The Waters of Mystery Cave

INTERPRETIVE REPORT

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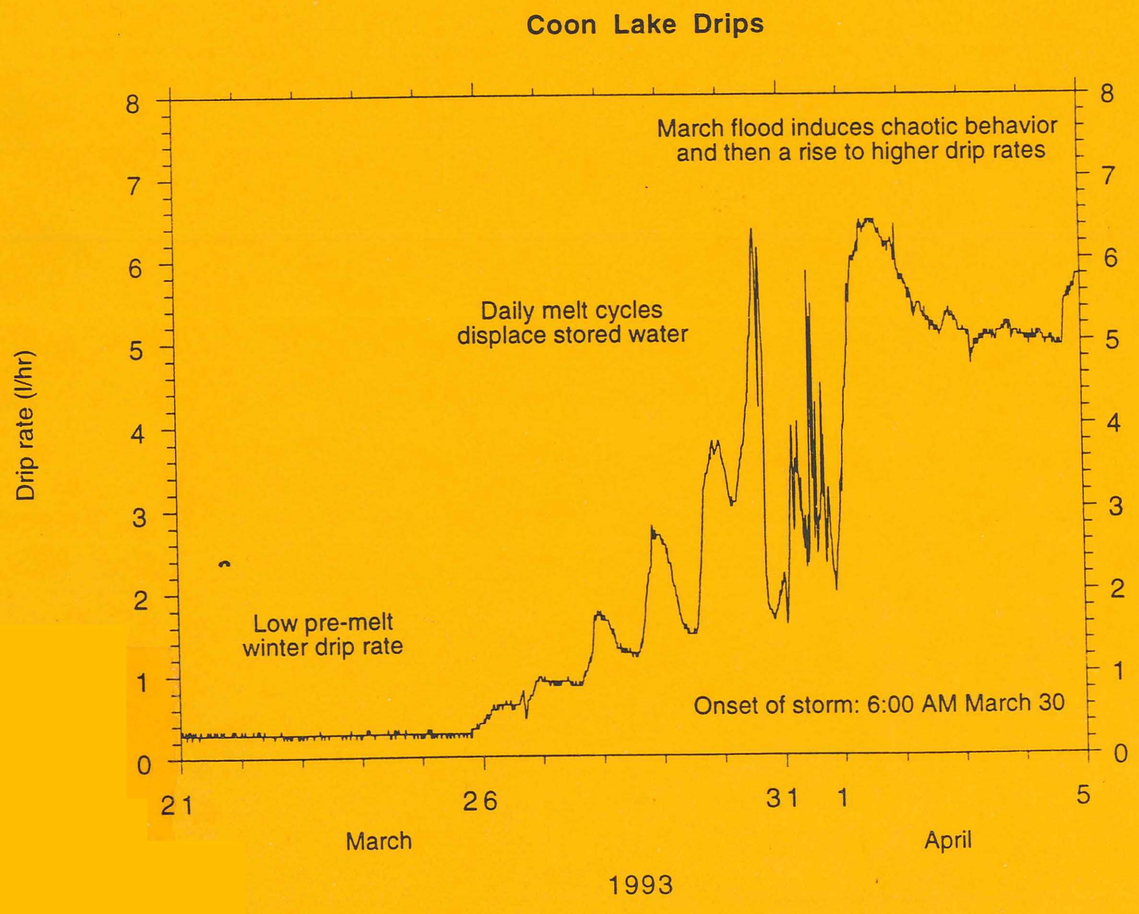

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Forestville State Park, Minnesota

Mystery Cave Resource Evaluation (Groundwater)

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May 1994

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INTRODUCTION

This is the interpretive portion of the final report for the LCMR project **Mystery Cave Resources Evaluation (Groundwater)** and is one part of the Mystery Cave Resource Evaluation. Funding for this project was approved by the Minnesota Legislature M. L. 91, Chapter 254, Article 1, Section 14, Subd. 3(1), as recommended by the Legislative Commission on Minnesota Resources, from the Future Resources Fund. This project concerns the waters and geohydrology of Mystery Cave in Forestville State Park. This Interpretive Report contains a summary of these topics in non-technical terms. The technical aspects of these topics are covered in a separate Technical Report. A separate Management Report contains recommendations on how best to protect the water quality in Mystery Cave, as well as recommendations for future research.

HYDROGEOLOGIC SETTING OF MYSTERY CAVE

Geomorphic Setting

Mystery Cave is in the Central Lowlands geomorphic province in southeast Minnesota. Mystery Cave is the largest cave in Minnesota and is in Fillmore County in the heart of southeast Minnesota's karst land. It is a joint-controlled network maze (Milske and others., 1983). A network maze consists of a net of intersecting passages with closed loops that formed more or less contemporaneously (Palmer, 1975; 1991). Over 13 miles of passage have been surveyed in sections known as Mystery I, II, and III (Figures 1 and 2). Mystery Cave has two entrances (Mystery I and II) and is owned and managed by the Minnesota Department of Natural Resources as part of Forestville State Park. The State Park staff conducts tours through the commercial parts of the cave from May to September.

The landscape around Mystery Cave is a gently rolling plateau cut by young river valleys. The South Branch of the Root, an east-draining tributary to the Mississippi River, is incising

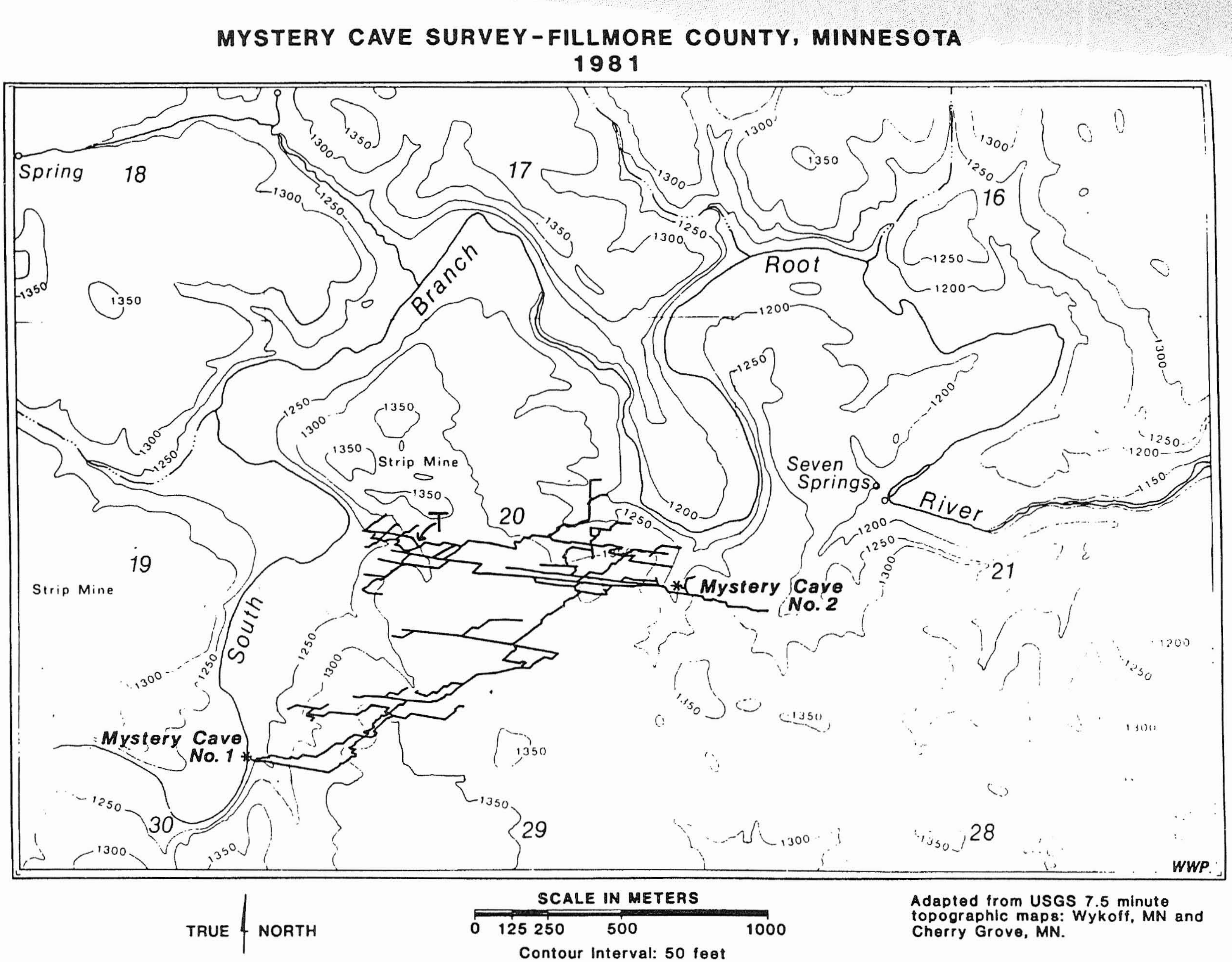


Figure 1. Topographic setting of Mystery Cave (from Milske, 1982).

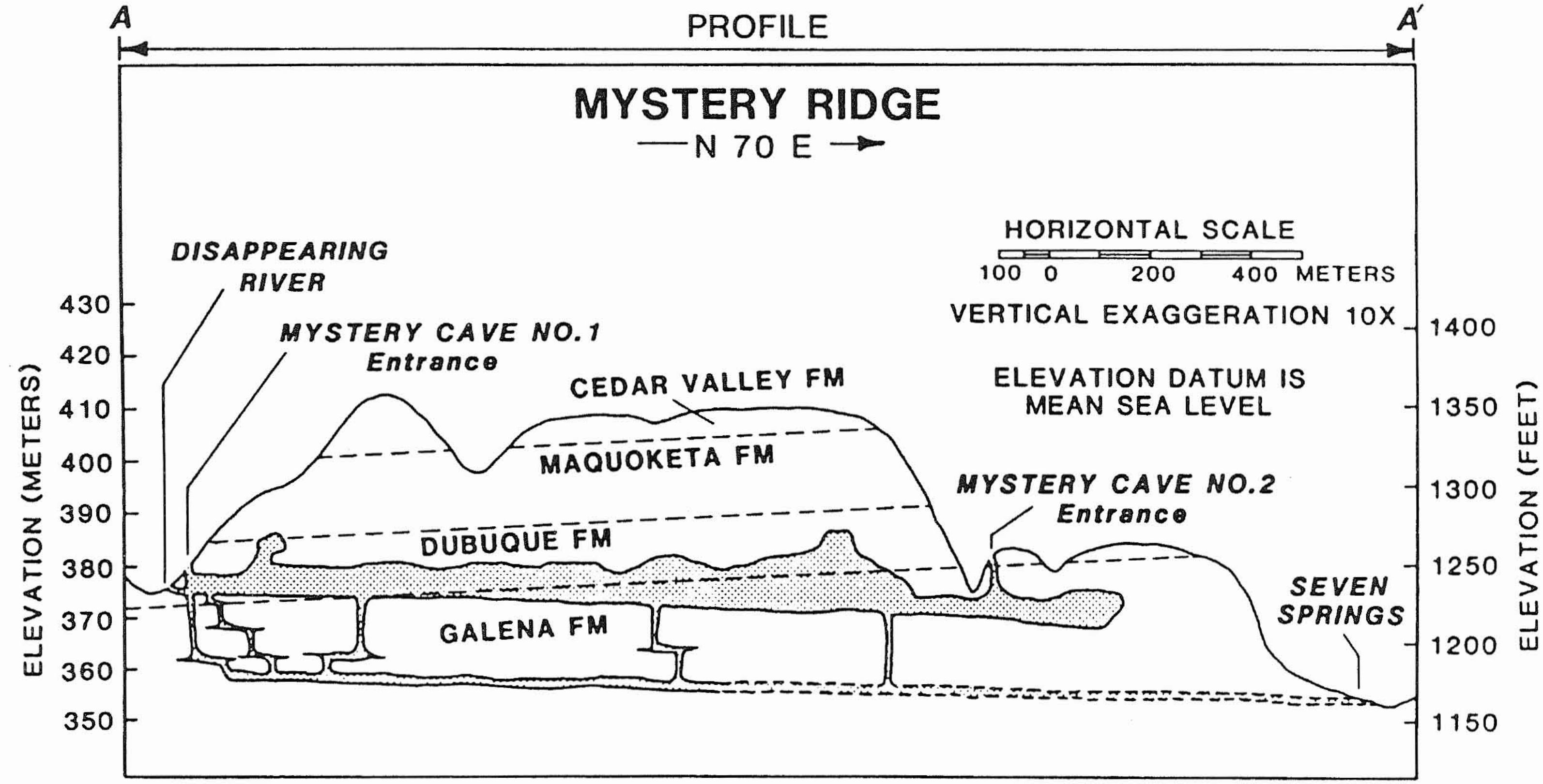


Figure 2. Profile of Mystery Cave (from Milske, 1982).

bedrock meanders into the plateau. Mystery Cave functions as a meander cutoff for the South Branch of the Root River. The maximum local relief is less than 200 ft. The bedrock has a soil and loess (fine wind-blown dust) mantle underlain by discontinuous patches of glacial materials (Figure 3). The loess is calcareous with a high percentage (often >50%) of dolomite rhombs. Mason (1992) correlated the loess with the Peoria loess (late Wisconsinan age) of Iowa, based on numerous core sampling sites in Fillmore and Houston counties. The loess fines eastward, which suggests an origin from glacial materials from the west.

The thickness of the loess varies considerably in southeastern Minnesota and northeastern Iowa. A distinct boundary between thick (>1m) loess to the east and thinner loess to the west trends northwest to southeast from near the Twin Cities into Iowa. This boundary, known as the "loess border," passes through western Fillmore County. Within the zone of thicker loess, which extends east to near the Mississippi River, the loess apparently thins eastward. Although the exact boundary is somewhat sinuous and uncertain in many areas, the loess border comes very close to, and in some locations, has been placed directly above Mystery Cave. For example, Mason (1992, p. 177) shows the boundary at topographic locations that place it almost directly above part of Mystery II (5th Avenue leading to Coon Lake Drips and Garden of the Gods). Maximum loess thicknesses measured by Mason (1992) range up to 7.7 meters near the loess border. Palmer and Palmer (1993b) used seismic methods to estimate a depth to bedrock as 22 ft above the Garden of the Gods. This depth must include soil, the Peoria loess, and any additional glacial materials above the sediment/bedrock interface.

