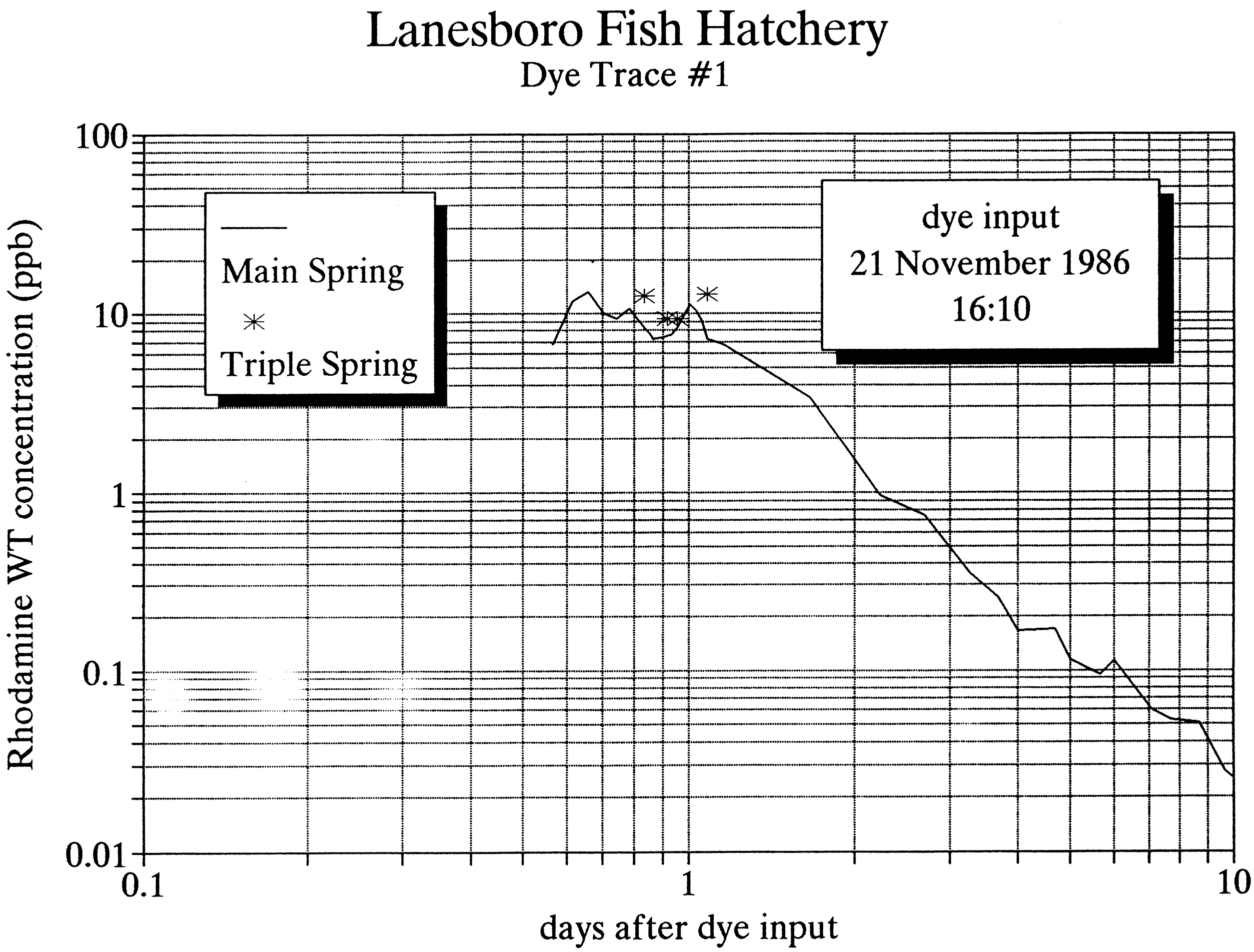
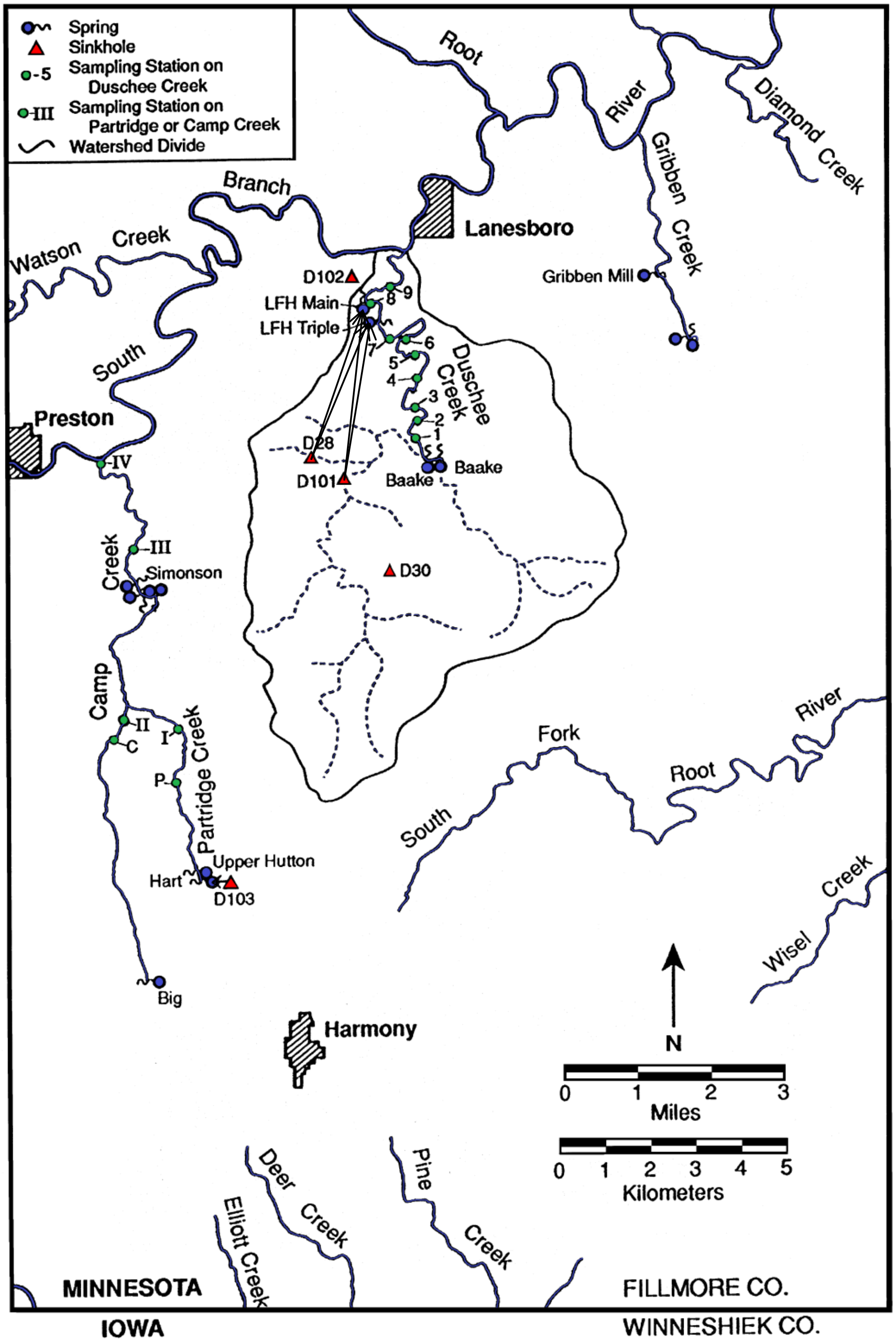


Figure 4. Dye trace map of the Duschee Creek karst basin.



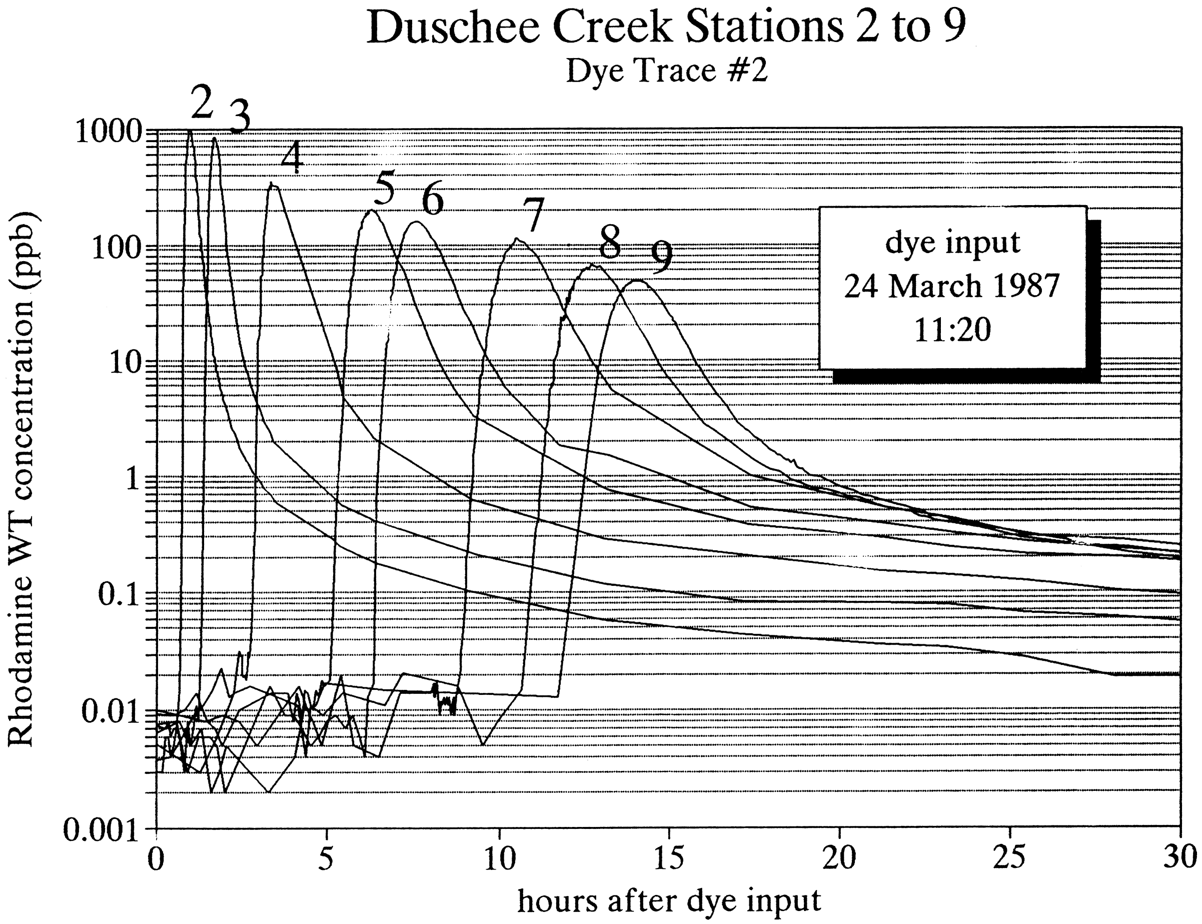
The first trace demonstrated that water entering a sinkhole about 3.4 km southwest of the Hatchery springs reaches the spring in less than 14 hours. The leading edge of the dye travelled at a minimum rate of 5.8 km per day.

The first trace also demonstrated that dye tracing could be used successfully in the Duschee Creek karst basin to establish connections between one or more surface karst features and the Lanesboro Hatchery springs. The first trace also demonstrated that at least one sinkhole in the area could contribute water to the Lanesboro Hatchery springs as a direct run-in component.

Dye Trace #2: The second trace was designed to determine if any of the surface water in the main channel of Duschee Creek sinks and contributes water to the Lanesboro Hatchery springs. Such a connection was suspected because the screens in the Hatchery occasionally trap aquatic animals. The dye was introduced directly into Duschee Creek at Station 1 (Fig. 1). Eight stations downstream, including two below the Hatchery springs, were monitored for dye around the clock for more than a day, until the dye peak passed the last station. The locations of the stream stations are shown in Figure 1, and are labelled 1 through 9. The Hatchery springs were also sampled frequently around the clock for three days, and then sampled once or twice daily for another three weeks.

Figure 5 is a log/linear plot of the breakthrough curves for the dye peak as it passed each station below the input point.

Figure 5. Dye Trace #2 log/linear composite breakthrough curves at Duschee Creek Stations 2 through 9. Log dye concentration is on the vertical axis. Time on the horizontal axis increases to the right.



Each of these curves shows a consistent pattern, including the following elements:

1) an initial time lag during which the fluorescence is at background levels, less than 0.035 ppb (35 ppt);
2) an asymmetric dye peak curve, with an initial sharp rise (rising limb);
3) a narrow peak region, with maximum concentration values consistently declining at stations farther downstream;
4) a relatively rapid decline (in the early part of the recession limb) but that is less rapid than the rising limb;
5) a long, narrow 'tail' (latter part of the recession limb) which extends several times the width of the main peak, before background values are attained; and
6) the curve is generally quite smooth.