Subsidence sinkholes are widespread on the plateaus elsewhere in southeastern Minnesota, but are not abundant near Mystery Cave. No sinkholes have been located over known cave passages. The few nearby sinkholes do not appear to have functioned as points of concentrated recharge during early stages of cave development, or to have provided long-term sources of concentrated recharge, as is common for branchwork caves (see Palmer, 1991). Nor do they serve as major points of concentrated recharge today. Instead, most of the water that falls directly on the plateau either infiltrates the soil and loess, evaporates, or is transpired, because surface drainage patterns suggest little water leaves the plateau as surface runoff.

Land Use

The plateau above Mystery Cave is used for agricultural purposes. The bulk of the plateau is in row crops, corn and soy bean rotations. A few dairy farms have more extensive pastures and hayfields, but little of the total area is used as pasture or for non-row crop agriculture. Areas of forested hillslopes are present on plateau margins and reentrant valleys, where the soil and loess cover thins and bedrock is locally exposed. Such areas directly overlie much of the Mystery I entrance area and adjacent passages. None of the Mystery I commercial route lies beneath row-crop land; it lies beneath a forested hillslope along the South Branch of the Root River and in a reentrant valley. Much of the central part of Mystery Cave, past the Bomb Shelter along the Door-to-Door Route, lies beneath cropland. Forested hillslopes directly overlie parts of Mystery II and III north of 5th Avenue, but much of Mystery II is close to the crop/forest boundary. Western Mystery III near the Root River is beneath forested hillslopes. Parts of

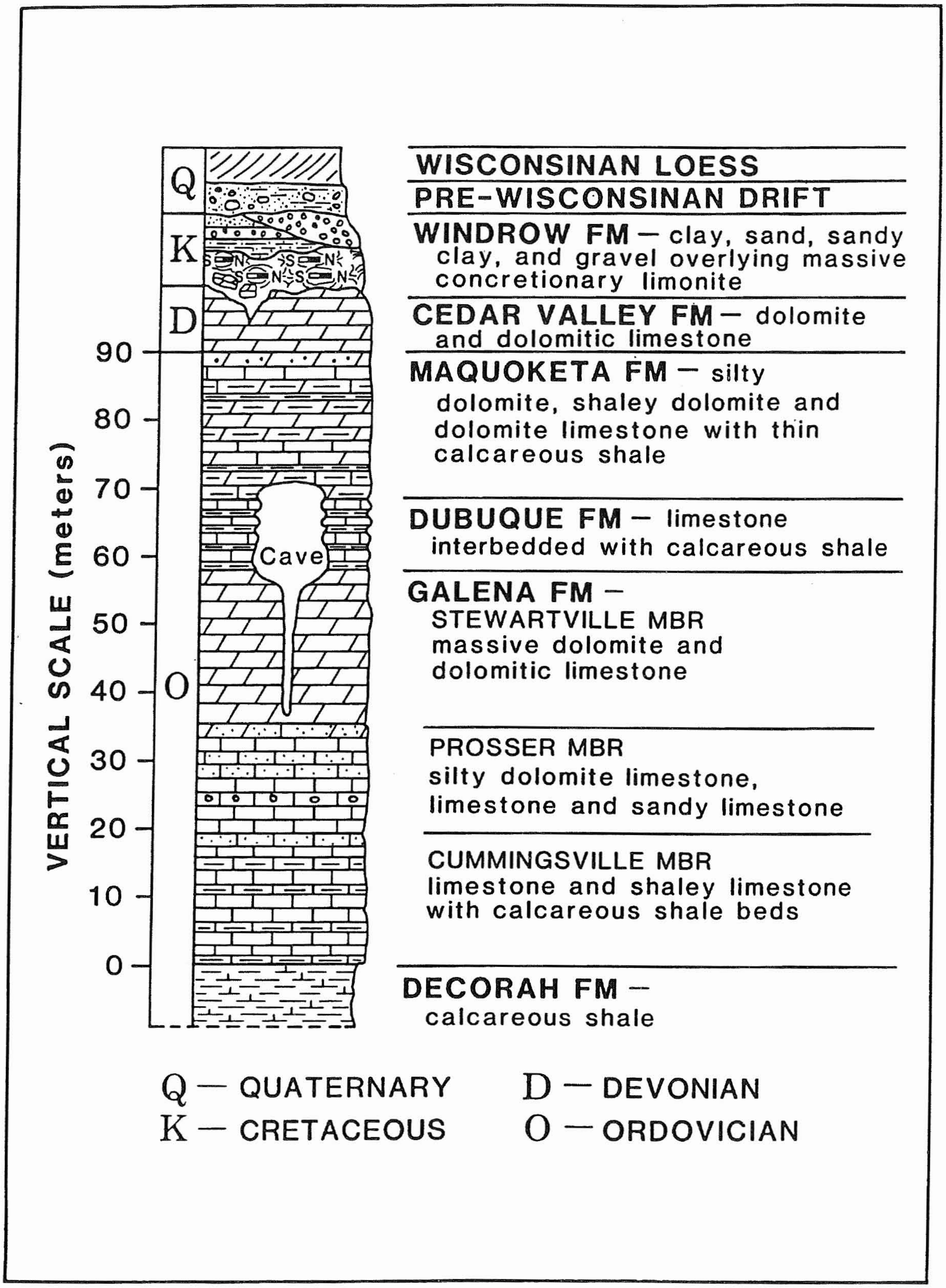


Figure 3. Stratigraphy at Mystery Cave (from Milske, 1982)

northern Mystery III are beneath row-cropped land; the rest is beneath forested hillslopes and reentrant valleys.

The Sinks, Underground Rivers and Springs near Mystery Cave.

As noted above, Mystery Cave functions as a meander cutoff for the South Branch of the Root River. Surface water in the South Branch drains underground through parts of Mystery Cave, short-circuiting the longer surface course (Figures 1 and 2). The Mystery I entrance is adjacent to the South Branch of the Root River on its south side (at the Mystery I entrance the river flows north and locally the entrance is on the east side of the river). Water sinks at discrete points which start near Mystery I and occur for several miles downstream. The sink points are vertical joints that have been solutionally enlarged and filled with sediment. The sink points have a collective capacity to accept surface water. When the flow in the river exceeds that capacity, water continues to flow through the entire surface reach of the South Branch near the cave. As the flow in the river recedes toward and then below the capacity of the sink points, a terminal sink develops on the South Branch. This terminal sink migrates upstream as the flow in the river decreases. During all but the wettest years several miles of the South Branch are dry during much of the summer and fall. The permanent flow in the South Branch resumes at Seven Springs about 1.5 miles east-northeast of the Mystery I entrance and about 0.5 miles east-northeast of the Mystery II entrance.

Seven Springs is one of three spring clusters (Figure 4); the others are Crayfish Springs and Saxifrage Springs. The Crayfish Springs are ephemeral and dry up when the terminal sink of the South Branch retreats upstream of the river bed immediately north of the Mystery II entrance. Saxifrage Springs are volumetrically the largest of the springs much of the year but may also dry up when the terminal sink has retreated above the bridge at the east end of the Mystery I driveway. Seven Springs are the most perennial of the three complexes. Seven Springs actually has more than seven springs. When surveyed in September, 1992, nine springs were identified at Seven Springs. The number of springs in each cluster probably varies seasonally with flow conditions; it also may vary over longer time spans because of changing sedimentologic conditions on the Root River. Many of the springs are at the base of bedrock cliffs. Rock falls from cliff collapses periodically block individual spring orifices or divert water so that flow is from two or more orifices. Most of the springs issue from joints or bed-joint intercepts, but some issue from rubble piles so that it is uncertain whether flow is actually from a single solutionally-enlarged fracture or several.

The flow from all three spring complexes is dominated by water from the sinks of the South Branch. The water temperature in all three spring complexes varies seasonally indicating relatively short underground residence times. On any given day the temperatures and conductivities in all three spring complexes are similar, but not identical. Stream flow measurements made above the start of the sinks at Mystery I and below Saxifrage Springs confirm that, within the errors of conventional stream flow measurements, nearly all of the water resurging at the three spring complexes can be sinking flow from the South Branch. Cave mapping, dye tracing, flow measurements, and careful observation of spring behavior relative to river flow and

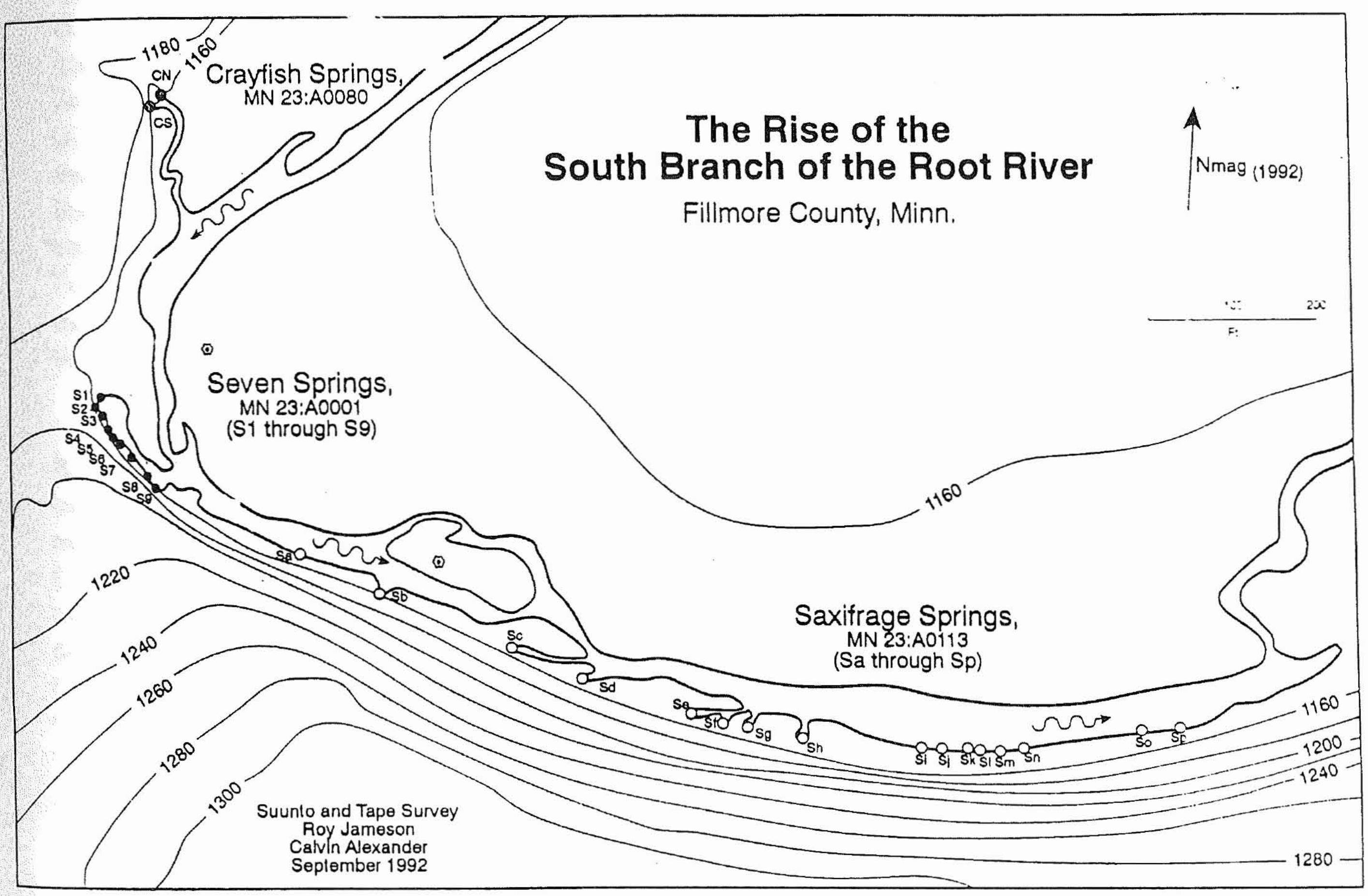


Figure 4. The Rise of the South Branch of the Root River

the position of the terminal sink, have begun to reveal a detailed picture of the underground plumbing system that flows beneath the ridge containing Mystery Cave.

By the mid-1970's, it was common knowledge in the local caving and southeast Minnesota karst communities that the resurgence of the Mystery Cave system was Seven Springs. The concept was simple. The South Branch sank to form the Disappearing River which flowed through the lower levels of Mystery Cave and resurged at Seven Springs. Quantitative dye tracing in and around Mystery Cave in the late 1970's and early 1980's documented that the Disappearing River system did indeed resurge at Seven Springs (Mohring, 1983; Mohring and Alexander, 1986). Mohring discovered that the situation was complicated, however. During high flow in particular there was strong evidence that a second source of water contributed to the flow at the northwest end of the Seven Springs group. Mohring hypothesized that a separate groundwater basin existed north of Mystery II, but he never caught the flow conditions right to do a trace from that area. Mohring also demonstrated that water which sinks at Matheson Sink, B3, near Rollie Copeman's farm splits underground -- part of it resurges at Seven Springs while most of it flows into the Forlorn River system and resurges at Moth and Grabau Springs on Forestville Creek. This meant that: 1) whenever the terminal sink of the South Branch was below Matheson Sink, part of the South Branch's flow is diverted into the springs heading Forestville Creek through a third groundwater basin, and 2) the hypothesized second groundwater basin could not extend very far to the west or north. Mohring and Alexander were unaware of the existence Crayfish Springs and Saxifrage Springs during much of their early tracing work.

Crayfish Springs were recognized in 1981, during a trace of the entire South Branch of the Root River (Alexander, 1987) about 100 meters north of Seven Springs. Crayfish Spring is the major outlet of Mohring's postulated second groundwater basin. That groundwater basin was named the Crayfish River Basin and its general location is shown in Fig. 10 of the 1984 MSS Corn Feed Guidebook (MSS, 1984). During the 1980s several traces were conducted through the Disappearing River system into the Seven Springs/Crayfish Springs complex. These traces demonstrated that under low flow conditions water from the Disappearing River system reached Crayfish Springs and dominated Seven Springs but under high flow conditions the flow from the Crayfish River Basin pushed the Disappearing River flow to the southeast part of Seven Springs. The boundary between the Crayfish River Basin and the Disappearing River Basin is mobile and moves in response to varying flow conditions.