These breakthrough curves are characteristic of open channel flow, where there are no significant diverging pathways, and where there is adequate mixing (Kilpatrick and Taylor, 1986).

All samples collected at the Hatchery springs for Dye Trace #2 were negative. If any water sinks in the main channel of Duschee Creek during the discharge conditions (normal or slightly below normal) present during Trace #2, that water apparently does not reach the Lanesboro Hatchery springs. This is an important negative result. It might have proved difficult to protect the water quality along the entire length of Duschee Creek had the trace demonstrated a direct connection to the Hatchery springs.

Dye Trace #3: The third dye trace repeated the November 1986 trace from Sinkhole D28 to LFH Main and LFH Triple Springs. The goals were: to measure the travel time of the leading edge of the dye pulse, to improve the resolution of the breakthrough curves, and to look for connections to local wells.

The dye was washed down with 6430 l of water. Four wells between the sinkhole and the springs were monitored during the trace. No dye was detected in any of the wells. The Hatchery springs were sampled at 5 minute intervals during much of the first two days to obtain high resolution breakthrough curves. The leading edge of the dye peak arrived at the Hatchery about 8-1/2 hours after the dye went into the sinkhole. This corresponds to a minimum velocity of about 9.6 km per day for the leading edge of the dye.

Figures 6 and 7 are log/log and linear versions of the same breakthrough data from LFH Main and LFH Triple Springs. The log/log plot emphasizes the details of the leading and trailing portions of the breakthrough curves while the linear plot emphasizes the structure near the peak of the curves.

The log/log breakthrough curve for Dye Trace #3 (Fig. 6) is similar to that from Dye Trace #1 (Fig. 3). The recession limbs are both quite long, requiring more than one week to return to background levels of fluorescence, and the slopes of the recession limbs are similar. The multiple peak (polymodal) behavior evident in Dye Trace #1 is clearly resolved in Trace #3 (Fig. 7), and the curve has many fine-scale oscillations. Note

Figure 6. Dye Trace #3 log/log composite breakthrough curves at LFH Main and LFH Triple Springs. Log dye concentration is on the vertical axis and log time is the horizontal axis.

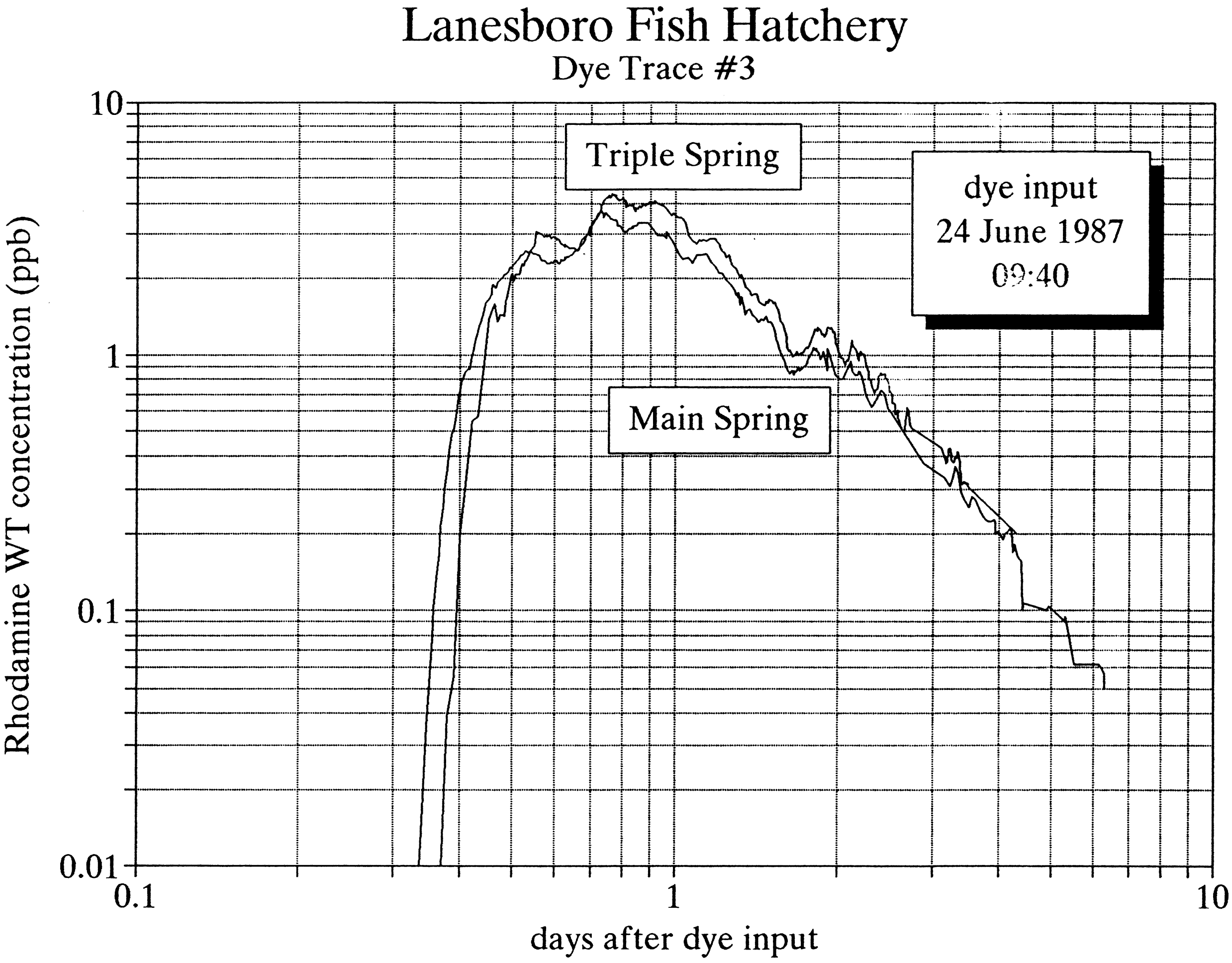
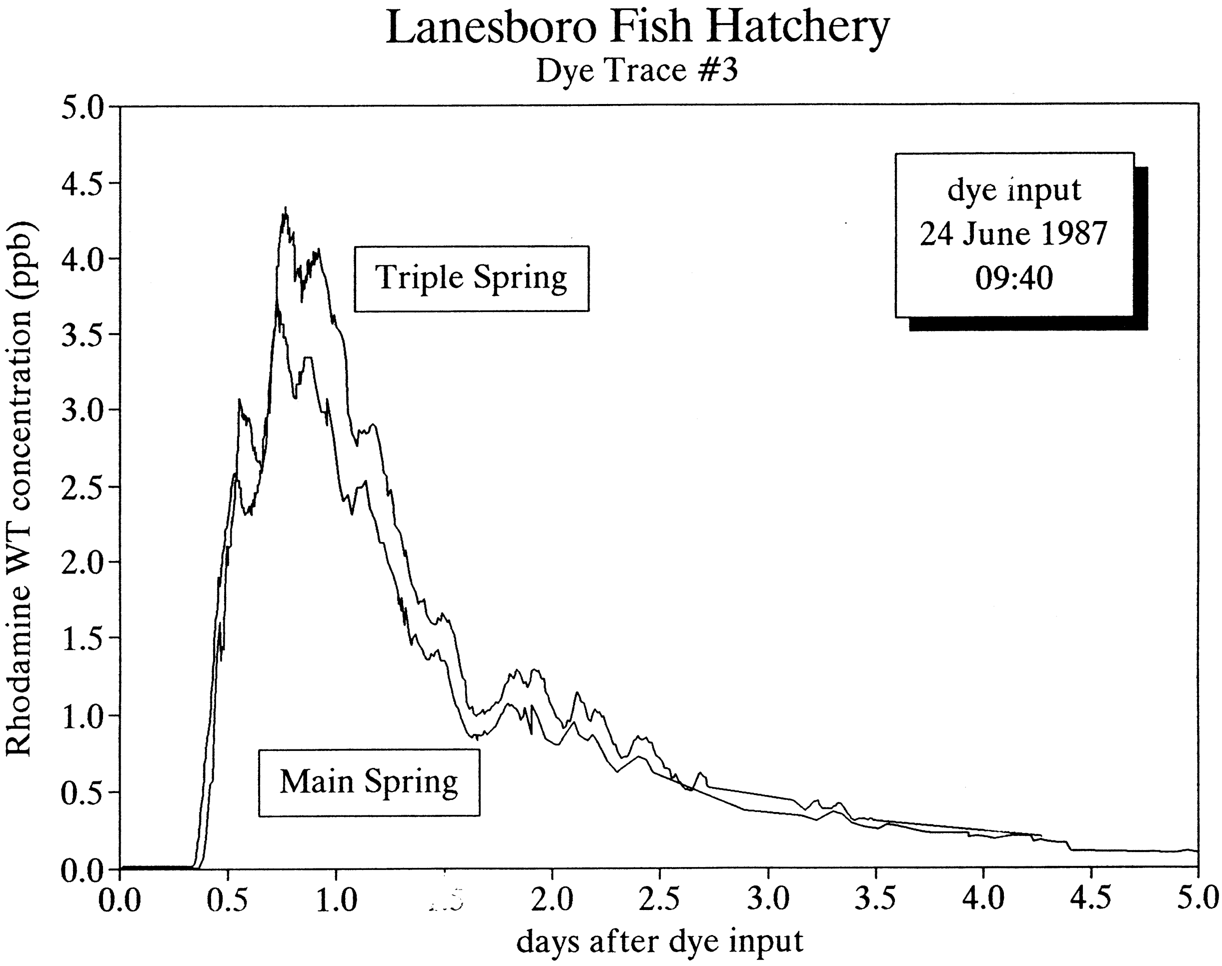


Figure 7. Dye Trace #3 linear composite breakthrough curves at LFH Main and LFH Triple Springs. Dye concentration is on the vertical axis and time on the horizontal axis.



that the fine-scale shapes are very similar in both curves and that many of the fine-scale sturcutres are less than an hour long. Traces #1 and #3 both occurred during similar, baseflow conditions.

The complex, broad, multi-peaked breakthrough curves seen at LFH Main and Triple Springs represent a type of flow which, to the author's knowledge, has not previously been documented in Minnesota aquifers. One explanation of the breakthrough curves is that flow through an anastamosing network of individual channels develops divergent flow routes. The recombination of such flow routes produces flow with multiple dye peaks (Smart, 1988). This type of flow and resulting dye curve are shown diagrammatically by Jones (1984, p. 46). This explanation suggests that the Duschee Creek karst basin is a complex hydrogeologic system that transports water through a number of discrete conduits. Each conduit carries a portion of the dye with a slightly different transit time, and each peak on the breakthrough curve represents a distinct peak arrival time. An alternative explanation, proposed by Green (1991), is that the multiple peaks represent different hydrodynamic conditions along separate conduits. Either of these two hypotheses could explain the phenomena or both mechanisms could act simultaneously and contribute to the complexity of the groundwater system. Either explanation proposes that water flowing to both Hatchery springs must pass through the same complex "black box" because all of the individual peaks are seen in both springs. This common structure must be located early in the flowpath before the routes to the LFH Main and LFH Triple Springs divide.

The peaks in the LFH Triple Spring breakthrough curve range between 10% and 20% higher than the peaks in the LFH Main Spring breakthrough curve. This presumably indicates that dye which emerges at the Main Spring is diluted after the flowpath leading to Triple Spring has split off of the common conduit. Beyond that divergence, an additional source of water is added to the flow which resurges at Main Spring.

Figure 8 is a diagram of one possible model for the flowpaths between Sinkhole D28 and the LFH Main and LFH Triple Springs. In this diagram, the cross-hatched "black boxes" represent branching networks of channels which have neither been seen, nor can be accurately drawn with the available data. However, these networks represent the simple explanation that the multiple peaks in the breakthrough curves result from the convergence of flow from multiple divergent flow routes in conduits. The arrow labelled "recharge zone" represents the addition of water to only the LFH Main Spring, which would account for the additional dilution of dye in the LFH Main Spring, compared to that of LFH Triple Spring.

Figure 9 is a superposition of the LFH Triple Spring data with the Station #8 data from the Duschee Creek trace and contrasts the shape and structure of the breakthrough curves from the two traces. In both traces, the dye moves comparable straight line distances. The single, simple, narrow peak from

Figure 8. A flow diagram connecting Solberg Sinkhole (MN23:D00028, aka, Sinkhole D28) with the Hatchery Springs to illustrate one possible model for the flowpaths between 23D28 and the Hatchery Springs. Diagram also shows the connection between Kulsrud Sink (MN23:B00062, aka, Stream Swallet D101) and the Hatchery Springs, from Dye Traces #8 and #9.

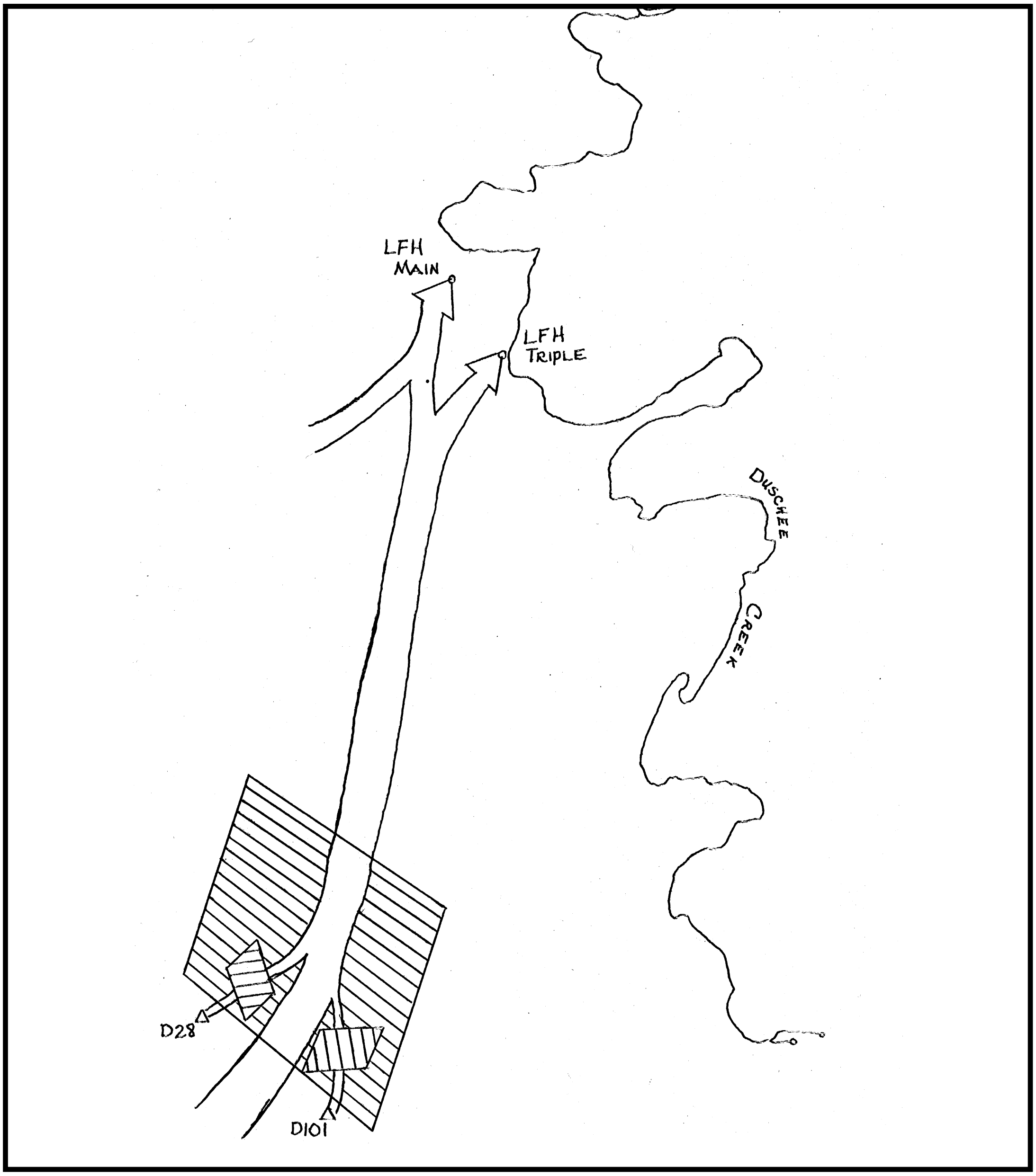
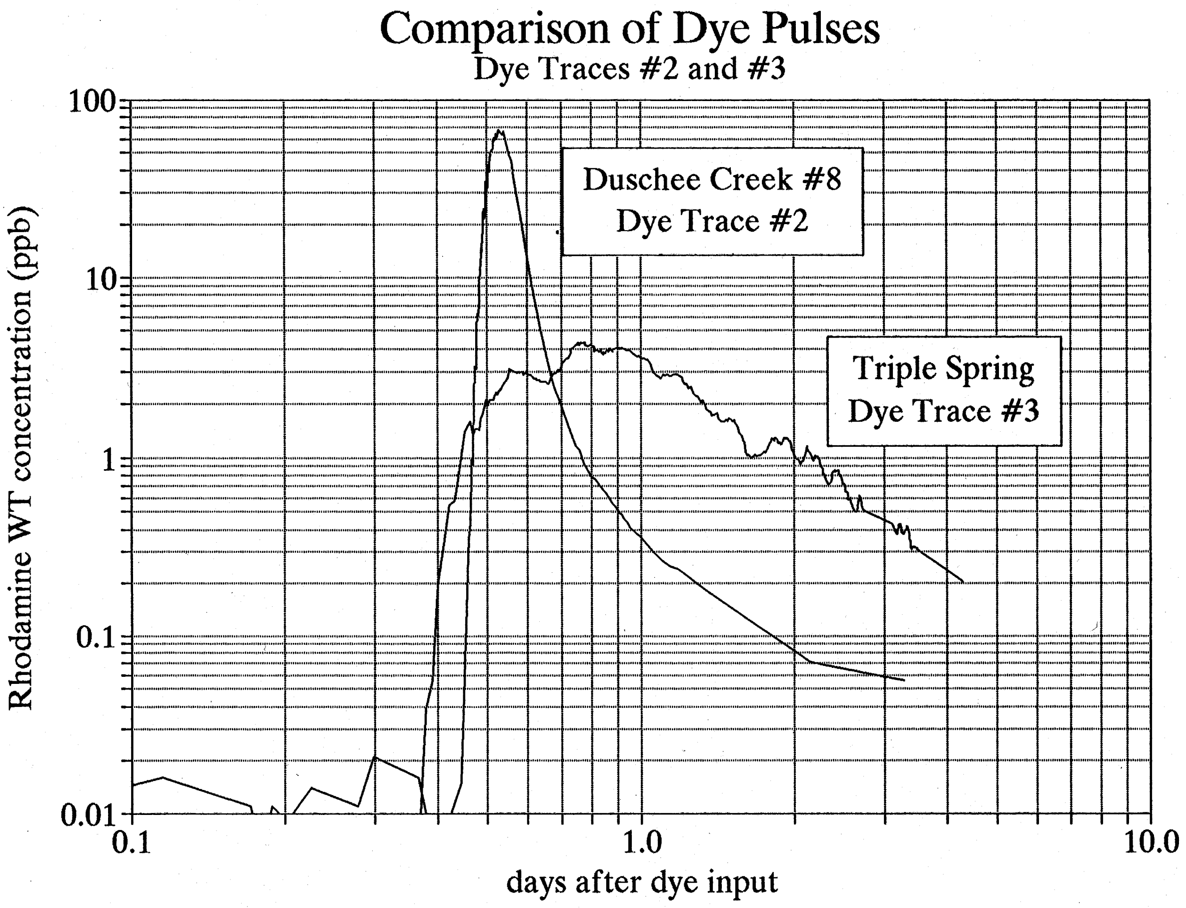


Figure 9. Comparison of breakthrough curves: Duschee Creek Station 8 (Dye Trace #2) with LFH Triple Spring data (Dye Trace #3).



the Duschee Creek trace was produced by mixing and dispersion in an open channel stream. This type of breakthrough curve is characteristic of groundwater flow in simple karst channels in the Galena Group rocks in Fillmore County (Mohring, 1983; Mohring and Alexander, 1986). The broader, more complex curve from Trace #3 records a more complicated underground flow system.

Dye Trace #4: The fourth trace was from a dry sinkhole, D30, which is located 5.9 km south of the Hatchery (see Fig. 1). This is another relatively large Prairie du Chien sinkhole within the Duschee Creek surface watershed. It is also quite close to State Highway 19, and located along an ephemeral waterway near a field. The location of this sinkhole makes it relatively vunerable to surface runoff, and perhaps to an accidental spill.

The dye was washed into the sinkhole with 6430 l of water. Daily samples were collected at the Hatchery springs from October 1987 through July 1988. No dye was ever detected. Negative dye trace results are always ambiguous. Dry weather from late summer, 1987 through mid-summer, 1988 may have prevented the dye from reaching the groundwater system. It is also possible that there is no direct connection between that particular sinkhole and the springs.

Dye Trace #5: The fifth trace was another stream trace using a double trace technique by putting Rhodamine WT into two different tributaries of the same stream system. Partridge Creek and Camp Creek are the two creeks immediately west of the Duschee Creek surface watershed (Fig. 1). Partridge Creek flows year-round below Hart Spring, over a distance of about 9.2 km, where it joins Camp Creek. Camp Creek is intermittent in its upper reach, but is a permanent stream below Big Spring. It flows a distance of about 16.2 km, where it joins the South Branch of the Root River. This trace had three objectives. Objective 1 was to determine, if possible, whether either stream had a losing reach. Objective 2 was to determine, assuming one or both streams were losing, whether the lost river water crosses under the western boundary of the Duschee Creek surface watershed and travels to the Hatchery springs. Source(s) of the surface water aquatic organisms which occasionally reach the Hatchery were sought. Therefore, the Hatchery springs were monitored as well as stations along the creeks. The third objective was to confirm the shape of the breakthrough curves for open stream channel flow on two additional creeks, and to investigate how those curves are modified when two dye peaks are superimposed.

Samples were collected along the creek at points which were easily accessible. Station I was at a County Highway 16 bridge on Partridge Creek approximately 1.3 km above the confluence with Camp Creek. Station II was at a County Highway 22 bridge on Camp Creek approximately 0.4 km above the confluence with Partridge Creek. Stations III and IV were at bridges on Camp Creek, about 5.4 km and 8.9 km respectively, downstream of the confluence. The Lanesboro Hatchery springs and several other small springs in the Camp Creek area were monitored for several days.

Discharges were measured by Wilton (1988) at each creek station during this dye trace, and are shown is Table 3. These data show that Partridge Creek has a losing reach between Station I and the confluence with Camp Creek. All samples collected at the Lanesboro Hatchery springs were negative. Dye was not detected at any of the other small springs in the area. Where the water that is lost in Partridge Creek resurges is not known.

The results of Dye Trace #5 are shown in Figures 10-14. Figure 10 is a log/linear plot, and Figure 11 is a linear plot, of the breakthrough curve from Station I on Partridge Creek. Both curves are included to contrast their shapes. The small oscillations far down on the recession limb in Figure 10 are not visible in the linear plot. These oscillations may be an artifact of unsteady flow within the mixing zone, or a result from sampling in different zones of the stream, perhaps where back eddies or slowflow zones exist near the streambank. Figure 12 plots the breakthrough curve at Station II, Figure 13 is from Station III, and Figure 14 is from Station IV, on Camp Creek.

The breakthrough curves show that the same basic curve shape and components occur in this trace as in the Duschee Creek trace, particularly as exemplified in Figures 10-12 from Stations I and II. At those stations, a single peak passed by the station, so a single narrow peak is recorded. Again, the components of open-channel flow with adequate mixing and diffusion are repeated.

The curves which represent the dye peaks at stations below

Table 3. Discharge data for Camp and Partridge Creeks, April 9, 1988 at the dye trace sampling stations (from Wilton, 1988).

Station on Camp or Partridge Creek	KFD Number[1]	UTMs (NAD 83, Zone 15)		Location (township, range, section, quarters)	Number of Replicates	Mean Discharge (m^3/s)	Standard Deviation (m^3/s)
		Easting	Northing				
Partridge Creek Dye Input 23X244 (aka, Point P)	MN23:X00244	577,254	4,828,111	102N, 10W, 28, CDCD	2	0.065	0.001
Partridge Creek Station I Bug Set (aka, Station I)	MN23:X00323	577,288	4,829,684	102N, 10W, 28, BAAB	2	0.047	0.005
Camp Creek Station II Bug Set (aka, Station II)	MN23:X00322	575,942	4,829,853	102N, 10W, 20, DCCB	2	0.158	0.013
Partridge Creek Station III Bug Set (aka, Station III)	MN23:X00321	576,185	4,833,689	102N, 10W, 8, ACDD	2	0.432	0.015
Partridge Creek Station IV Bug Set (aka, Station IV)	MN23:X00320	575,429	4,835,655	102N, 10W, 5, BDBB	2	0.551	0.068

[1] From: Gao (2002)

Figure 10. Dye Trace #5 log/linear breakthrough curve at Station I on Partridge Creek.