In the late 1980s, it was recognized that under most flow conditions a lot of water emerges from a series of springs along the south bank of the South Branch in the quarter mile downstream from Seven Springs -- more even than emerges from Seven Springs proper. This complex was named Saxifrage Springs after the Nature Conservancy's Saxifrage Hollow Preserve that starts a few feet uphill from the springs. The Preserve protects the rare and endangered plant and animal species that inhabit the aligific talus slopes immediately above the springs. The Preserve is totally closed. Please refrain from walking on or disturbing the slope above the springs in any way. The number of discrete springs in the Saxifrage Springs group is a matter of judgment, but 16 separate rise points are designated on Figure 4.

In October, 1991 a triple-trace was performed in and around Mystery Cave during relatively high flow. The terminal sink of the South Branch was between Steve Landsteiner's house and the ford to the Grabau Quarry. Rhodamine WT was introduced into Ground Hog Sink about 350 m west northwest of the Mystery I entrance. Fluorescein was introduced in Cold Air Sinks in the South Branch just in front of Cold Air Cave down the ravine from the extended Mystery II parking lot. Sodium bromide was introduced into a dry sinkhole immediately adjacent to the parking lot at Mystery II. The bromide ions reached Seven Springs in about two and a half hours with a pattern of increasing concentration toward the high numbers (the downstream or east end of the Seven Spring group). That pattern is diagnostic of flow through the Disappearing River system under relatively high flow conditions. None of the bromide was detected at Crayfish Springs or at the western-most of the Saxifrage Springs.

The fluorescein came out the middle of the Seven Springs group (S4 under the existing flow conditions) in about two hours and did reach Crayfish Springs but was not detected at any of the Saxifrage Springs. This pattern confirms the existence of the hypothesized Crayfish River underground Basin immediately north of Mystery II. This basin feeds Crayfish Springs and the west (low numbered) end of Seven Springs under high flow conditions. Under low flow conditions when the terminal sink of the South Branch is upstream from the Mystery II area, the Crayfish River Basin is essentially dry, Crayfish Springs stop flowing, and all of the flow from Seven Springs comes from the Disappearing River Basin.

The Rhodamine WT was detected in the Saxifrage Springs, in the east end of Seven Springs at S8, but was not detected in Crayfish Springs. This represents, to our knowledge, the first documented trace into the Saxifrage Springs and is the first evidence of a fourth, independent groundwater basin in the area of Mystery Cave. This new basin is named the Saxifrage River Basin. Its location is not very well defined, however.

Chemical analyses of water samples collected at Crayfish and several of the Seven Springs and Saxifrage Springs in July, 1992, indicates that water in the three springs is very similar and suggests that it comes from the South Branch. The temperatures in the Seven Springs and the Saxifrage Springs were similar and well above normal groundwater temperatures indicating that the waters in both springs come from the same surface source and had spent comparable, short periods of time underground. Stream-flow measurements indicated a rough water balance through the system. The South Branch had a flow of roughly 20 cubic feet per second (cfs) immediately upstream from Mystery I. The combined flows of Etna Creek and the South Branch 2 miles west of Mystery I also summed to about 20 cfs. Seven Springs was flowing about 5 cfs and the flow in the South Branch in the first riffle downstream of the Saxifrage Springs group was about 20 cfs. Under the flow conditions present in July, about 75 % of the South Branch flow was flowing through the Saxifrage Springs and only about 25 % was flowing through the Disappearing River system and resurging at Seven Springs. Where is all of that water going into the ground?

There are some anecdotal observations that may be relevant to this question. During a very low flow period in the summer of 1988, the terminal sink of the South Branch retreated to Blakeslee Sink about 100 meters downstream from the new culverts into the Mystery I parking area. DNR personnel measured the stream flow immediately upstream of Mystery I and downstream from Seven Spring and those two flows were the same at about 3 cfs. At that time DNR personnel were unable to find the Saxifrage Springs, i.e. the springs may have been dry at that time. During the late summer and early fall of 1992, the most upstream terminal sink of the South Branch was sink Beaver Sinks, which are a few meters east of the Township Road bridge near the start of the driveway to Mystery I. Under those flow conditions the Saxifrage Springs were reported to be flowing. Taken at face value, the 1988 and 1992 observations would indicate that water sinking at Beaver Sink or immediately upstream, is the source of the Saxifrage Springs. If that area is the source of the Saxifrage Springs, that flow must either: 1) cross the Disappearing River system, or 2) flow west, then south, then back east around the west end of the Disappearing River system.

Stratigraphy, Passage Character, and their Influence on Flow Patterns

Mystery Cave is primarily in the dolomite of the Stewartville Formation, and in the limestone, dolomite, and shale of the overlying Dubuque Limestone (Figures 2 and 3). Some of the highest parts of the cave are near-surface breakdown rooms in dolomite and shale of the lower part of the Maquoketa Formation (Palmer and Palmer, 1993a). Many passages appear to have originated as vertical fissures at or near the Dubuque/Stewartville contact, then enlarged upward by a combination of collapse with dissolution and downstream transport of the debris. Most of the present void space of passages is in the Dubuque Formation.

Passages in the Dubuque Formation tend to be tubular with rectangular or elliptical cross sections. There is abundant breakdown from wall collapse and upward collapse of thin alternating shales, limestone, and dolomite. Collapse has produced blocky but arched cross sections and passage widenings that produce small rooms; the rooms have ceilings that resemble the breakout domes of caves in the eastern United States and are produced by the same processes (collapse and solutional removal and downstream transport of the debris). Such locations can best be described as incipient breakout domes, for few such locations are fully developed with both domes and conical debris piles. Passages in the Dubuque formation have so much breakdown that they have irregular, ungraded floor profiles. Passage cross sectional area can abruptly change from about 10 square ft (5 ft wide by 2 ft high) to hundreds or, at the extreme, even a thousand square feet (20 ft wide by 50 ft high). Sites of greater cross sectional area imply more efficient removal of the collapse debris. Usually these sites can be correlated with underlying fissures in the Stewartville Formation that allowed lower level streams direct access for removal of the breakdown.

Most of the water movement in the Dubuque Formation is vertically downward along the steepest available paths, which are joints. Above the cave there may be some significant lateral movement along solutionally enlarged joints, but such movement is unlikely to exceed a few hundreds to a thousand feet. Water tends to enter cave passages as drips and falls out of ceiling joints, or as seeps and flows out of joints in walls. Many of the smaller seeps and flows from walls issue from the bases of vertical joints at locations where the joints die downward at contacts with bed partings or shaly interbeds. No stream entering a Dubuque passage can be expected to be followable a significant distance horizontally today, because the stream would disappear downward in breakdown and enter joints or fissures in the Stewartville Formation. Nearly all of the movement of water in the Dubuque passages thus has a strong vertical component of flow.

Passages in the Stewartville dolomite are often narrow fissures or are keyhole shaped as tubes over fissures. The larger passages, such as parts of 5th Avenue, are tubular with arched or rectangular cross sections, but sediments hide fissures in the floor. Thus the actual shape of the lower part of the primary solutional void may be obscured. Consequently, it is not entirely clear whether deep floor fissures are universal in the Stewartville passages. Silt, and silt and gravel fills (see Milske and others, 1983) are common in passages developed in the Stewartville Formation; in places silt and gravels overlie breakdown or are interbedded with breakdown. Many fissures in the Stewartville are extensively filled with silt, which perches small streams that are incapable of removing the silt. Perching by silt limits water contact with bedrock, thus impeding bedrock dissolution and preventing more direct downward vertical movement of water to the water table.

In many areas, Mystery Cave has two levels: an upper level of tubular shape, and a lower level in the Stewartville fissures (Figure 3). The primary cave streams (Disappearing River, Formation Route Creek, and Flim Flam Creek) obtain most of their discharge by recharge from the streambed of the Root River; they flow laterally through the cave within the lower level fissures. None of the streams is normally visible along the tour routes, although Flim Flam Creek has been known to flood sufficiently high to be visible at the Bar in Mystery II.

Recharge and Water Flow Patterns

Recharge to Mystery Cave takes both diffuse and concentrated forms. Diffuse recharge occurs through the soil and loess. This water moves vertically downward and probably collects in discrete zones at the regolith/bedrock contact, to then follow joints downward. In unglaciated temperate-zone karst, there is often a well developed subcutaneous or epikarst zone of fractured and solutionally modified bedrock at and below the regolith/bedrock contact (Williams, 198x ; Gunn, 198x). Repeated glaciations and burial by loess may have impeded the development of the subcutaneous zone in southeastern Minnesota. It is difficult, given the poor exposures available, to ascertain the extent of development of the subcutaneous zone, or to estimate the radius of influence of bedrock basins within the zone, which should concentrate the diffuse infiltration to individual joints. Given the lack of sinkholes above Mystery Cave, or near it elsewhere on the plateau, it is probable that the radius of influence is small. In other words, most of the diffuse infiltration is likely to move into the nearest available major joint, rather than collecting over larger areas. If this is true, then most of the plateau away from the cave is drained by infiltrate dispersed over most of the available joints.

Although a) most of the plateau has a thick permeable soil and loess mantle, b) sinkholes above the cave are rare, and c) little water flows as surface runoff from the plateau, it is clear that concentrated recharge still provides most of the water that actually flows through Mystery Cave. The concentrated recharge via leakage in the streambed of the Root River is volumetrically the largest component of recharge to the system. Concentrated recharge via sinkholes does not appear to be volumetrically important for Mystery Cave, for there are few sinkholes near the cave, and none appear to contribute to known flows in the cave. However, concentrated recharge is important in some near-surface sections of cave, such as the Mystery I and II entrance areas. At these, and perhaps a few other locations, concentrated recharge must take the form of flow into open joints on hillslopes with exposed bedrock, or flow into macropores in thin soil and loess. For example, at Mystery I, direct connections to the forested hillslope surface are indicated by: 1) rapid response to rainfall, 2) water temperatures that reflect surface water temperatures only slightly modified, and 3) increases in turbidity and decreases in conductivity in response to storms, at such drip and waterfall locations as Frozen Falls Drips, Drips Across Bridge, and the Pipe Organ. At Mystery II, similar responses are found at drip sites in the entrance passage and in the stairwell, which gushes water out of cracks in the concrete following storms. Similar responses also appear at the Ramp stream in Mystery II, which occasionally (much of the wet summer of 1993) has a discharge sufficient to leave the ramp area past 17 Layer Rock and spread out over the floor, inundating a 50 ft stretch of 5th Avenue.

CHEMISTRY OF CAVE WATERS

A Few Basic Concepts

pH. The pH is a measure of the acidity of water. Soda pop is acidic; so is vinegar. Acidic water can dissolve limestone and dolomite. An acidic solution at room temperature has a pH less than 7. Water with a pH of about 7 is neutral. Water with a pH greater than 7 is basic. Soap solutions are generally basic. The water in a cave is often slightly basic. In Mystery Cave, pH typically is between 7.5 and 8.2. The water is not acidic. It has already dissolved some rock and used up much of its acidity, which is derived from carbonic acid.

Chemical formulas. Limestone is calcium carbonate. Its chemical formula is $CaC0_3$. It contains an atom of calcium (Ca) and a group of one carbon and three oxygen atoms (CO_3). The group is called carbonate. Dolomite is calcium magnesium carbonate. Its chemical formula is $CaMg(CO_3)_2$. Dolomite differs from calcite in that magnesium is also present. Also, there is a second carbonate group.

Carbon Dioxide. Water obtains much of its acidity from carbon dioxide (CO_2). Carbon dioxide is an odorless gas present in the atmosphere. We breathe in the air, extract oxygen, and exhale even more carbon dioxide than is present in air. The extra carbon dioxide that we respire is a waste product of our metabolism. Carbon dioxide is also produced in great quantities in the soil zone by respiration by organisms. Finally, carbon dioxide is produced by decay of plants and other organic matter. The gas that provides the fizz of soda pop is carbon dioxide.

Carbonic Acid. Carbon dioxide dissolves in water to form a mild acid, carbonic acid. Carbonic acid has the chemical formula H_2CO_3. This is the acid that does nearly all of the dissolving of limestone and dolomite. Enough carbon dioxide is present in the atmosphere to produce a weak carbonic acid solution in rainwater, or other waters at the earth's surface. However, most of the carbonic acid forms in the soil, where large amounts of carbon dioxide are present. This soil water can, and will dissolve soluble material in the soil. Soils often have soluble material, such as fragments of bedrock. At Mystery Cave, the loess below the soil also has soluble components, primarily as dolomite crystals, but calcite is also present. Thus much of the acidity of the soil water is lost before the water actually encounters bedrock.

Solution of limestone and dolomite. Carbonic acid attacks limestone and dolomite, causing it to dissolve. A minor amount of dissolving is also done by sulfuric acid. In Mystery Cave, this occurs next to iron pyrite grains and nodules present in some beds of the Dubuque and Stewartville Formations.

Solutes. When limestone dissolves, the atoms of calcium, carbon, and oxygen enter the water. In the water, the atoms are present as solutes. Some of the atoms are single atoms, such as the calcium from the dissolution (dissolving) of limestone. The calcium is present in the water as an **ion**. An ion has an electrical charge. If the charge is positive, the ion is a **cation**. Calcium is present as a cation. It has a charge of +2. We write it as: Ca^{+2}. Some of the atoms in the water are in groups, such as the carbonate group. We write it as: CO_3^{-2}, because it has a charge of negative two. An atom or group of atoms in water with a negative charge is called an **anion**. The carbonate group is an anion. Other important anions include bicarbonate (HCO_3^-), chloride (Cl^-), nitrate (NO_3^-),and sulfate (SO_4^{-2}).

Water Chemistry and Water Quality

We collect water samples to learn about the chemistry and quality of the water. The **chemistry** of the water is a summary of what is in the water and records how that water has reacted with various substances. The term **water quality** is sometimes used in a similar fashion, to signify a list of the substances in the water. The use of the term is at other times restricted to discussions in which the main concerns are: 1) the effects of the water's constituents on organisms (such as fish), or 2) the human use of the water for a particular purpose.

Some water needs to be pure enough for humans or animals to drink. Other waters such as those used to irrigate crops need not be so pure. Cooling water used in a factory might not have to be as pure as water intended for drinking. While we don't normally drink cave waters, they need to be suitable for the cave animals that live in them. The waters need to remain pure throughout their journey to the cave and through it.

This brings up a point important enough to repeat. The waters in the cave flow through the cave. They originate as rain or snow. Some of the rain infiltrates through the soil and loess; other water simply flows down the sides of sinkholes to move underground. But whatever its pathway into the cave, the water flows through the cave on its journey back to the surface at springs on the Root River.

However pure the water is, it always has substances dissolved in it. What is critical is to know what substances are present, and how much there is of each one. The amount of a substance in water is its **concentration**. The concentration of the dissolved solids in water are often expressed in units of milligrams per liter **(mg/l)** or equivalently as parts per million **(ppm)**. Trace substances are expressed in units of micrograms per liter **(μg/l)** or parts per billion **(ppb)**.

Common Measurements Made on Cave Waters

Some common measurements and analyses made on cave waters are:

1. Water temperature
2. Conductivity
3. pH
4. Alkalinity
5. Cations such as Ca, Mg, Na, and K
6. Anions such as NO_3^-, Cl^-, and SO_4^{-2}

Other measurements may be made, particularly if certain types of pollution are suspected:

7. Fecal coliform bacteria
8. Pesticides such as atrazine
9. Trace metals such as zinc (Zn)
10. Organic chemicals such as gasoline or other petroleum products

Why Measure and Analyze Cave Waters?

The measurements made on water samples can tell us much about the water and the cave. They help in interpreting how the cave was formed and how the cave formations grew. They help us understand the structure of the paths the water takes to get to the cave and how long the water is in transit. If the water is contaminated, we want to know what pollutant is present and how much.

Some measurements allow us to compare water chemistry and cave development in Minnesota with that found elsewhere, in different climates, or under different geologic settings. In the eastern United States, such as in Kentucky, Tennessee, and West Virginia, most of the caves are developed in limestone rather than in dolomite and limestone as in Minnesota. This makes a considerable difference in the amount of certain substances in the cave water. For example, the waters of Mystery Cave are harder waters, they contains more calcium, magnesium and bicarbonate, than do typical waters in eastern caves. Because they have dissolved significant amounts of dolomite, the waters of Mystery Cave contain much more magnesium than do waters that dissolve only limestone. Further comparisons of the chemistry and hydrology of Mystery Cave with those of caves elsewhere, are made in a later section, "Mystery Cave: Selected Comparisons with other Caves."

WATERS AT SELECTED SITES ALONG THE TOUR ROUTES IN MYSTERY CAVE

Sites in Mystery I

Turquoise Lake

Turquoise Lake is in Mystery I on the commercial tour route, in a side alcove about 30 ft south of the main passage. The pool is about 800 ft west of the South Branch of the Root River.

In its present configuration, Turquoise Lake is an artificial pool. Its depth is controlled by a small dam and a pumping system that turns on when the water reaches a level about one foot below the crest of the dam. Turquoise Lake is fed by a free-surface stream with a normal flow of a few liters per minute. The stream enters via a joint, traverses a small room behind the pool, spreads out over flowstone. From the flowstone, the water drips and flows into the back of Turquoise Lake. Sources of the stream have not been determined, but chemical data and measurements of temperature (discussed below) provide some indications of possible sources and rule out other sources.

In the past, Turquoise Lake was a natural pool, as shown by abundant subaqueous speleothems and folia. Folia at several levels on the walls extend past the dam toward the main passage. Folia are rare calcite speleothems that form along the water's surface at cave walls; they record extended periods of still stands of the water level. At the time the speleothems were deposited, the water must have been at or above saturation for calcite. Such conditions continue to exist in the current Turquoise Lake. All 17 samples collected between June, 1991 and April, 1993 were supersaturated with respect to calcite, aragonite, and dolomite.

The water at Turquoise Lake is clear but has a distinct bluish cast -- hence its name. The color is caused by Rayleigh scattering by calcite molecules ($CaCO_3^{o}$) and complexes of up to a few thousand molecules in the water. Molecules and particles much smaller than the wavelength of light selectively scatter the blue wavelengths relative to the red wavelengths. When a light beam shines into the water the calcite molecules selectively scatter the blue light toward the observer. (This is the same process that causes the sky to appear blue except in the sky nitrogen and oxygen molecules and very small aerosols produce the scattering. When you look directly at the light source, say a rising or setting sun, it appears reddish due to the removal by scattering of part of the blue light.) These calcite complexes probably form in Turquoise Lake rather than being transported in. During this study, the water at Turquoise Lake became turbid only once. The silt and clay particles in the muddy water are much too large to cause Rayleigh scattering and this turbidity causes the water to appear gray or the color of the particles. The major flood on the Root River on March 30, 1993 back flooded Turquoise Lake with muddy water from the surface.

During this study, water temperature in Turquoise Lake (Figure 5) was remarkably constant at about 8.60-8.70°C. The nearly constant water temperature rules out the Root River as a direct source for the water of Turquoise Lake. Water temperature in the Root River varies up to about 4°C on a daily basis in the summer, and ranges from near 0°C in the winter to over 20°C in the summer. The Root River is sufficiently close, that were it a primary source, we would

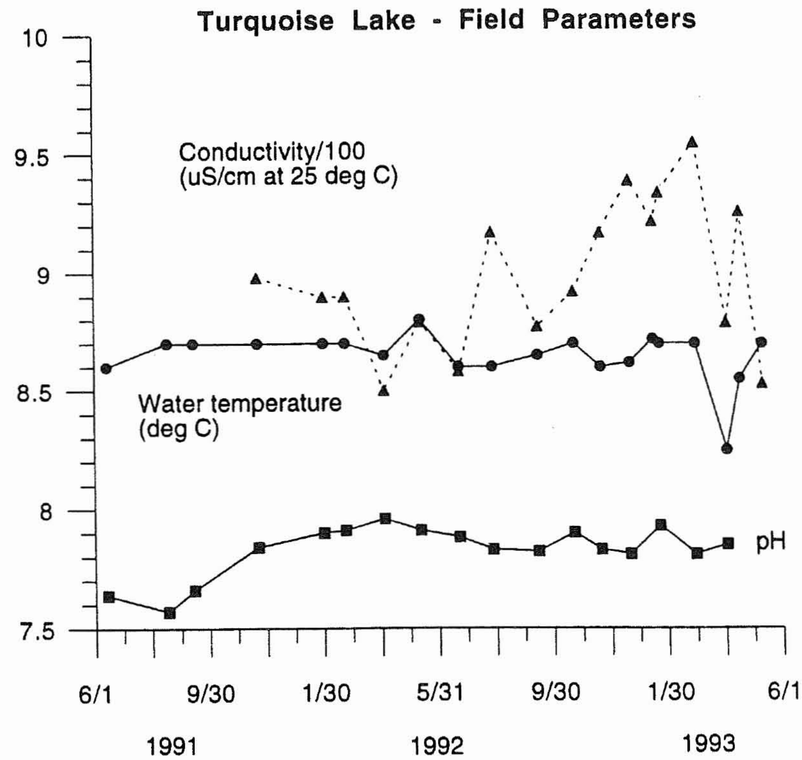


Figure 5. Time series of Turquoise Lake field parameters.

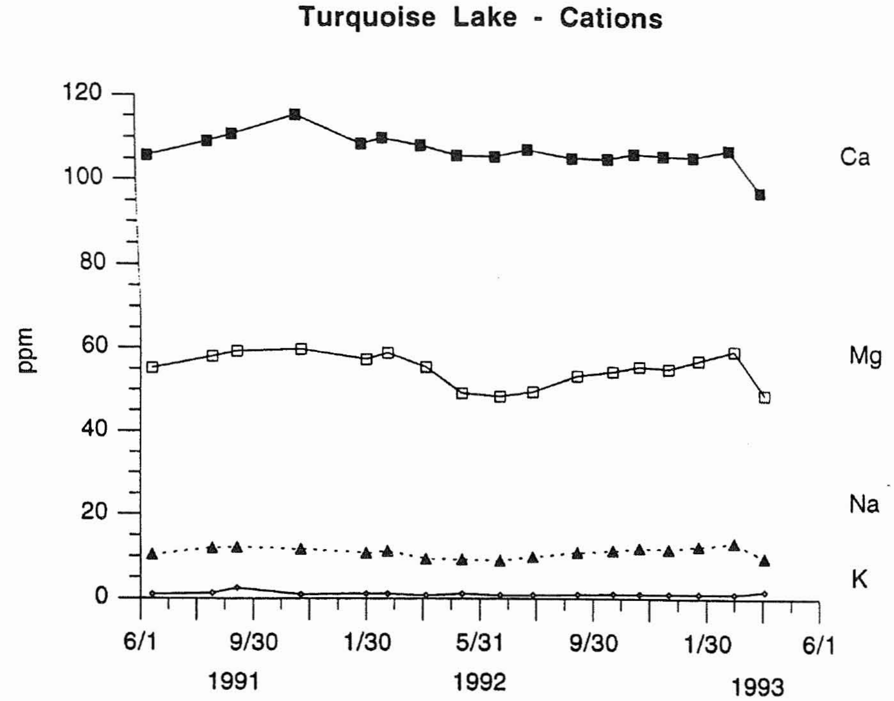
have detected large seasonal temperature variations (such as were detected in the nearby Lower Level Stream, which clearly does receive water from the Root River), and probably would have detected smaller daily temperature variations as well.

However, the Root River introduced cold water (probably as cold as only a few °C) from rain on snow and snow melt during the March 30, 1993 flood. Water temperature four days later on April 3, 1993 was colder than normal, at 8.25°C. Evidently, the flux of water at about 8.70°C into Turquoise Lake from its normal source (combined with heat transfer from bedrock at Turquoise Lake and the air above it) was nearly sufficient to return Turquoise Lake to its normal temperature over a four day period.

In all probability, the water in Turquoise Lake was completely flushed during the flood. We do not know whether any Root River floodwaters entered via the normal source. However, we do know that the water level from waters rising out of the lower-level fissures was sufficient to flow past the Turquoise Lake area in the main passage toward and past the Bomb Shelter. To flow past the Bomb Shelter, the water level at Turquoise Lake must have crested at least as high as a foot or two below the ceiling at Turquoise Lake, well above the height of the dam. At the time of the flood, a canoe and several planks were stored in the passage. The floodwaters transported the planks into Turquoise Lake, where they were observed floating on April 3, 1993.

During the flood, the water in Turquoise Lake was replaced with colder, more turbid, and more chemically dilute floodwaters derived from rain and snow melt. As the flood receded, the dam trapped floodwater (in addition to the planks and a considerable amount of silt). The trapped floodwater was then gradually replaced by influx from the Turquoise Lake feeder stream. Evidence for the initial floodwater replacement and the partial return to normal conditions can be seen in the sharp but limited decreases in conductivity, Ca, Mg, Na, HCO_3, SO_4, and Cl at the end of the time series plots (on April 3, 1993), Figures 5 and 6, for field parameters, cations, and anions.

Throughout the study, concentrations of Cl^- and NO_3-N at Turquoise Lake were relatively high (29.2-40.5 ppm for Cl^- and 8.7-12.3 ppm for NO_3-N) compared to other cave waters. Chloride has a spiky curve with peaks following recharge events. This response suggests intermittent mobilization of chloride, which is probably derived largely from KCl-bearing fertilizers rather than from road salts or natural sources. Nitrate nitrogen, in contrast, has a more uniform curve with a slight but very consistent rise of more than 3 ppm during the study period. NO_3-N can be derived from a variety of anthropogenic and natural sources, including human and animal wastes, fertilizers, and nitrogen fixing bacteria in the soil. Most sites in Mystery Cave show relatively uniform but lower levels of NO_3-N. Some sites show more variation, with peaks associated with recharge events. The remarkably constant but high NO_3-N suggests (but does not prove) a relatively constant source of NO_3-N within the tributaries to Turquoise Lake. Both Cl^- and NO_3^- are extremely mobile anions that should be readily flushed from surface stores during recharge events. If fertilizers were the direct primary source of both anions and they were applied simultaneously to fields recharging Turquoise Lake, then we would expect near-simultaneous peaks in their concentrations. This does not occur. Other processes or separate source areas must be involved.



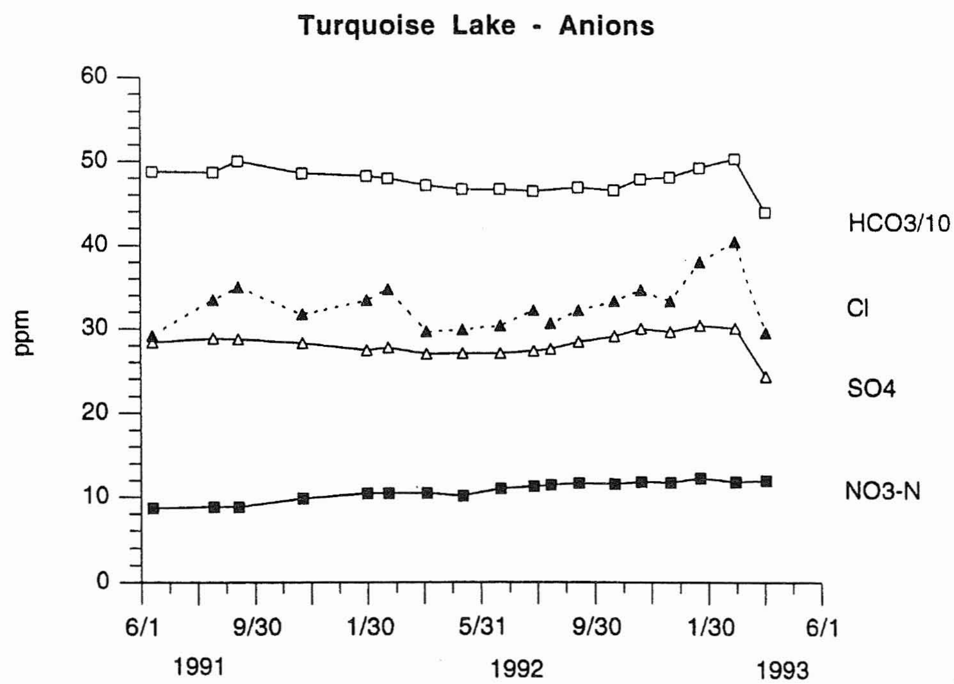


Figure 6. Time series of cations and anions at Turquoise Lake

Frozen Falls Area

Frozen Falls Pool is a perennial pool in the main passage, about 400 ft from the Mystery I entrance. The pool is normally about 3 ft deep at its deepest point and measures about 5 x 10 ft. A large and somewhat irregular breakdown block fills perhaps a quarter of that area, making an estimate of the pool's volume difficult. The pool has a speleothem-lined bottom. Drainage is through a small hole in the wall on the north side of the passage.