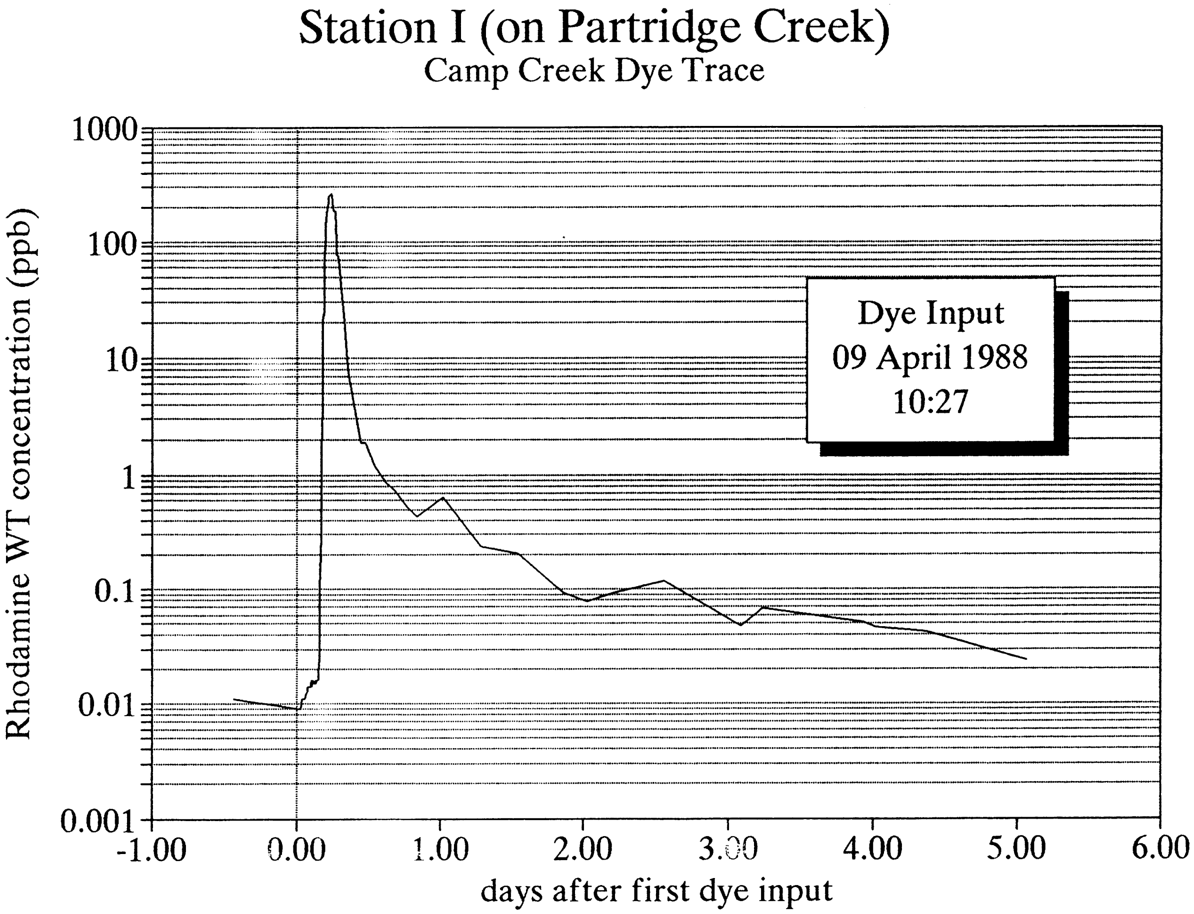


Figure 11. Dye Trace #5 linear breakthrough curve at Station I on Partridge Creek.

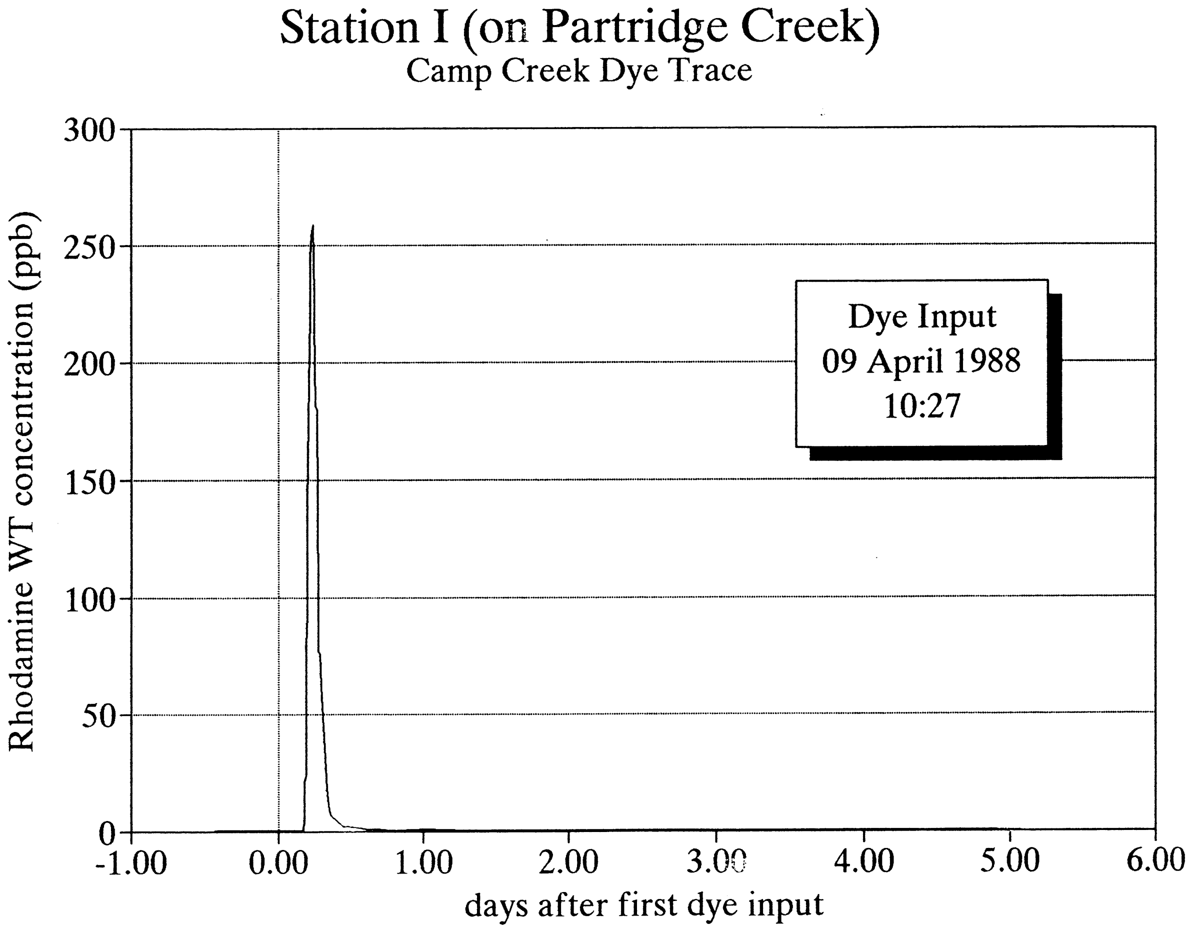


Figure 12. Dye Trace #5 log/linear breakthrough curve at Station II on Camp Creek.

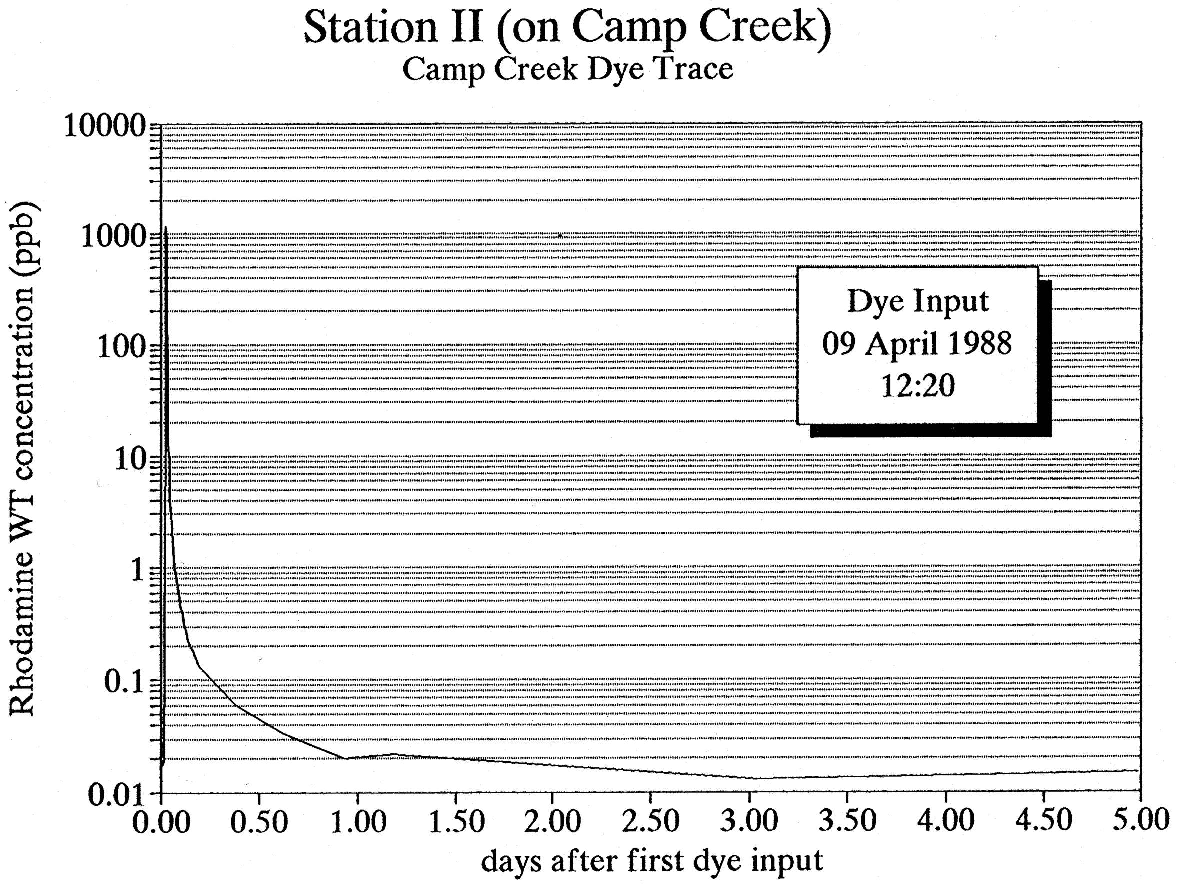


Figure 13. Dye Trace #5 log/linear breakthrough curve at Station III on Camp Creek.