The Frozen Falls area includes Frozen Falls Pool (FFP) and its four primary tributaries: 1) Frozen Falls Drips (FFD), 2) the Drips Across Bridge (DAB), 3) the Pipe Organ (PO), and 4) the drips Across from the Pipe Organ (APO). Below the Pipe Organ are several small flowstone pools with a few liters volume. Most of the water from the Pipe Organ passes through the largest of the pools, known as the Pipe Organ Pool (POP).

The water at FFP varies from clear to turbid, depending on weather conditions. Turbidity rapidly increases during storms as silty water flows from FFD, DAB, and the PO. No turbid water has been noted at the drips Across from the Pipe Organ. A rapid change from clear to turbid water during brief but intense thunderstorms has been observed several times. Clearly, direct and open flow paths connect the surface above the Frozen Falls area to the cave. The surface above this part of Mystery I is a hillslope in a reentrant to the dissected plateau adjacent to the Root River. The hillslope has thin soils, a limited loess cover, and areas of exposed bedrock, allowing for direct sediment-laden recharge to joints.

The primary tributary to Frozen Falls Pool is a set of stalactite drips on the ceiling directly above the pool. In the winter, during low flow conditions, when the land surface is frozen, most of the drip points here and elsewhere in Mystery I are inactive or have very low discharge rates. At low flow, most of the drips are from the ends of several large stalactites hanging out of a joint-guided cupola in the ceiling. Some of this water drips from the tips of the stalactites, but much of the water actually comes from ceiling joints and spreads out on the sides of the stalactites before falling. During periods of greater discharge, water cascades from additional sites in the ceiling as flows from joints.

The **Pipe Organ** is the second most important tributary to Frozen Falls Pool. Water issues mainly from joints and bed-joint intercepts on the wall and moves as sheet flow down the flow-stone to drip points. After passing through small flowstone pools (including Pipe Organ Pool) the water flows steeply down a flowstone slope into Frozen Falls Pool.

The final tributaries, **Drips Across Bridge** and the drips **Across from the Pipe Organ**, contribute only small amounts of water (less than a liter per minute at high flow) to Frozen Falls Pool. Drips Across Bridge are less than 30 ft from Frozen Falls Drips, immediately adjacent to the opposite side of the bridge spanning Frozen Falls Pool. The drips issue from a distinctive cluster of incipient stalactites on the upper south wall. At times of high discharge, much of the water drips directly onto the bridge or splashes onto it from the wall.

The water at **Across from the Pipe Organ** issues from a small joint on the south wall of the passage about 8 ft above the floor. A small flowstone mound has built up at the opening of the joint. The water issuing from the joint is probably perennially supersaturated with respect to calcite and must be rapidly degassing as it enters the cave. The water spreads out as a thin film over the flowstone-covered wall, wetting an area about 4 ft across. Samples were taken from a small drip point on the flowstone about 4 inches above the floor, rather than from the joint, which is too high to reach. It is worth noting that the immediate area of flowstone on the wall is perennially wet. This keeps the flowstone in a stable, uncorroded condition as long as the water is not undersaturated and aggressive. Adjacent flowstone covering the wall a few feet farther into the cave (east) apparently is now perennially dry, and has deteriorated in its condition since its source was cut off. The adjacent, dry flowstone is noticeably corroded and flaky, a typical result of long-term drying of flowstone.

The major-ion chemistry of Frozen Falls Pool is determined by the mixing of its tributary waters, and by minor changes that occur in water chemistry within the pool, after mixing occurs. Such minor changes are most common during the coldest period of the winter, in which influx is small. Then, most of the sources are partly cut off due to the freezing of the land surface. The water is supersaturated and precipitation of calcite, particularly of calcite rafts, may occur. Scattered rafts have been observed in Frozen Falls Pool during the winter several times during this project. Precipitation of calcite will result in a decrease in the concentrations of calcium and bicarbonate.

Apart from the middle of winter, the chemistry of Frozen Falls Pool can best be described as highly variable. Time-series plots of chemical parameters (Figures 7 and 8) are extremely spiky, with abundant abrupt variations. This is not surprising, because several of its tributaries respond directly to surface recharge events, in which surface water rapidly flows into the cave, raising discharge above lower base-flow discharges. During recharge events, dilute waters from the recharge mix with waters already present, thus lowering concentrations of major ions such as calcium, magnesium, bicarbonate, nitrate-nitrogen, sulfate, and chloride. Even sodium -- which rarely shows significant variation in Mystery Cave waters, shows a spiky response. Conductivity, which reflects the total dissolved solids concentration, or TDS (TDS is the sum of all the ions, expressed as ppm or mg/l), also is spiky.

Water temperature shows much less of a tendency to vary. The water temperatures of Frozen Falls Pool and its primary tributary, Frozen Falls Drips, are usually close. The other tributaries show much greater variation in water temperature, but contribute much less water to the pool.

During the March 30-April 2, 1993 flood, water rose from lower level fissures in Mystery I and flooded much of the commercial trail. The flood completely inundated Frozen Falls Pool and changed its chemistry. The effects are not so easy to see as they were at Turquoise Lake, because the chemistry at Frozen Falls Pool is highly variable, while that of Turquoise Lake is not. Nonetheless, examination of the the last sampling on the time-series plots of Figures 7 and 8 (a few days after the March 30-April 2 flood) shows distinct drops in water temperature, conductivity, calcium, magnesium, sodium, bicarbonate, nitrate-nitrogen, sulfate, and chloride. In contrast with circumstances at Turquoise Lake, however, water temperature was slower to return to the near-normal water temperature of about 9°C. The temperature was at 7.65°C when measured on April 3, 1993.

The Frozen Falls area has galvanized steel railings, or railings and bridges, near or immediately below drip points. Thus the water draining into Frozen Falls Pool has a significant drip and splash component that has come into contact with a source of zinc. These bridges were installed during the re-commercialization project in Mystery I at various times during the winter, spring, and summer of 1992. We were able to measure elevated zinc concentrations in Frozen Falls Pool, compared to waters feeding the pool and waters elsewhere in Mystery Cave. Zinc concentrations were in the parts per billion range and do not exceed regulatory concentration limits.

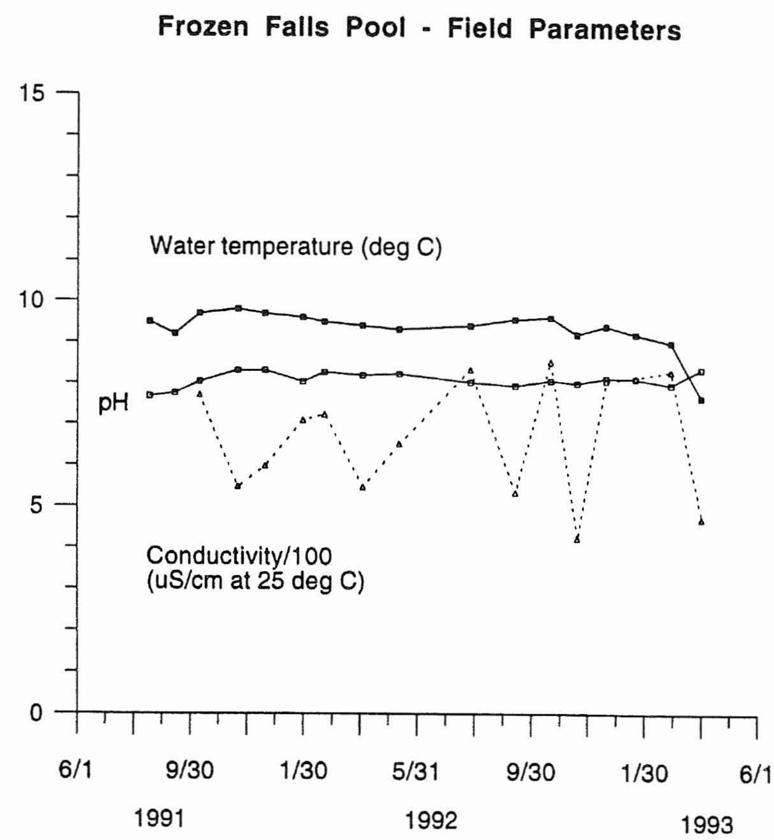
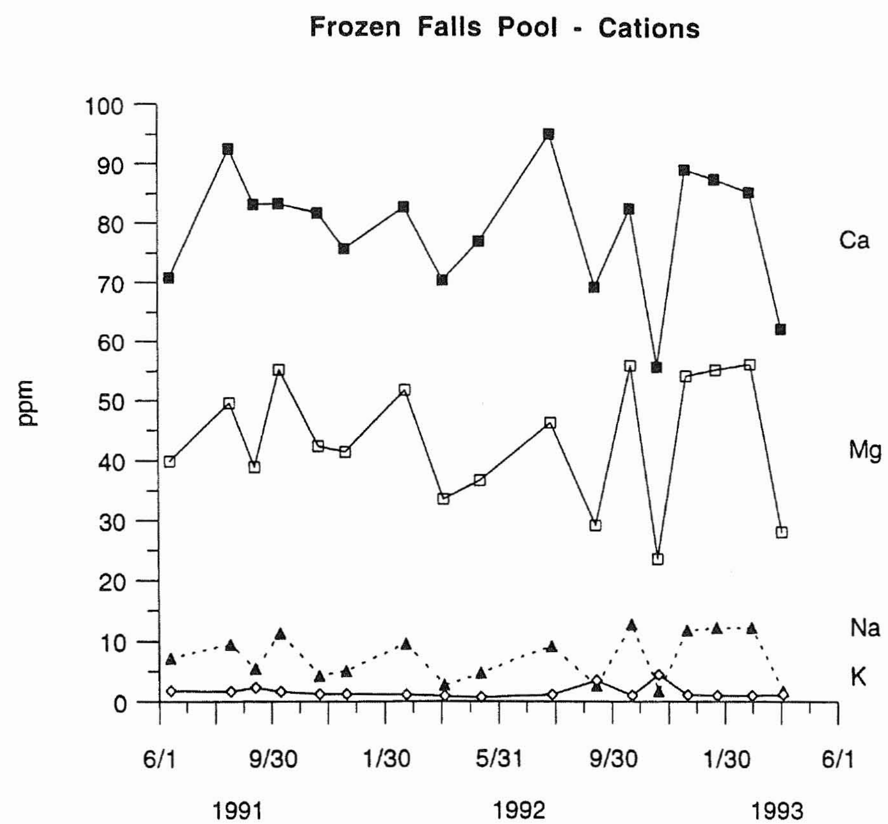


Figure 7. Time series of field parameters from Frozen Falls Pool.



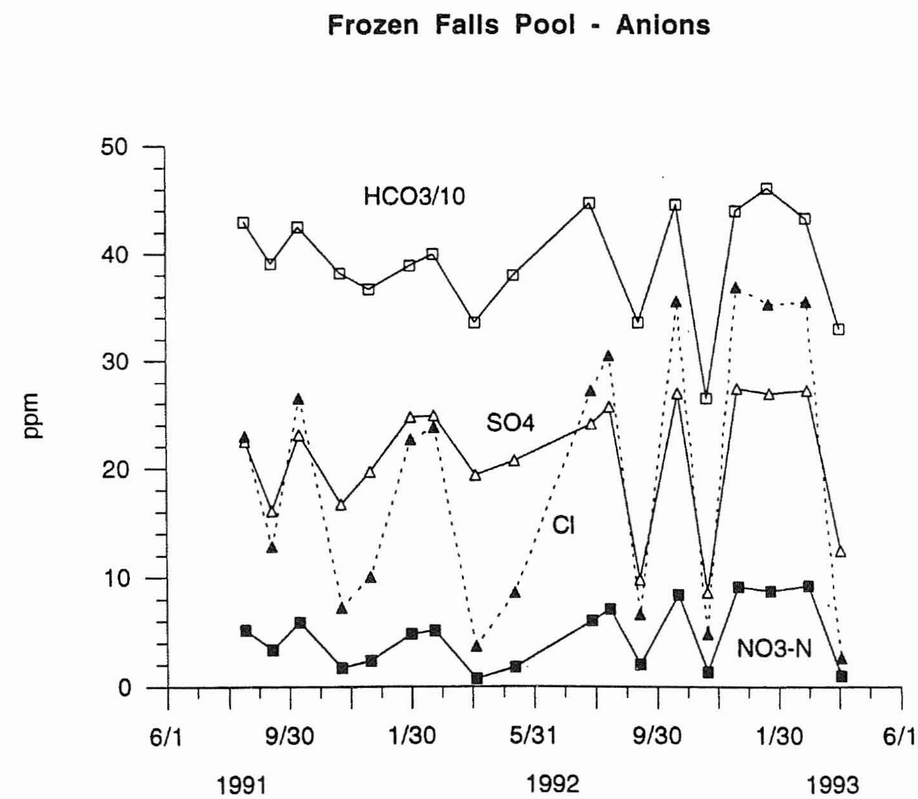


Figure 8. Time series of cations and anions from Frozen Falls Pool.

Sites in Mystery II

Blue Lake, Blue Lake Springs, and Blue Lake Drips

Blue Lake is in 4th Avenue of Mystery II, between the Hills of Rome and Diamond Caverns. **Blue Lake Springs** are intermittent springs in the floor of the gravel trail, about 60 ft to the east of Blue Lake. **Blue Lake Drips** are a drip site below a large flowstone mound immediately west of Blue Lake.

Immediate Sources and Sinks of Flow at Blue Lake

The water of Blue Lake comes primarily from a passage to the north of 4th Avenue. Some water may also enter from beneath the flowstone mound. Alternately, water from the mound may drain through nearby breakdown without entering Blue Lake.

Water leaves Blue Lake in several ways. Most of the water leaks slowly through sediments (silt and breakdown) in the floor. Some loss may be through fractures in the walls of the passage, which is in the Dubuque Formation (interbedded limestone, shale, and dolomite). A minor amount of the water must evaporate. When the water level is high, some water drains out the retaining wall at the east end of the bridge, flows through floor sediments beneath the graveled tourist trail, and then reappears as seeps and springs at Blue Lake Springs. At high stage in Blue Lake, Blue Lake Springs discharges up to a few liters per minute.