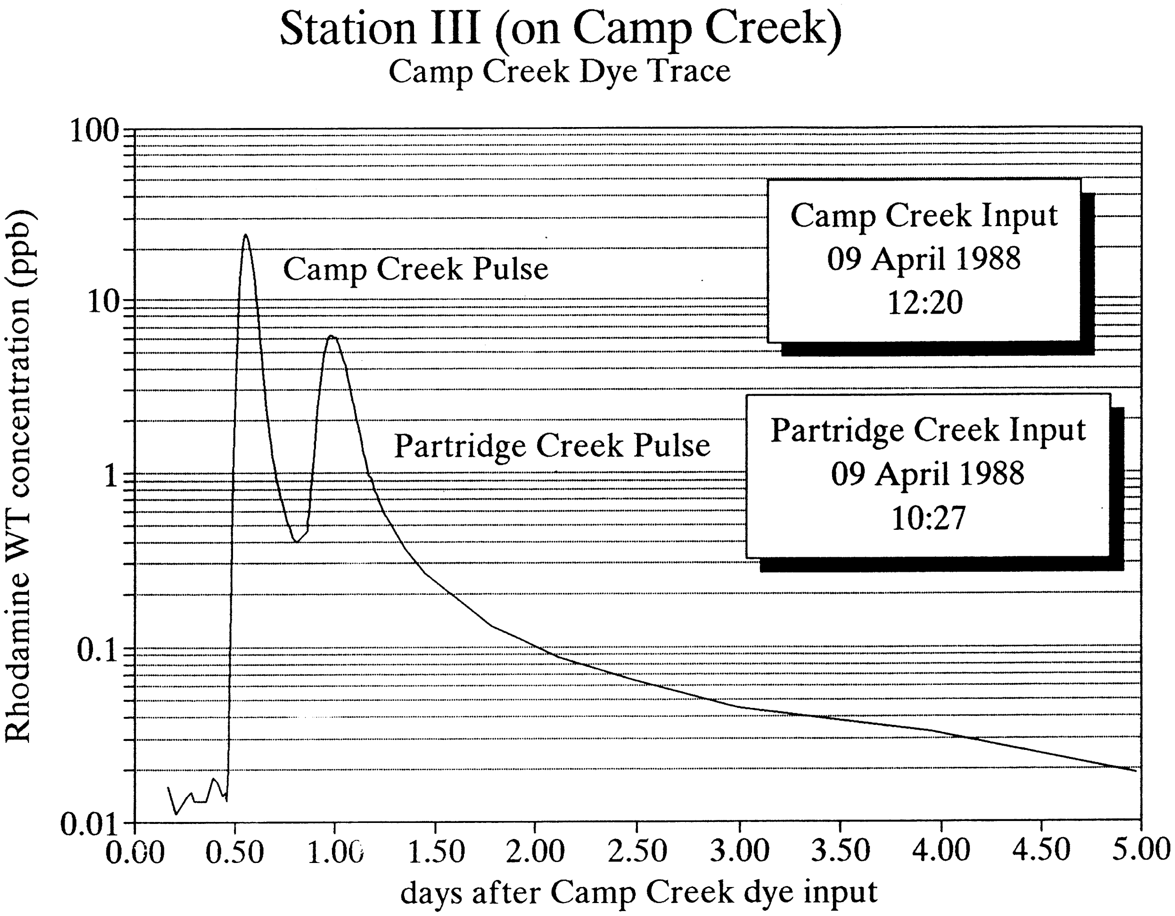
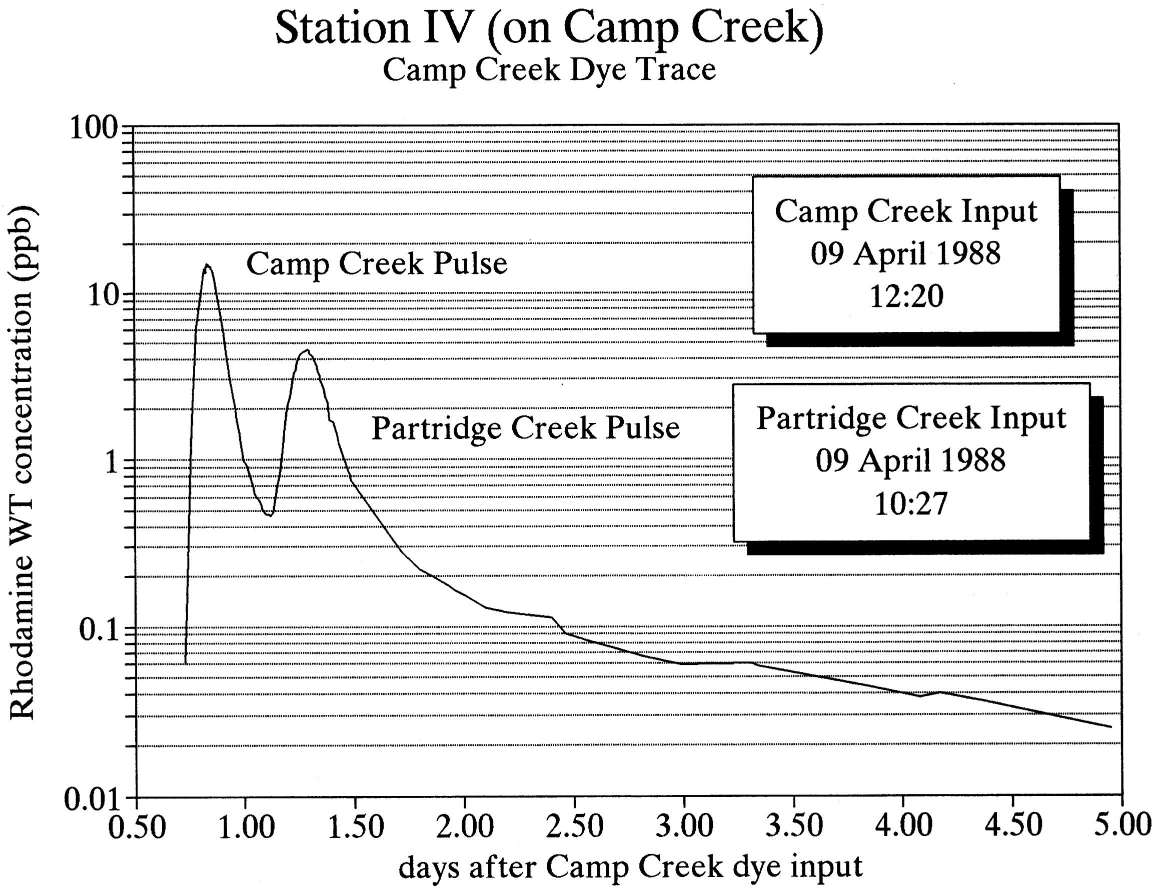


Figure 14. Dye Trace #5 log/linear breakthrough curve at Station IV on Camp Creek.



the confluence each have a double-peaked shape, showing the additive effect of two separate dye peaks passing that station with different arrival times. (Note that the Camp Creek pulse arrives ahead of the Partridge Creek pulse because the dye input site on Camp Creek was much closer to the confluence than was the input site on Partridge Creek.)

Kilpatrick and Taylor (1986) describe this multipeaked, additive effect in open-channel flow as superposition of multiple pulses. Jones (1984) shows that very similar patterns can also result in karst groundwater tracing from the additive effects of an anastomozing network, but in this case an anastomozing network was not present.

Dye Trace #6: The sixth dye trace was conducted from a sinkhole, D103, on the ridgetop north of Harmony. The sinkhole chosen was located approximately 0.3 km east of Hart Spring on Partridge Creek. The dry sinkhole is shown on the 1965 Harmony Quadrangle (7-1/2 minute series). Several substantial trees occupy the sinkhole. It is located on the southwest side of the ridgetop north of Harmony; stratigraphically it occurs on the Galena Limestone. It is only one of hundreds of sinkholes on this ridgetop. The anecdotal information about the correlation of turbid water at the Lanesboro Hatchery springs with rainfall in the Harmony area was the impetus for this dye trace.

Hart Spring and Upper Hutton Spring are two of several springs in the upper part of the Partridge Creek stream valley.

According to Hutton (1988) Partridge Creek flows year-round below Hart Spring, although the topographic map shows it as intermittent. Above Hart Spring, Partridge Creek is ephemeral. Hart Spring and Upper Hutton Spring are less than 0.3 km apart. Hart Spring is at approximately 347 m (1140 feet) elevation; Upper Hutton Spring is close to 344 m (1130 feet).

The dye was washed into the sinkhole with more than 5000 l of water. Hart, Upper Hutton, and LFH Main Springs were sampled around the clock for over four days after the dye was poured. LFH Main Spring was sampled two to three times daily until July 11, 1988, twenty-one days after the dye was poured. Upper Hutton was sampled a final time on July 11. No dye was ever detected at Upper Hutton Spring, nor at the Lanesboro Hatchery springs. Dye began emerging at Hart Spring approximately 7-1/2 hours after injection. Hart was sampled again on July 10 and 11, when a very low residual fluorescence was detected.

Figure 15 is a log/linear breakthrough curve of the dye at Hart Spring. Figure 16 is a linear plot of the same data which more clearly illustrates the multipeaked character of the curve, and resolves the fine-scale oscillations. Similar to the Trace #3 curves from the Hatchery springs, the few sharp peaks in the linear plot take on a broader convex shape with subdued oscillations in the log/linear plot.

The results from the sixth dye trace indicate that at least one sinkhole on the ridgetop north of Harmony is directly

Figure 15. Dye Trace #6 log/linear breakthrough curve at Hart Spring.

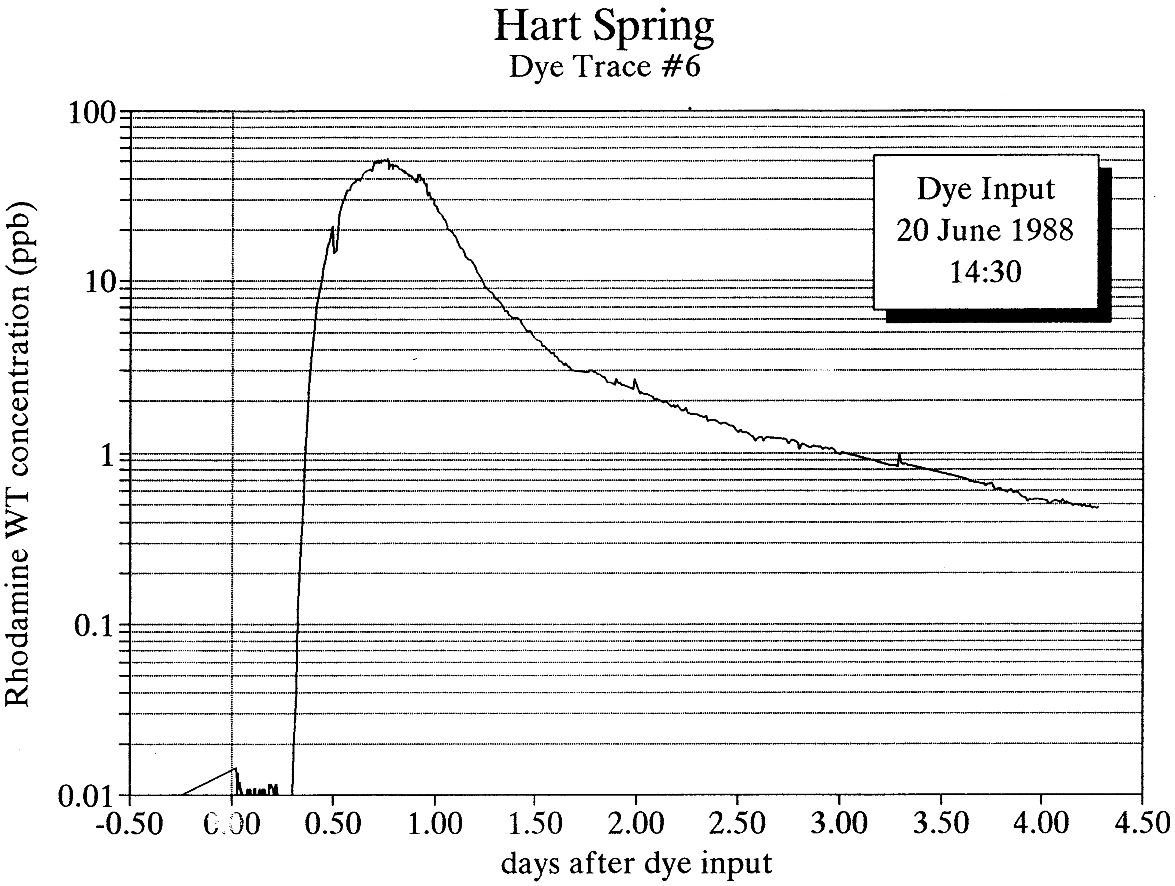
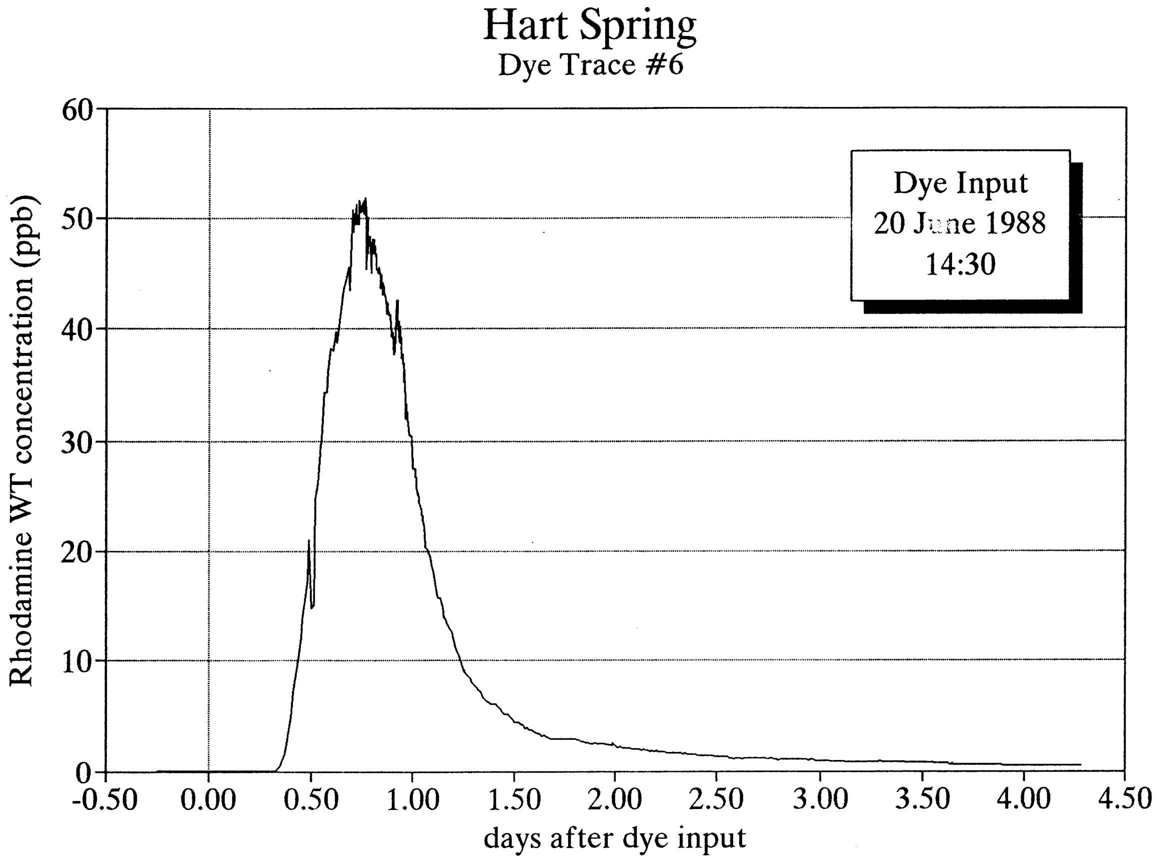


Figure 16. Dye Trace #6 linear breakthrough curve at Hart Spring.



connected with Hart Spring on Partridge Creek; however, it does not appear to be connected with Upper Hutton Spring. These results were somewhat surprising, because the two springs are so close spatially, both horizontally and vertically. Also, this sinkhole does not appear to be directly connected with the Hatchery springs.

The breakthrough of the leading edge of the dye peak translates to a velocity of just under 1 km per day. This is a significantly lower leading edge velocity than the velocity of the dye in both November, 1986 and June, 1987 from Sinkhole D28 to the Hatchery springs. Much of the Midwest, including southeastern Minnesota, had undergone a very dry period of weather from late summer, 1987 through mid-summer, 1988. The slower leading edge velocity in this trace might be related to significally reduced recharge, resulting in a lower underground water table, and a concomitant reduced water table gradient. An alternative explanation is that the hydrological connections between this sinkhole and Hart Spring are not as well developed as those between Sinkhole D28 and the Hatchery springs. If so, flow would be primarily through much narrower and less integrated fractures, resulting in a reduced flow velocity.

These results suggest that each of the hundreds of sinkholes on the Galena Limestone probably has its own unique but direct hydrological connections to an underground plumbing system. Each particular plumbing configuration determines connections to surface water. Such connections may also show variability under differing (high vs. low) flow conditions.

Dye Trace #7: The seventh dye trace was conducted from a sinkhole along a gravel road southwest of Lanesboro. This sinkhole, numbered D102, is located northwest of the Lanesboro Hatchery. This was done to determine if water moves southward in the groundwater basin to the Hatchery springs.

The dye was washed into the sinkhole with 6800 l of water. A continuous analog stage recorder was operating on the LFH Main Spring during this trace. A small but distinct peak was recorded in the stage record when the dye and water were flushed into D102. Samples were collected at the Lanesboro Hatchery springs, the Melvin Hall Spring Pond (east of the sinkhole), and at the springs in Sylvan Pond, (a pond in the city park in Lanesboro). Also two sites on Duschee Creek were sampled. One of the sites on Duschee Creek (Station 7 from Dye Trace #2) is upstream of the input from the Hatchery springs; the other site (Station 9 from Dye Trace #2) is downstream from the Hatchery springs input.

No dye was detected at any of the springs that were sampled nor from the sites on Duschee Creek. However, a pressure connection apparently exists between D102 and LFH Main Spring.

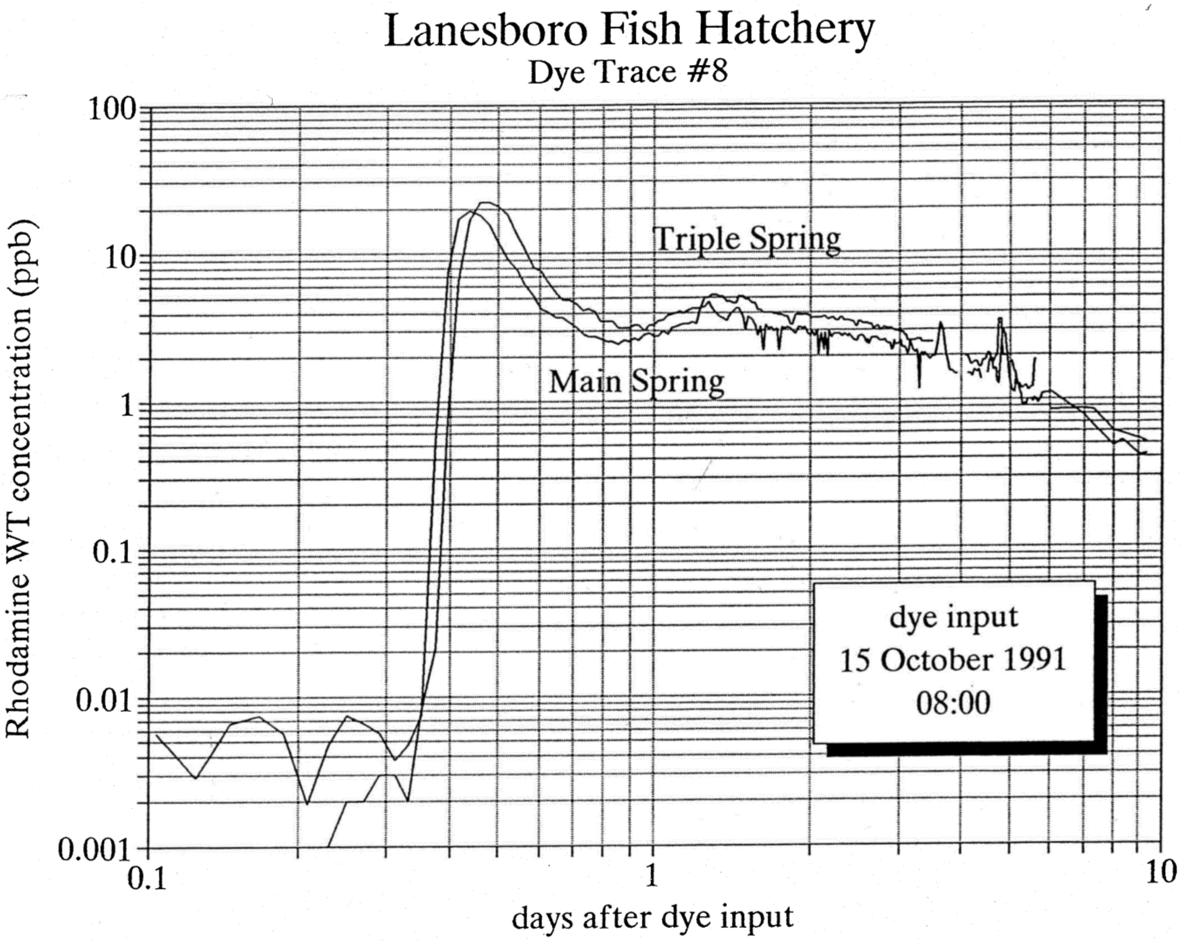
Dye Trace #8: The eighth trace was from Stream Swallet D101 along an intermittent branch of Duschee Creek (Green, 1991). It is about 0.5 km east of Sinkhole D28 and is developed in the Prairie du Chien Group. The drainage area to the stream swallet covers approximately 23 km^2 (9 $mi.^2$). The proximity of D28 and D101 suggests the possibility that water from D101 flows to the Hatchery springs through much of the same flow path as does water from D28.

The permanent Duschee Creek tributary below Springs A373 and A381 was flowing in October, 1991, but the intermittent stream was not flowing. Minnows (possibly brook sticklebacks) were observed in the permanent reach of the stream (Green, 1993). It was hypothesized that if a positive connection could be demonstrated between Stream Swallet D101 and the Hatchery springs, then the occasional appearance of wild aquatic organisms at the Hatchery springs could be explained. The minnows permanently live in this upper reach. During wet seasons when Duschee Creek flows down to D101, the minnows are sometimes washed downstream, then underground into D101, and finally emerge at the Hatchery springs.

The dye was flushed into the sinkhole with 7200 l of water. This trace was conducted under baseflow conditions. Samples were collected for several days at four sites: LFH Main and LFH Triple Springs, Gribben Mill Spring, and Bakke Springs (Green, 1991).

Dye was detected at the two Hatchery springs, but not at either the Gribben Mill Spring nor at Bakke Springs. Figure 17 shows the breakthrough curve for the dye to LFH Main and LFH Triple Springs. The leading edge of the dye peak occurred approximately 8-1/2 hours after dye injection. This translates to a leading edge velocity of about 10.4 km per day (cf. 9.8 km

Figure 17. Dye Trace #8 log/log composite breakthrough curves at LFH Main and LFH Triple Springs.



per day, from Sinkhole D28 in Dye Trace #3).

The breakthrough curve for Dye Trace #8 displays both similarities and differences from the curves of Dye Traces #1 and #3. Trace #8 has multiple peaks (polymodal) and fine-scale oscillations, the curves for the LFH Main and LFH Triple Springs are very similar, the dye in Triple Spring is more concentrated than that of Main Spring, and the dye arrived at Main Spring first. However, the leading edge of Trace #8 has a more pronounced initial peak, a much higher maximum concentration, and the recession limb is longer; nearly two weeks were required to return to background levels of fluorescence. This timeframe correlates well with the observations of the Hatchery personnel. They have noted that after heavy rains, the Hatchery springs remain turbid for up to two weeks. In addition, the watershed which can contribute surface flow to D101 extends about 7.2 km (4-1/2 mi.) south toward Harmony. This explains why Hatchery personnel have observed turbid water in the Hatchery springs after heavy rains in the Harmony, but not Lanesboro, area.

Dye Trace #9: The ninth trace was a repeat trace from stream swallet D101. This trace was conducted under wet conditions. Approximately 50 mm of rain fell during the previous 48 hours. Green (1993) estimated the stream to be flowing at about 0.021 m^3/s (0.75 cfs). The swallet was taking all of the upstream runoff when the dye was injected; no water was flowing below the swallet (Green, 1993). Apparently D101 can take much more water when the creek is flowing higher upstream. On one occasion, Stork (1993) estimated the creek flowing at between 0.14 and 0.57 m^3/s (5 to 20 cfs), and it completely disappeared underground at D101. This observation is borne out by the morphology of the streambed. Just below D101, the channel elevation is between 0.30 and 0.46 m (1 to 1-1/2 ft.) higher than the elevation just upstream of D101; thus, the creek would have to flow deeper than that to overtop the swallet (Green, 1993).

Samples were collected from LFH Main and Triple Springs, the Melvin Hall Pond Spring, and Baake Springs. No dye was detected from either the Melvin Hall Pond Spring or the Baake Springs. The leading edge of the dye arrived at the Hatchery at about 9-1/4 hours after dye input.

Figure 18 is a log/log plot of the breakthrough curves for LFH Main and LFH Triple Springs. The break in the Triple Spring curve indicates the termination of 30-minute sampling, and the beginning of 2- or 3-times per day sampling. Several characteristics are similar to previous curves; for instance, dye emerges first at Main Spring, the two curves are very similar in shape, the dye in Triple Spring is more concentrated than in Main Spring, and there are some small-scale oscillations.

Figure 19 shows a comparison of the breakthrough curves from Dye Traces #3, #8, and #9 at LFH Main Spring on a log/log graph. The curves have a few similarities but many more differences. The leading edge on each trace is fairly close in time, occurring between 8-1/2 and 9-1/4 hours after dye input. All three curves

Figure 18. Dye Trace #9 log/log composite breakthrough curves at LFH Main and LFH Triple Springs.