Significance of Blue Lake and Adjacent Sites

The hydrology and chemistry of Blue Lake are produced by several processes that are significant throughout the cave. For example, the changes in the water levels and chemistry of Blue Lake are a record of movement of water from the surface into the soil and loess and then into the cave. They provide information on water storage in the area upstream of Blue Lake as well as at it. Finally, they provide information relevant to our understanding of the raft cones at Blue Lake. Blue Lake is on the tour in Mystery II and provides a natural opportunity to discuss some of these topics with visitors.

The following discussion uses observations of stage (water level), drip rates, water temperature, conductivity, and chemical analyses, to explain the hydrology and chemistry of Blue Lake and its companion sites. A number of rather complicated graphs are shown. Only parts of the features in these graphs are discussed. The discussion concentrates on the primary conclusions. Further details may be obtained from the technical report.

Raft Cones and the Chemistry of Blue Lake

Part of the charm of Blue Lake derives from the presence of raft cones. The lake has the only raft cones visible along the tour routes in Mystery Cave. Raft cones are relatively rare conical speleothems built up of accumulations of calcite rafts. At times, Blue Lake water is sufficiently saturated with respect to calcite to precipitate thin calcite flakes known as rafts.

Although calcite is denser than water, the rafts initially float on the surface of the water due to surface tension. Drips from individual points over the lake which fall on the rafts cause them to sink. As the rafts sink they fall straight down and accumulate as piles beneath the ceiling drip points. As the rafts accumulate, they are cemented together by further precipitation of calcite, eventually building up into the conical mounds seen in the lake.

Fluctuating water level can also play a role in the formation of raft cones. As the water levels fall during dry periods and drop below the tops of the cones, rafts floating on the water can drift into the cones and become attached. Raft cones are extremely delicate and fragile, in part because of their porous nature (imagine a cone made of corn flakes held together by chocolate). Unlike stalactites and stalagmites, which tend to be firmly cemented to bedrock substrates, and which tend to be strong, raft cones are relatively weak accumulations of rafts and are less solidly cemented. The raft cones at Blue Lake appear brown because of mud and silt, but this fine material does not merely cover the cones, it is also incorporated within their structure. Raft cones tend to be only weakly attached to pool floors and run the risk of being dislodged if pressed sideways.

Blue Lake water was supersaturated or at saturation with respect to calcite, aragonite, and dolomite on all 21 of the sampling dates from 1991 to 1993 (Figure 13). Blue Lake water probably is saturated with respect to calcite all of the time, assuming that water is always present. However, floating calcite rafts were noted on only a few occasions during the study. Although no systematic check was made for rafts, the chemistry of Blue Lake is compatible with their continued deposition. No matter when they may have begun growing, the raft cones, in all probability, are still actively being deposited.

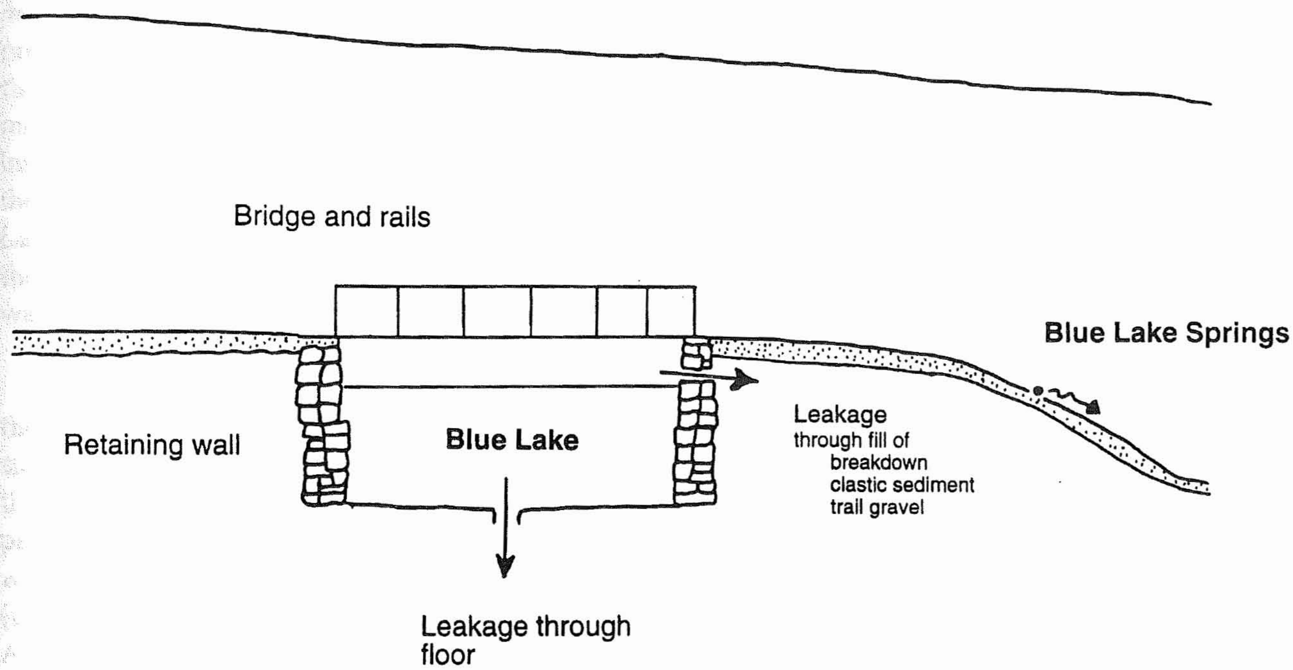
Is Blue Lake Perennial?

We do not know if Blue Lake is perennial. It may be, or it could dry out entirely over a period of extended drought. Water level fluctuated over 10 ft between 1991 and 1993. At extremely low stage, the lake breaks up into a series of pools at 4th Avenue and in the tributary passage to the north. At the lowest levels observed, water depth was less than half a foot in the deeper of two isolated pools immediately below the center of the bridge over Blue Lake. At the highest levels, water was ten and a half feet deep and only four feet below the top of the third rail post from the west end of the bridge. (The third rail post is our local reference point, datum, for water level measurements in Blue Lake.)

Interpreting the Hydrology and Chemistry: Blue Lake as a Leaky Bathtub

Blue Lake can be pictured as a huge but leaky bathtub (Figure 9). Water flows into it only *after* the largest recharge events each year. If flow into the lake exceeds the capacity of the drains to accept water, then the lake starts to fill. If the recharge rate is sufficiently high, Blue Lake fills rapidly. Periods without recharge at the surface lead to a decrease in flow into Blue Lake and the water level declines. At low stage, a small volume of water is stored at Blue Lake; at high stage, a large volume of water is stored.

A. Blue Lake and Blue Lake Springs



B. Hydrologic model for Blue Lake and Blue Lake Springs

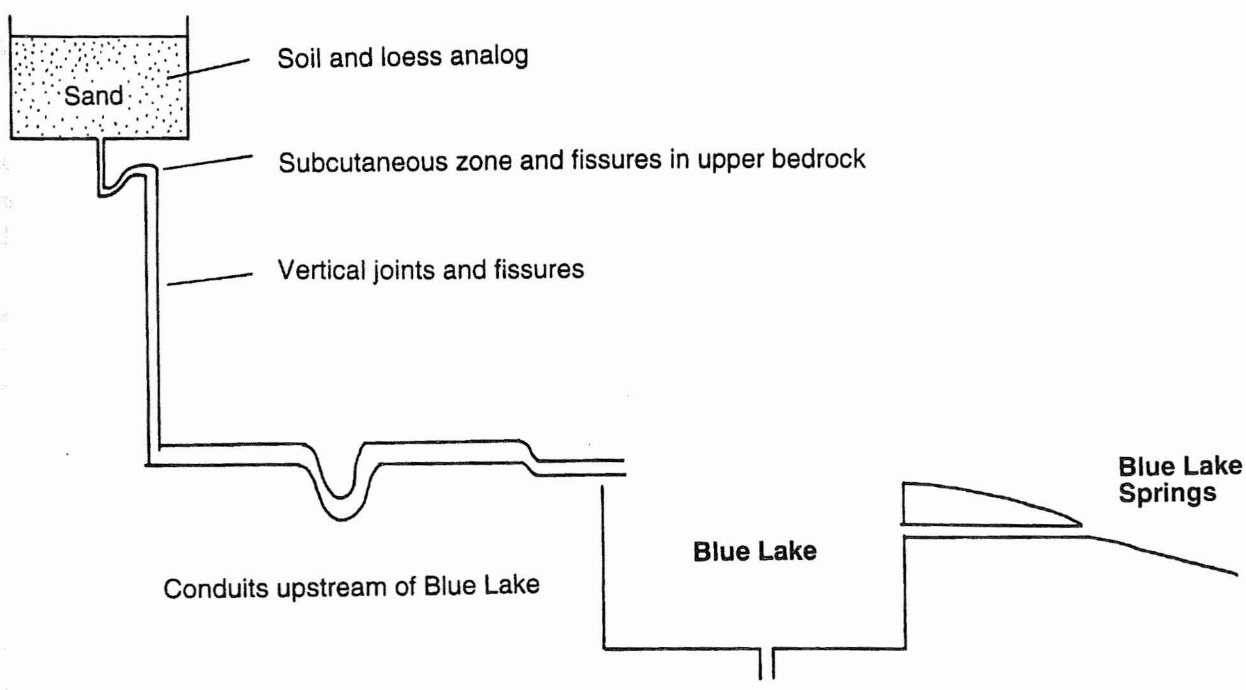


Figure 9. The hydrology of Blue Lake.

The water that flows into Blue Lake varies in its chemistry. We have no *direct physical access to the chemistry of the incoming water*, except at very low stage, and then only if we are present to sample that water upstream of its discharge point into Blue Lake. As water level rises, the passage is flooded. We then lose direct access to input water, and can only sample the mixture of incoming water and Blue Lake water. When we are not present, at very low stage, our instruments (which measure water level, water temperature, and conductivity) can readily detect the influence of the incoming water, if the temperature and conductivity vary from that of Blue Lake. The volume of incoming water is large compared to that of the water already present, and the two probably mix well. Thus we can see the chemical and temperature signals of the incoming water.

However, as stage rises, the volume of incoming water becomes small compared to that of the water already present. Under these conditions, mixing may be slow, especially at the highest stages. Moreover, because the instruments are at a fixed location near the center of the lake near the deepest point, they can only detect temperature and conductivity at that point. If these parameters vary significantly with location (vertical or horizontal) as water level varies, then we will not see these variations. The periodic sampling (approximately monthly) for field parameters (temperature, conductivity, and pH), and for cations and anions, was made on 'accessible' water. Accessible water varied in its location depending on stage, but usually was collected at the west end of the lake, from the top foot of water. The easiest part of the record to interpret should be periods of very low stage and periods immediately following an influx of water when stage is low. It is these periods that we shall concentrate on here, for they provide the most readily interpretable signals -- signals that contain information about the recharge to Blue Lake, and water storage upstream of Blue Lake.

Drain and Fill Events at Blue Lake: Nomenclature

Between January, 1992 and June, 1993, Blue Lake underwent two and a half major cycles of fill and drain events. Figure 10 is a summary of the water level record for Blue Lakes for this study and shows the numbering system we have adopted. The record begins when the lake was full in the late winter of 1992. We see the end of a fill event that began before the Blue Lake instrumentation was installed. After installation, Blue Lake underwent one complete drain event, a partial fill and drain event, and another major fill event. The instrumented events will be referred to as Drain event 1, Fill event 2, Drain event 2, and Fill event 3. Because the fill event before Drain event 1 was not instrumented except near its end, it will not be discussed. Nor will the later Drain event 3, which covers the late summer and fall of 1993, be discussed here.

Drain Event 1

Figure 11 shows the stage, water temperature, and conductivity (as 1/volts) for Blue Lake for 1992. At the start of the record (March 27, 1992), stage was high, about -5 ft (five feet below datum). Stage fluctuated slightly over the following three weeks, rising to a height of nearly -4 ft. The stage then fell from May 1 onward in a smooth curve over most of 1992. By early October (day 275 = October 1) water level had fallen to a minimum at about -14.15 ft (point X on Figure

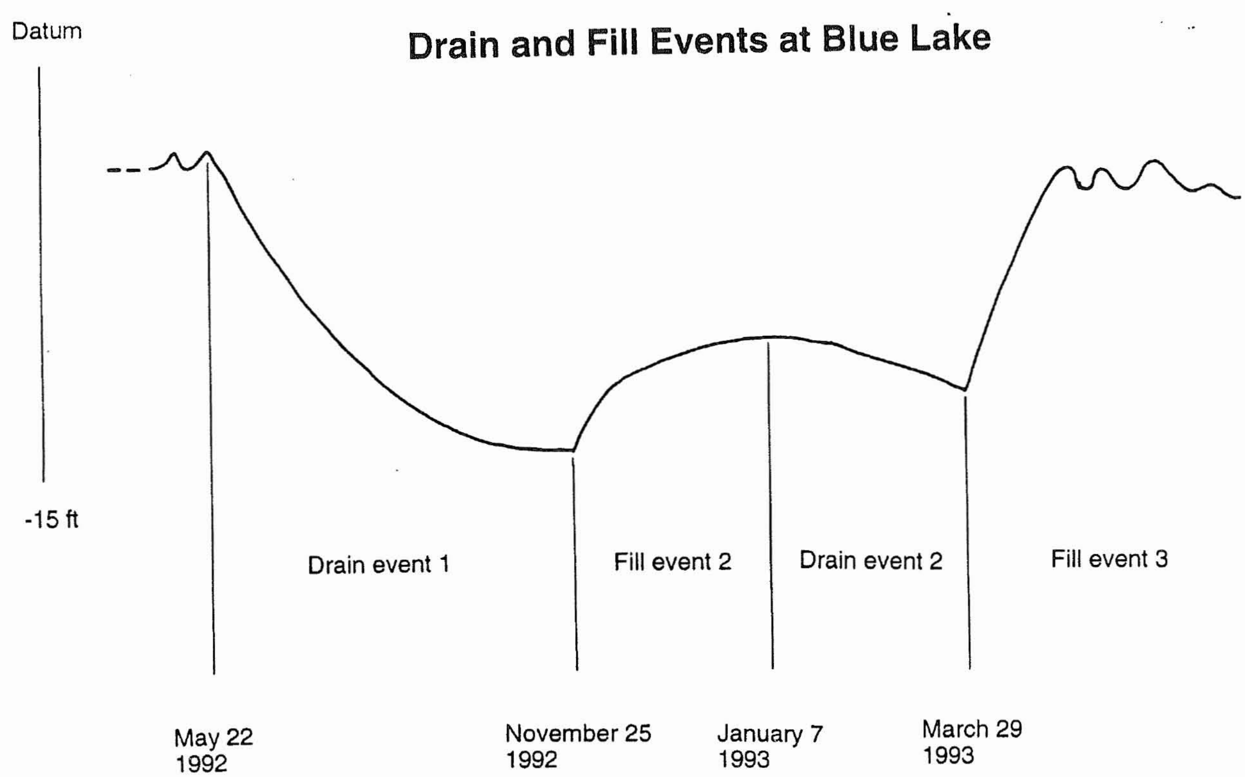


Figure 10. Nomenclature for instrumented events at Blue Lake.