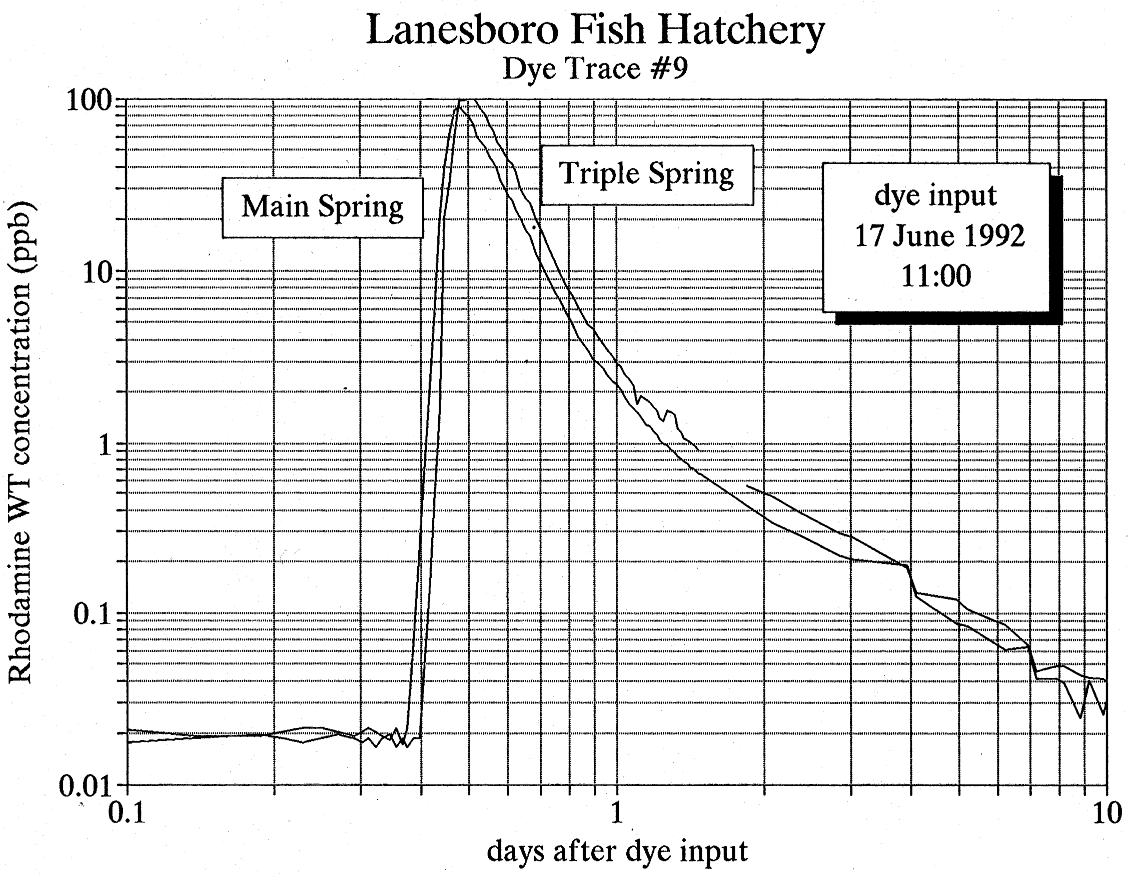
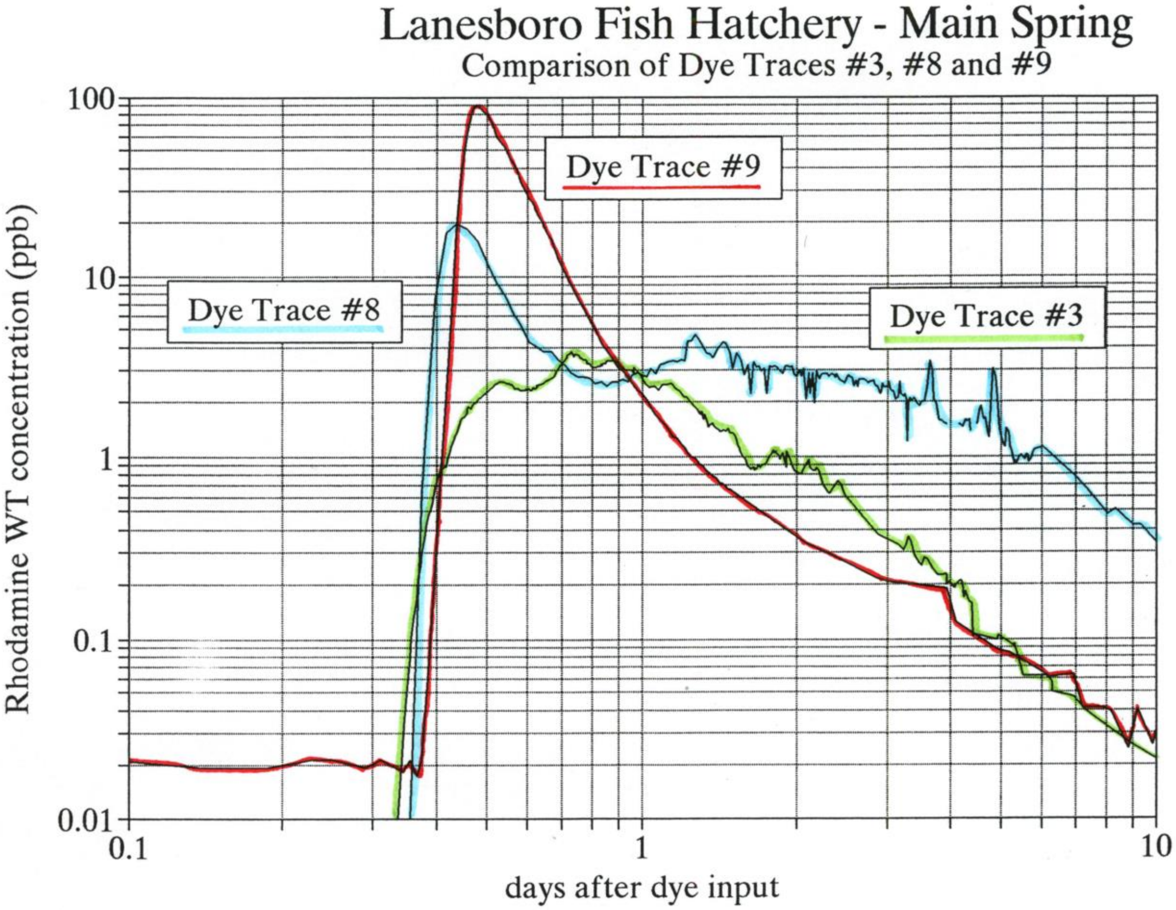


Figure 19. Comparison of breakthrough curves of Dye Traces #3, #8 and #9 at LFH Main Spring.



have at least a few small scale oscillations at concentrations well above background levels. The rising limb on all three traces is nearly vertical and generally smooth over most of its length. However, the rising limb of Trace #3 is slightly less steep than those of the other two, and subsequently the curve begins a pattern of fluctuations without producing a definite initial peak. Traces #8 and #9 each have a very pronounced initial peak. The maximum concentration of Trace #3 is less than 4 ppb, that of Trace #8 is nearly 20 ppb, and that of Trace #9 is nearly 90 ppb; however, the traces were run with roughly similar dye masses (between 2.4 and 3 kg). Trace #9 has a smooth overall shape, with the small scale oscillations appearing only far down the recession limb. Trace #8 is similarly smooth over the initial peak and for a short distance down the recession limb, beyond which it shows small scale fluctuations. The curves of Traces #8 and #9 have a definite concavity in shape in their recession limbs, while the Trace #3 curve does not.

The differences in these three curves is thought to reflect dye traveling through different structures, combined with changing hydrostatic conditions during the recessions in the curves. The Trace #3 curve is quite different from the other two, as would be expected because it reflects the trace from Sinkhole D28, while the other curves both reflect traces from Stream Swallet D101. The anastomozing network is envisioned to be made up of small conduits existing at the relatively lowest stratigraphic position, and during baseflow conditions is not entirely filled with water. The flowpaths to the Hatchery springs from D28 and from D101 encounter different portions of this network. The network along these two flowpaths could either be one large system or in small disjunct pieces (see Fig. 8). Also, the leading edge of dye arrives first in Trace #3; this could be explained if the shortest flowpath length through the network from Sinkhole D28 is less than the flowpaths followed in Traces #8 and #9 from D101.

The curve from Dye Trace #1 (Fig. 3), which also traced from D28, appears to be significantly different from those of #8 and #9 but similar to that from #3. Although the leading edge was missed in curve #1, the convex shape of the apparent peak area and recession limb is quite similar to that of curve #3. Also, the small-scale oscillations are of approximately the same magnitude in the two curves. These comparisons substantiate the postulated difference between the flowpaths from D28 and D101.

The shapes of the Trace #8 and #9 curves were interpreted to result from water traveling through different conduits at disparate elevations under changing hydrologic conditions. The author envisioned that there are two vertically stacked overflow conduits; in turn, the conduits exist stratigraphically higher than the anastomozing network. The overflow conduits are large, master conduits, which are dry during baseflow conditions. Under increasing flow, water completely fills the network first, rises into the first overflow conduit, continues to rise and eventually fills that conduit, and finally rises into the upper conduit.

Water in the master conduits is carried along what might effectively be a single pathway, entering the conduits on the upstream end and passing through to the downstream end, similar to the description of 'in-line' storage described by Smart (1988). The conduits of the anastomozing network were interpreted to be individually much smaller than the overflow conduits, but they may have a much larger cumulative capacity.

The early parts of curves #8 and #9, including the rising limbs, the initial peaks, and the first parts of the recession limbs, appear quite similar to the open-channel flow curves from Traces #2 and #5. The author proposes that these parts of the curves reflect the dye traveling through the overflow conduits. Dye in Trace #8 only flowed through the lower overflow conduit, but dye flowed through both conduits in Trace #9.

Hydrostatic pressure in the overflow conduits might impede flow through the lower anastomozing network. The dye, poured into the system from the top, initially only mixes with the water in the overflow conduits and is thereby diluted relatively less. At the Hatchery springs, the higher maximum concentrations are produced while the dyed water is draining from only the overflow conduits. After the master conduits are drained, the tail of the dye slug travels through and mixes with water in the lower anastomozing network; this water subsequently emerges at the springs. This process could explain the delay before the oscillations in the curves begin.

Hydrostatic pressure in the upper overflow conduit may also impede flow through the lower conduit, so that only one peak in Trace #9 is produced. The upper conduit drains first, then the lower conduit drains, and finally the network begins to drain. This sequential draining allows the tail of the dye at each level to become diluted with successively greater amounts of water, and the gradual release of hydrostatic pressure produces the mostly smooth recession curve shown from Trace #9. Note that the recession limb of Trace #9 drops lower than those of #3 and #8. This results from the much increased dilution of the tail of the dye by the water from the completely filled lower conduit and the anastomozing network. Also, the morphology of the upper master conduit may result in a longer flowpath length than that of the lower conduit, thereby explaining the slight delay of the dye leading edge in Trace #9.

Trace #8 was run under baseflow conditions. Apparently the water from the fire truck quickly overtopped the anastomozing network, sending an early pulse of dyed water through the lower overflow conduit. This could reflect a very low water capacity in the network. However, these results more likely occurred from exceeding the rate at which the network could accept the water into its conduit system from the fire truck in the vicinity of D101. Downgradient from D101, more of the water probably entered the network so the tail of the dye pulse traveled through the network. This is much less diluted than the tail of the pulse in Trace #9 because the downgradient portion of the network was not water-filled. The Trace #8 curve is thus the superposition of the dye pulses from two different conduit morphologies; compare this curve to the two curves in Figure 9. The author speculates that the volume of dyed water in the upper conduit during Trace #9 must have been less than 7200 liters because the peak of curve #9 is higher than that of #8.

The different portions of the anastomozing network would undoubtedly have different configurations and water capacities. This explains why the fine-scale oscillations during network drainage do not match in traces through different parts of the network (cf. Trace #3 and #8). If it can be assumed that baseflow conditions during Traces #3 and #8 were similar, then the fact that the dye from Sinkhole D28 is relatively more diluted suggests that the portion of the network traversed from D28 has a greater water capacity than the part of the network traversed from D101.

ANALYSES

Generalized Water Budget of the Lanesboro Hatchery and Duschee Creek

The flow measurements summarized in Table 4 allow the comparison of the discharge from the Hatchery springs to the total water budget of the Duschee Creek basin. First, assume that the water flowing into the Hatchery from the springs equals the outflow. The Hatchery is a small temporary reservoir and evaporatranspiration losses are probably negligible. Second, assume that the difference in the discharges at Stations 7 and 9 on Duschee Creek equals the discharge of the two Hatchery springs. There are no other known water source(s) to Duschee Creek in that reach. The data compiled in Table 4 is from the information supplied by Troelstrup (1987a), Perry and others (1988), and Huber (1989), and from the discharge measurements by Wheeler and Alexander (1989).

Some of the data are apparently more representative of long-term averages than other data. For instance, the decade-long average for the Hatchery springs and the quarterly mean values computed from 35 results during 1986-87 are certainly more representative of average conditions at those times than are the one-day results in March, 1987 and April, 1989. On the other hand, the latter results were obtained during or very near the times of the dye traces. Also, Huber (1989) said that some long-term drop in the discharge of the Hatchery springs has been postulated; however, the drop between the 1970s average and the

Table 4. Summary discharge data for the Lanesboro Hatchery Springs and the lower Duschee Creek.

Date	Duschee Creek Site	Duschee Creek Discharge (m^3/s)	Hatchery Springs Discharge (m3/s)	Comments
1970s			0.309	decade average
Fall, 1986	lower Duschee Creek	0.370 ± 0.075	(not available)	mean of 14 results
Winter, 1987	lower Duschee Creek	0.468 ± 0.184	(not available)	mean of 2 results
Spring, 1987	lower Duschee Creek	0.303 ± 0.098	(not available)	mean of 16 results
Summer, 1987	lower Duschee Creek	0.402 ± 0.195	(not available)	mean of 3 results
24 Mar 1987	Station 7	0.325 ± 0.016	0.304	Hatchery discharge calculated by subtraction
24 Mar 1987	Station 9	0.629 ± 0.010		
25 Mar 1987	Station 7	0.354 ± 0.016	0.276	Hatchery discharge calculated by subtraction
25 Mar 1987	Station 9	0.630		
Oct 1988	(not available)	(not available)	0.300	
16 Apr 1989	Station 7	0.123	0.240	Hatchery discharge calculated by subtraction
16 Apr 1989	Station 9	0.363		

October, 1988 data which he quoted is only 3%.

The values in April, 1989 appear to be significantly lower than the others. These may be too low because of the author's lack of experience in making discharge measurements. Therefore, these values were assumed to be outliers and were not used in further calculations.

The two March, 1987 results were only one day apart; if these values were unusually high due to spring runoff or weather conditions, it would be better to use only their average because using both values gives them too much weight with so limited data.