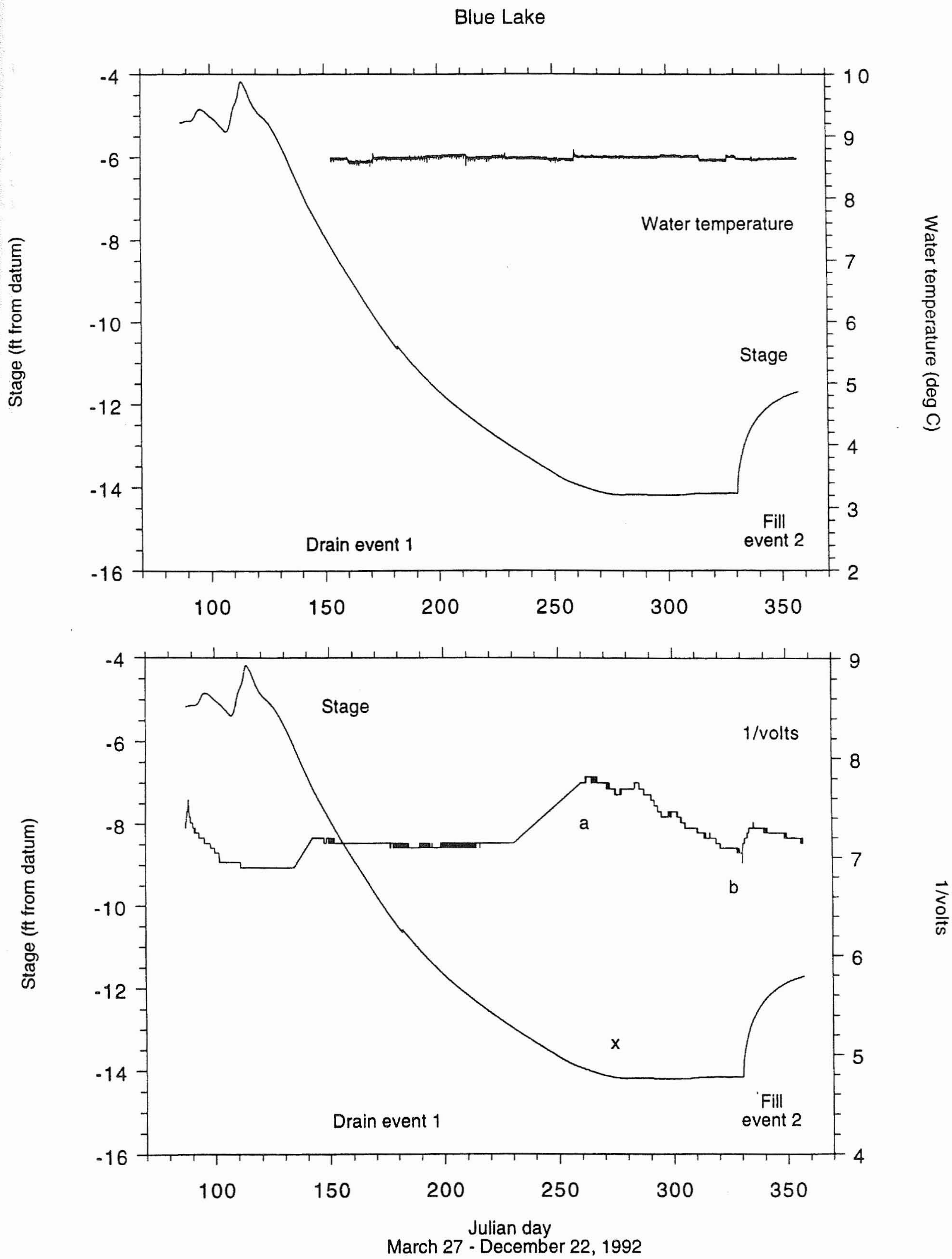


Figure 11. Stage, water temperature, and conductivity (1/volts) at Blue Lake in 1992.

11). Stage remained nearly constant until the onset of Fill event 2 in late November. During this time of constant low stage, no visible inputs (either as streams or seeps) to Blue Lake were noted.

Figures 11, 12, and 13 compare the stage, water temperature, conductivity, water chemistry and saturation indices for Blue Lake for 1992. During the first drain event, conductivity as 1/volts remained constant, rose, and then declined. The decline is shown on Figure 11b between points a to b. Field conductivity (Figure 12; independently measured at the times of water sampling) behaved similarly. Rises in conductivity are generally correlated with increases in the concentrations of dissolved ions; decreases are correlated with decreases in the concentrations of dissolved ions.

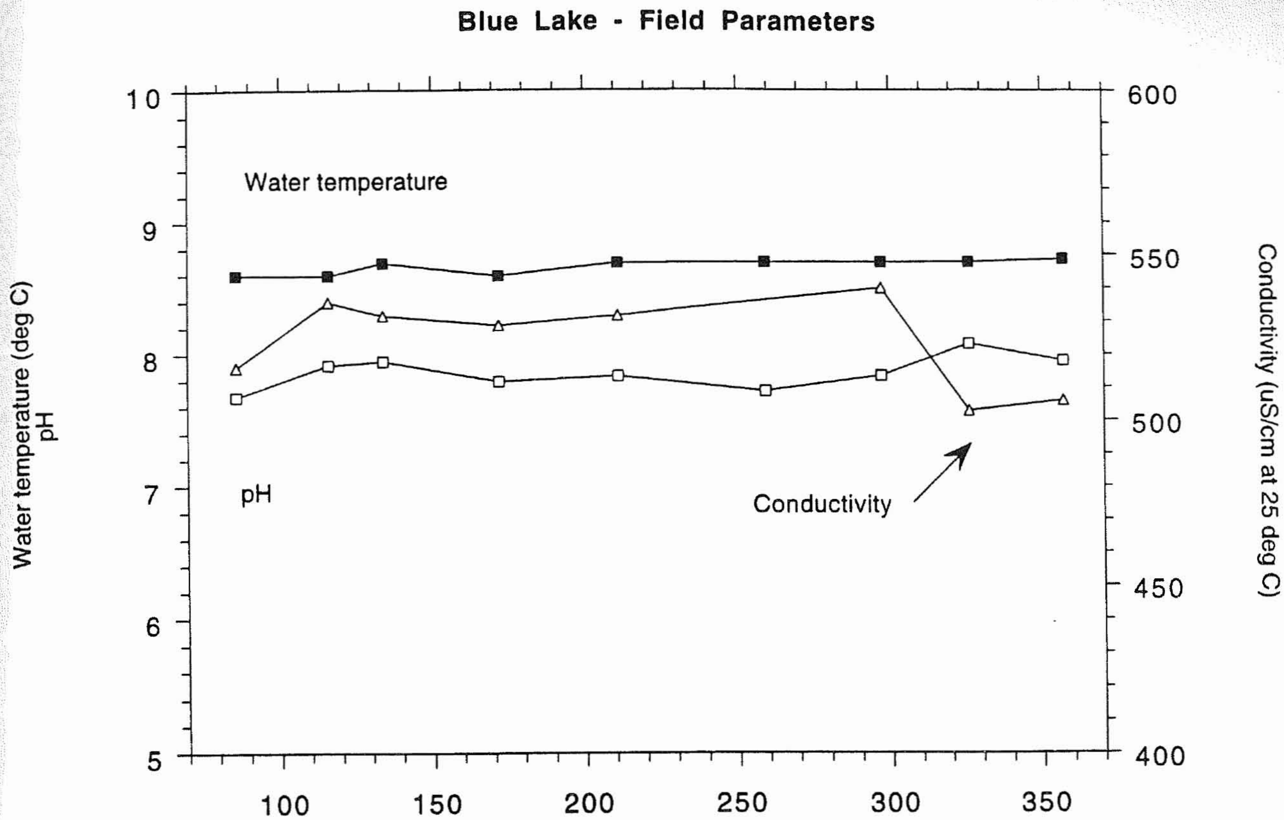
It is probably not possible to correlate chemical variations and stage in a detailed fashion during the bulk of the drain event. Among other problems, we do not know exactly when input to the lake ceased, and there are problems in correlating recharge during a declining stage.

However, at the end of the first drain event, from day 255 (September 11, 1992) until the onset of the second fill event on day 330 (November 25), stage is very low and only slowly declining or constant. During this time (points a to b in Figure 11), conductivity (as 1/volts and field conductivity, Figure 11b) declined, as did concentrations of Ca^{+2}, Mg^{+2}, and HCO_3^- (Figure 13). Only SO_4^{-2} of the major ions increased.

One possible explanation, but not the only explanation, is as follows. As stage declined, the pressure head at the base of the pool declined, and so the infiltration rate of water into the basal sediments declined. Eventually, so little water was left that the driving force to produce infiltration into the fine-grained sediments was practically nil, and the remaining water sat and evaporated slowly. At this point, calcite precipitated, probably forming calcite rafts and other speleothems. This removed Ca^{+2} and HCO_3^- from the water, producing the observed drop in conductivity (Figure 11b).

Fill Event 2

Fill event 2 followed a storm that began on November 19 (day 324) at 2:30 PM and ended about 37.5 hours later at 4:00 AM on November 21, 1992 (Figure 14a). Total precipitation at the Weather Station at Mystery I was 2.18 in. The air and rain temperature varied in a complex fashion during the storm (details of this event are in the Technical Report). The net effect is that recharge water from the storm was probably < 5°C and well below the cave temperature. The temperature of the upper soil should have been colder than 5°C, based upon air temperatures, which were below 2°C nearly all of the time from November 14 to the onset of the storm. In any case, the bulk of the precipitation recharging the soil zone was probably colder than the mean cave temperature of 8.7°C. Any surface recharge which rapidly reached cave locations should therefore have carried water with a temperature less than 8.7°C. More slowly recharging water, water that had a longer contact time with lower layers of soil, the underling loess, and bedrock, would have warmed to the mean cave temperature of 8.7°C.



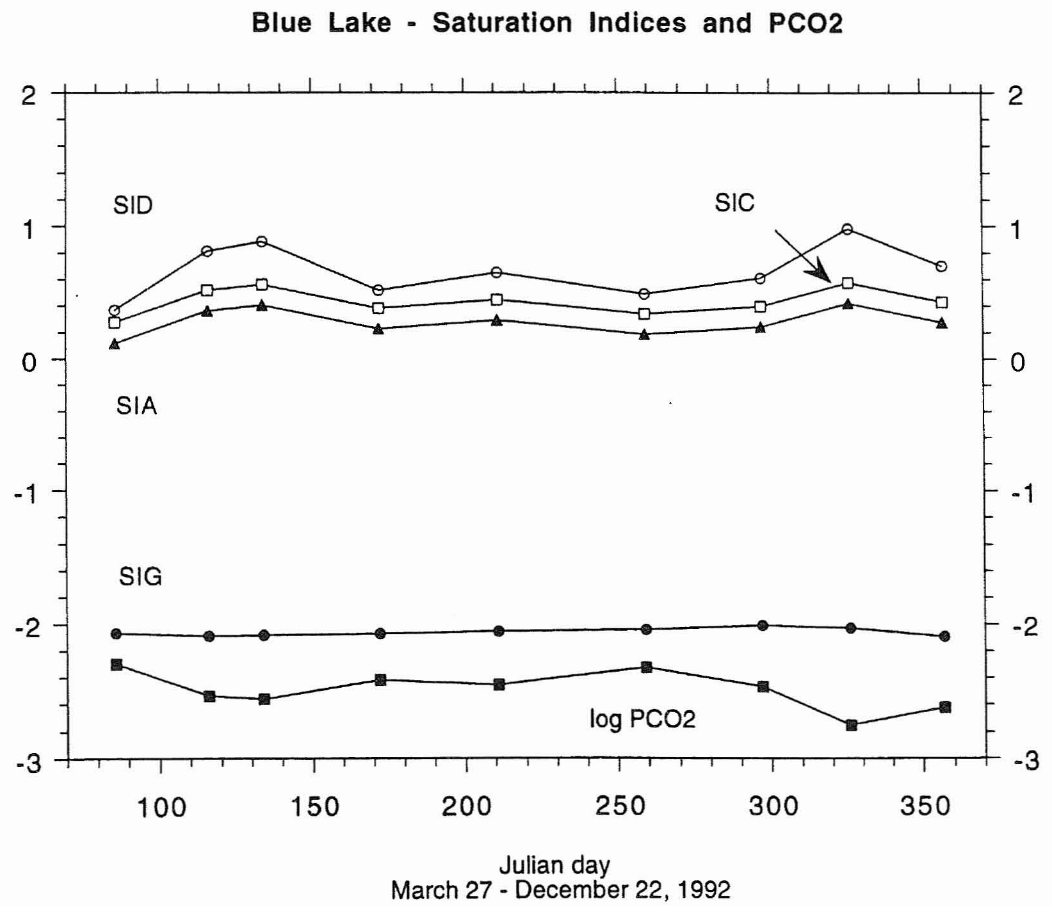


Figure 12. Field parameters, saturation indices and PCO_2 at Blue Lake in 1992.