With these caveats, the discharges are calculated, and the results are as follows:

$$Q_H = 0.300\ m^3/s; \quad Q_{DC} = 0.348\ m^3/s.$$

The Root River watershed hydrologic atlas (Broussard and others, 1975) shows a water budget. Based on average annual stream-gaging records for the years from 1940 through 1969, the average annual runoff in the Duschee Creek area is approximately 183 mm (7.2 inches), which is also the average runoff generalized over the entire Root River watershed. The "runoff" in this calculation includes both surface runoff and spring and groundwater contributions to surface stream flow. To calculate the area which contributes runoff to Duschee Creek and Hatchery springs the following relationship can be used:

$$\text{Area} = \text{Discharge} \times \text{Time} / \text{Annual Runoff}.$$

The symbols are defined as follows:

A_H = area contributing water to the Hatchery springs from precipitation

A_{DC} = area contributing water to Duschee Creek (above the Hatchery) from precipitation

Accounting for the unit conversions, the results are:

$A_H = 51.7\ km^2 = 20.0\ mi^2$ and

$A_{DC} = 60.0\ km^2 = 23.2\ mi^2$.

About twice as much water actually flows from the mouth of Duschee Creek as theoretically runs off, via both surface and subsurface routes, from the surface watershed. All of the discharge of Duschee Creek above the Hatchery springs could be accounted for within its 59-km^2 (22-3/4 square mile) surface watershed assuming no significant gains or losses across the watershed boundary. However, the area contributing water to the Hatchery springs would then have to be almost entirely outside of the Duschee Creek watershed. That area is nearly as much area as the area of the Duschee Creek watershed. The dye traces have shown that surface run-in from much of the southwestern portion of the Duschee Creek watershed reaches the Hatchery springs at least part of the year. Therefore, both Duschee Creek and the Hatchery springs must be receiving water from beyond the watershed boundaries. The source of the outside groundwater could be regional groundwater flow, sinkhole/stream swallet run-in, or both. There is not enough data to calculate how much water from beyond the watershed reaches Duschee Creek or the Hatchery springs. More dye traces and detailed, accurate potentiometric data will be needed to precisely define the area contributing water to the Hatchery springs.

Leading Edge Travel Time

The minimum leading edge travel time is an indicator of the length of time available to respond to a contaminant spill after the material enters Stream Swallet D101. The two positive traces from the swallet constitute only a sample size of two; therefore, only an estimate of the minimum leading edge travel time to the Hatchery from Stream Swallet D101 can be made. This information is also limited to the hydrologic conditions which existed in October, 1991 and June, 1992. From Dye Traces #8 and #9, the mean leading edge travel time is:

$LE_m = (LE_1 + LE_2) / 2 = 8.88$ hours.

The calculated range is: $9.25 - 8.5 = 0.75$ hours. To be generous, this calculated range should be doubled as a margin of safety. The lower and upper values for the leading edge range with a safety margin, LE_{sm} are:

$LE_{sml} = 8.5 - 0.38 = 8.12$ hrs; $LE_{smu} = 9.25 + 0.38 = 9.88$ hrs

This suggests that if a contaminant is somehow introduced into Stream Swallet D101, any response at the Lanesboro Fish Hatchery must be made within 8.1 hours. Also, if additional traces are conducted from D101, sampling at the Hatchery springs should begin no later than 8.1 hours after dye input.

Average Velocity of the Leading Edge

The average velocity of the leading edge of the dye pulses can provide some additional information. Here, the sample size is increased to three because the average velocity of the leading edge of the dye pulse in Dye Trace #3 from Sinkhole D28 can also be included. The actual underground pathway(s) are unknown; therefore, only straight-line distances taken from the map can be used. To simplify, the distances are measured only to LFH Main Spring. Again, these calculations use data collected under extant hydrologic conditions in 1987, 1991, and 1992.

The leading edge of the dye pulse of Dye Trace #3 arrived at the Hatchery 8.33 hours after dye input. The straight-line distance from Sinkhole D28 to LFH Main Spring is 3.4 km; from sinkhole D101 is 3.7 km. The average velocities are as follows:

v_1 = 3.4 km / 8.33 hrs = 0.408 km per hour

v_2 = 3.7 km / 8.50 hrs = 0.435 km per hour

v_3 = 3.7 km / 9.25 hrs = 0.400 km per hour

The mean ($\underline{v}$), the variance (s_v^2), and standard deviation (s_v) are:

$\underline{v}$ = 0.414 km per hour

$s_v^2 = 3.36 \times 10^{-4}$

s_v = 0.018 km per hour

The Student's t test can be used even with a small sample size, with the assumption that the population is symmetrical about the mean. Although the actual distribution of the population is unknown, this assumption allows for more variability than an assumption of normality. The average velocity, with a 95% confidence interval, is: (0.414 ± 0.020) km/hr. With rounding, the range of straight-line leading-edge velocities to LFH Main Spring is between 0.39 km per hour and 0.43 km per hour. These values are actually minimum leading-edge velocities because the underground pathways are undoubtedly not straight, and therefore longer than straight lines.

These results allow anyone to calculate the expected leading edge arrival time of a proposed trace from an untried sinkhole in the vicinity of the study area. However, an important caveat is that such a prediction must apply to hydrologic conditions similar to those existing during Dye Traces #3, #8, and #9. Jones (1984) illustrates data from Smart (1981), which shows an exponential relationship between discharge and travel time. Although the relatively high flow conditions of Dye Trace #9 produced a slightly slower leading edge travel time, it is unknown whether the average velocity to the Hatchery springs might be significantly higher under true flood conditions.

The leading edge velocities were precisely defined in Dye Traces #3, #8, and #9 translate to between 9.6 and 10.4 km per day (about 6 to 6-1/2 miles per day). These values are also significant in that they are on the same order of magnitude as surface stream velocities.

To simply compare the straight-line and actual mapped distances on Duschee Creek from the Trace #2 dye input to Station 8 (near the Hatchery), these lengths were measured on a 1:24,000 scale topographic map with a straight edge and a Dietzgen map measure. The straight-line distance is 3.12 km, and the map length of the creek measures at 7.25 km. The map length measured by this method may yet underestimate the true creek length, but it is at least more than twice the straight-line distance.

Average Flushing Rate

The average flushing rate can be used to calculate the time required to remove the dye from the hydrologic system from the source (sinkhole inputs) to the Hatchery springs. The flushing endpoint will be defined as the earliest time after passage of a dye pulse when the fluorescence of several samples consistently correspond to a dye concentration of less than 30 ppt (0.030 ppb); this value is approximately the upper limit of background fluorescence at the Hatchery springs under normal conditions. These results must be used with caution, however, because the definition of the endpoint is chemical-specific, and for every different chemical, the flushing rate would need to be recalculated. The practical endpoint at the Hatchery is when, after passage of a pulse of a given contaminant, the remaining concentration is at its highest level which can be shown to produce no adverse effect in trout.

The results of Dye Trace #1 can be included in this calculation. For the dye in these traces, the endpoint times, symbolized by T_x, and the straight-line distances, D_x, are as follows:

T_1 = 14 days; D_1 = 3.4 km; (Dye Trace #1)

T_2 = 9 days; D_2 = 3.4 km; (Dye Trace #3)

T_3 = 21 days; D_3 = 3.7 km; (Dye Trace #8)

T_4 = 11 days; D_4 = 3.7 km; (Dye Trace #9)

Let R_x be defined as the flushing rate for each trace, and $\underline{R}$ as the mean flushing rate. Let s_r^2 be the variance and s_r be the standard deviation of the flushing rate. Therefore:

$\underline{R}$ = 3.86 days/km

$s_r^2 = 1.88$

s_r = 1.37 days/km

A 95% confidence interval for the mean flushing rate per kilometer is: (3.86 ± 3.41) days/km. This results in a range of flushing rates at the Hatchery of between 0.5 days per kilometer and 7.3 days per kilometer, for the existing hydrologic conditions when these traces were run. Again, these values are based on straight line distances. To be conservative, the Hatchery should consider that the flushing time is at the top end of that range, at least one week.

This result produces a serious problem for the Hatchery if a contaminant is introduced in the groundwater basin and reaches the Hatchery springs. There is no backup water source which can supply water to the Hatchery at or even near the discharge of the springs. The one existing well is only a domestic well designed to supply the drinking water in the Hatchery facilities. In a "best-case" scenario where the Hatchery personnel are immediately alerted to a contaminant spill to allow for the maximum response time, the Hatchery personnel can only partially mitigate the effects of the contamination. LFH Triple Spring can be totally diverted to Duschee Creek. LFH Main Spring can be totally diverted from all raceways and the Hatchery/Nursery Building. All of the water from LFH Main Spring would then flow through Pond #3 (Stork, 1993). Therefore, any contaminant introduced in the groundwater basin that reaches the Hatchery springs will move through at least one trout-rearing pond and remain in the water for days.

CONCLUSIONS

Nine dye traces were conducted in this study in the area of the Duschee Creek watershed. The following conclusions are drawn from those results.

1) Certain sinkholes and intermittently dry stream swallets stratigraphically located in the Prairie du Chien Group acquire surface water during and shortly after precipitation events; this water flows underground to the DNR Fish Hatchery springs at Lanesboro, Minnesota. This study positively identified one such sinkhole (D28) and one stream swallet (D101).

2) A major proportion of the water quality problems of the Hatchery springs is probably due to the contribution of a run-in component from a limited number of such sinkholes and stream swallets.

3) Sinkhole D28 and Stream Swallet D101 are located within the Duschee Creek watershed boundaries. While sinkholes located beyond the boundaries may be contributing to the spring flow, no sinks outside of the Duschee Creek watershed have, as yet, been positively connected to the Hatchery springs by dye tracing.

4) Under low to moderately low flow conditions, Duschee Creek, Partridge Creek, and Camp Creek have not been shown to be directly connected to the Hatchery springs.

5) The travel time from Sinkhole D28 to the Hatchery springs has been documented at 8.3 hours, and from Stream Swallet D101 at 8.5 and 9.25 hours.

6) If a contaminant is somehow introduced into Stream Swallet D101, any mitigating response at the Lanesboro Fish Hatchery must be made within 8.1 hours.

7) On the basis of Dye Traces #3, #8, and #9, straight-line, leading-edge velocities to the LFH Main Spring averaged 0.41 km/hr, with a range of between 0.39 km per hour and 0.43 km per hour at a 95% confidence level. These results could be used for calculating the expected leading edge arrival time of a proposed trace from an untried sinkhole in the vicinity of the study area. However, such a prediction must consider whether the hydrologic conditions are similar to those existing during Dye Traces #3, #8, and #9. Under much higher discharge conditions, the average velocity to the Hatchery springs might be significantly different.

8) Based on the four positive traces, the flushing rate at the Hatchery averages 3.9 days/km, with a range of between 0.5 days per kilometer and 7.3 days per kilometer, under the hydrologic conditions when Dye Traces #1, #3, #8, and #9 were run. To be conservative, the Hatchery should consider that the flushing time is at the top end of that range, at least one week.

9) Any contaminant introduced in the groundwater basin that actually reaches the Hatchery springs will move through at least one trout-rearing pond and remain in the water for days.

RECOMMENDATIONS

The following is a list of recommendations to the Minnesota Department of Natural Resources Southeast District and to the Lanesboro Fish Hatchery Personnel.

1) Divert flow from and seal D28 and D101. Of the two, D101 is the higher priority due to its vulnerable location and much larger drainage area.

2) Conduct an additional trace from Stream Swallet D101 under high flow conditions (greater than 0.028 m^3/s, or 1 cfs). If an additional trace is done, sample Station 9 to determine the flushing time of the internal Hatchery facility.

3) Routinely test the water from the springs for a variety of chemicals that could possibly reach the groundwater system within the basin. The list of the contaminants of concern includes those which are routinely or occasionally used within the groundwater basin area, or have been used or disposed of there in the past, with special attention to those which have a demonstrated effect on aquatic organisms. In addition, consult with other local and regional officials for their expertise as to what chemicals are or have been used in the area. For instance, the regional Minnesota Department of Transportation (MnDOT) officials can be asked for a list of all chemicals which are transported on any of the roads within the area of the

groundwater basin. The final list will, at a minimum, include agricultural pesticides (particularly the organophosphate pesticides and the common herbicides, such as Atrazine), petroleum products, and PCBs (Stork, 1993).

4) Develop mitigation procedures for the final list of contaminants that could adversely impact the water quality of the springs.

5) Discuss these results with other local and regional officials, such as county commissioners, Agriculture Extension agents, and personnel with such agencies as the Agricultural Stabilization and Conservation Service (ASCS), the Soil Conservation Service (SCS), MnDOT, etc. These officials can be made aware of the potential threat to the Hatchery water quality and asked to immediately alert DNR Hatchery personnel if a spill in the basin is reported to any official.

6) Support the Fillmore County Soil and Water Conservation District continuing its efforts to improve water quality throughout the Duschee Creek study area. This will have a general beneficial impact on the groundwater quality due to the direct links of surface water and groundwater.

7) More dye tracing work needs to be done in this study area to identify any additional sinkholes and stream swallets that are directly connected to the Hatchery springs, and to help define the groundwater basin boundaries.

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Betty Wheeler sampling at the Lanesboro Fish Hatchery Triple Spring.
(Photo by E. Calvin Alexander, Jr.)

Betty Wheeler pouring dye into Partridge Creek.
(Photo by E. Calvin Alexander, Jr.)