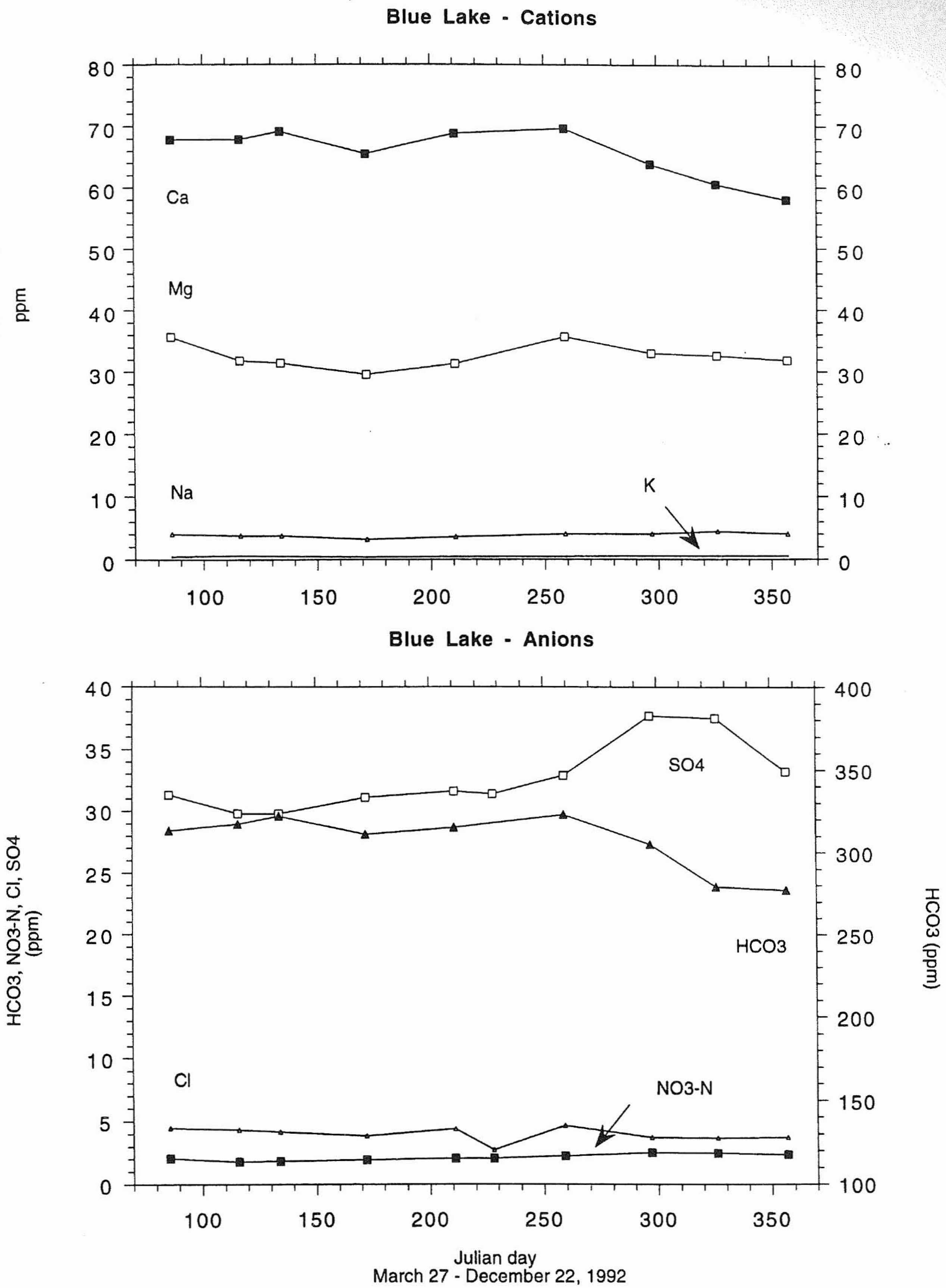


Figure 13. Chemistry of Blue Lake, 1992.

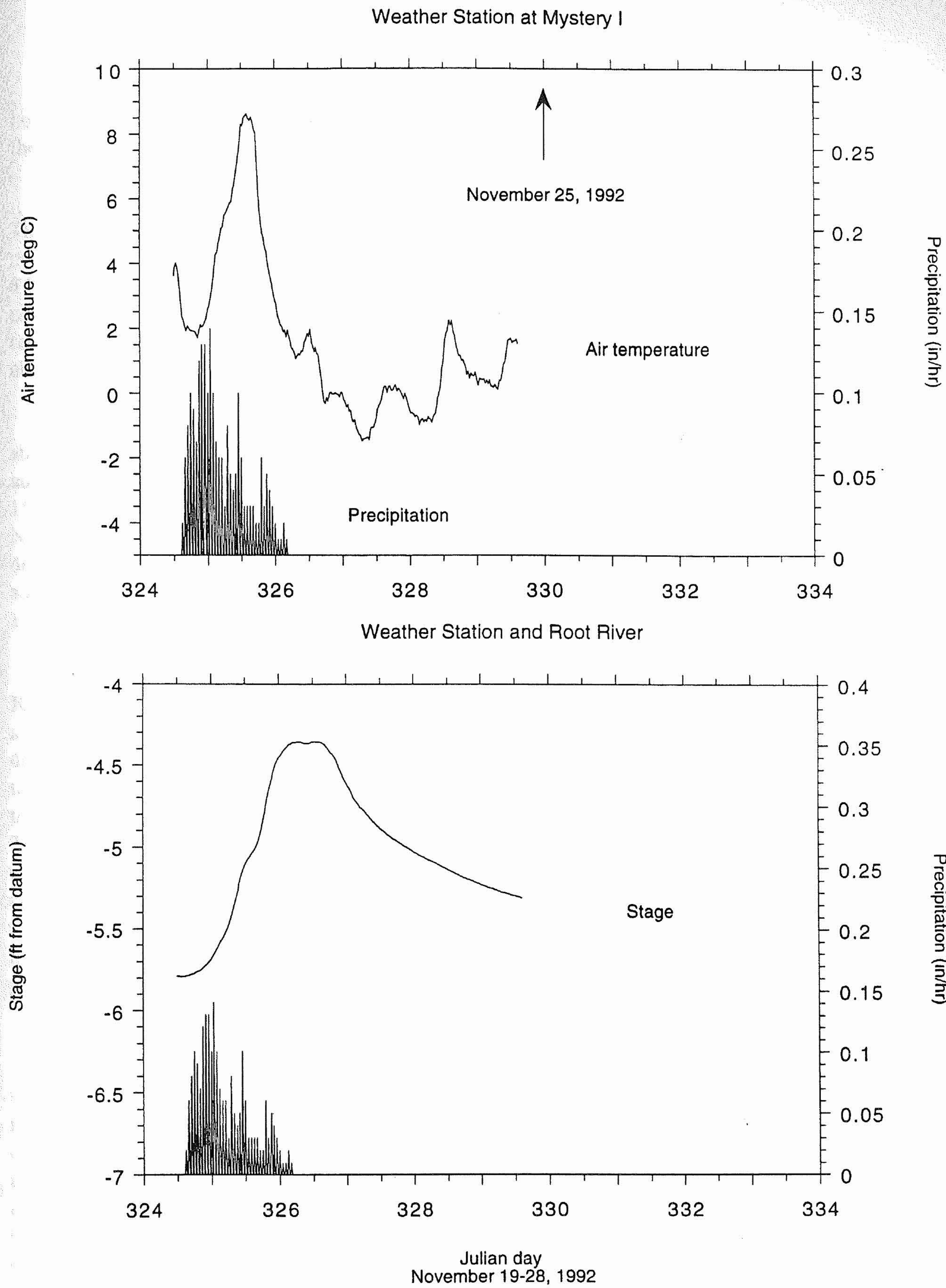


Figure 14. The November, 1992, storm and the response in stage on the Root River.

In response to the storm, the Root River rose about 1.5 ft to a flat crest lasting eight hours. The crest began near midnight at the end of November 21, about 4 hours before the end of the storm.

No major response in stage was recorded at Blue Lake until November 25 (Figure 15). The water level data in Figure 15 for Blue Lake shows that stage was nearly constant at -14.15 ft until November 25 (day 330). [The fluctuations in water temperature and the offset from 8.6 to 8.7°C beginning about 12:00 on Julian day 326 are artifacts. The site was visited that day and the conductivity and water temperature probes were adjusted. It is possible that this visit is responsible somehow for the slight offset in the stage on day 326 although that offset occurred about 4 hours after the visit.]

Fill event 2 began almost 6 days (141 hours) after the onset of the storm (Figure 15), at about 11:15 AM on November 25, 1992 (Julian day 330). Water temperature initially declined at about 11:15, and fell by .04°C total over the next day. Conductivity, expressed as 1/volts (Figure 15), initially dropped at about 11:30, but then began to rise. Conductivity continued to rise until November 28, 1992 (day 333), remained at a peak until about December 7 (day 342), and then declined through late March of 1993 at the start of the Fill event 3 (Figures 16a and 17). The stage, in contrast, rose throughout December to a peak of about -11.58 ft from January 7-16, 1993. The stage then fell smoothly until the start of Fill event 3.

Any interpretation of these observations needs to begin with a comment on response time. **Response time** can be defined as the time it takes for a signal to be transmitted from a specified site of origin to a specified observation site. Several types of response times can be distinguished depending on the signal being observed. Water that flows between two sites has an associated travel, or transit time. This is the time it takes for water molecules to physically move between the sites. This response time has been called the **flow through time** (Ford and Williams, 1989). There is also an hydraulic response time. This is the time it takes for a hydrologic response to travel between the sites; it has been called the **pulse through time**. The pulse flow through time can be much faster than the water flow-through-time. For example, imagine a stream flowing at 3 ft/second. If an explosion were set off in the stream, the water away from the explosion continues flowing at 3 ft/sec, but the sound created by the explosion travels through the water as a pressure pulse at the speed of sound in water (about 5000 ft/sec).

More relevant to the present discussion is a second example. Imagine a plastic, clear-sided tank filled with very fine sand (Figure 9). (The sand is analogous to the soil and loess above the cave.) A narrow, clear plastic tube comes vertically out of the base of the tank, curves horizontally, and then has a U-shaped loop in it before turning vertical again. (The tube and U-loop are analogous to the fissures in the subcutaneous zone and fissures in the upper bedrock above the cave that can store water. The second vertical part of the tube represents vertical joints and fissures above the cave.) The narrow tube leads to a wider horizontal tube that has another U-loop before reaching a tank representing Blue Lake. (The lower horizontal tube and U-loop represent inaccessible voids that can store water, upstream of the point of interest in the cave.)

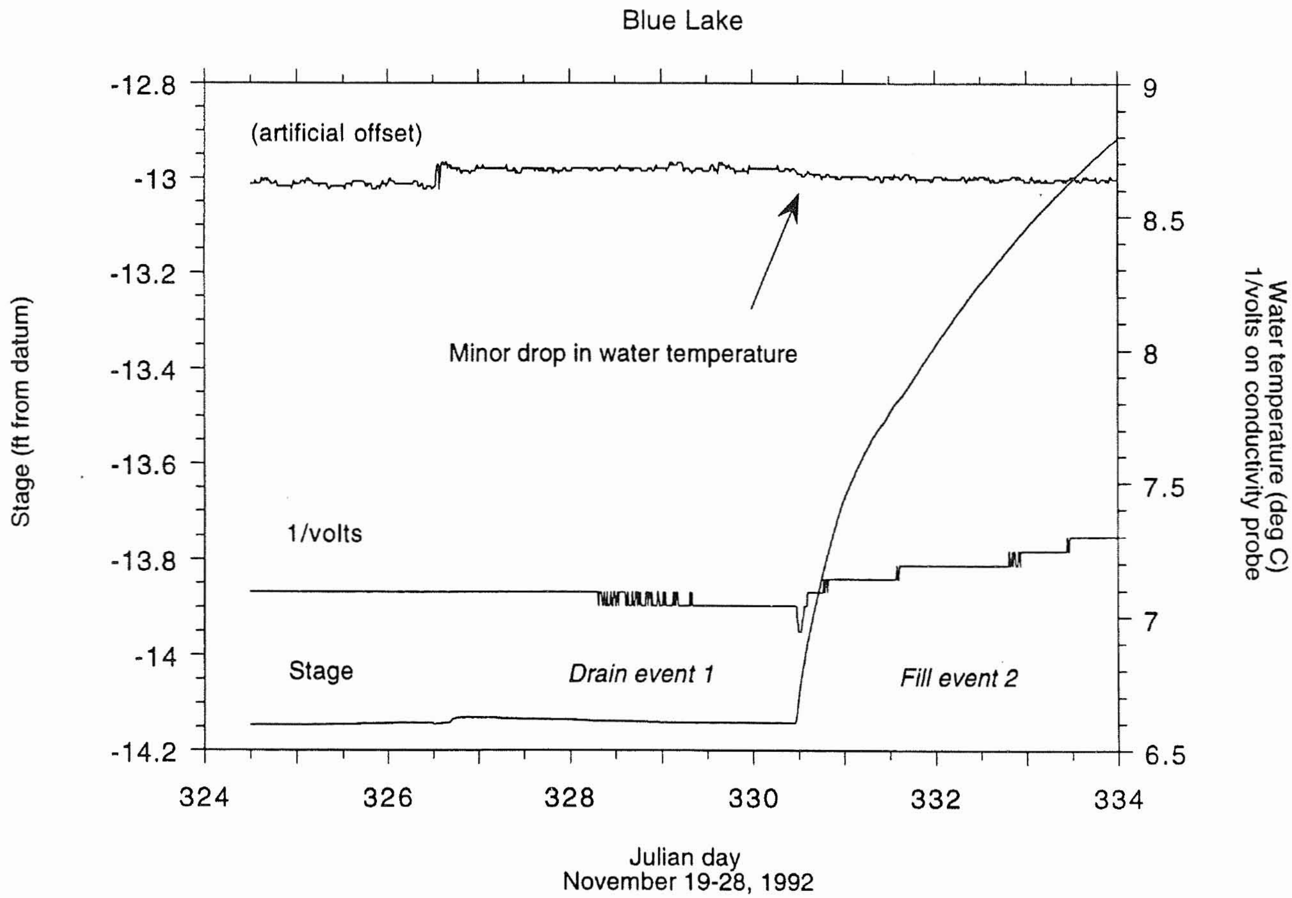
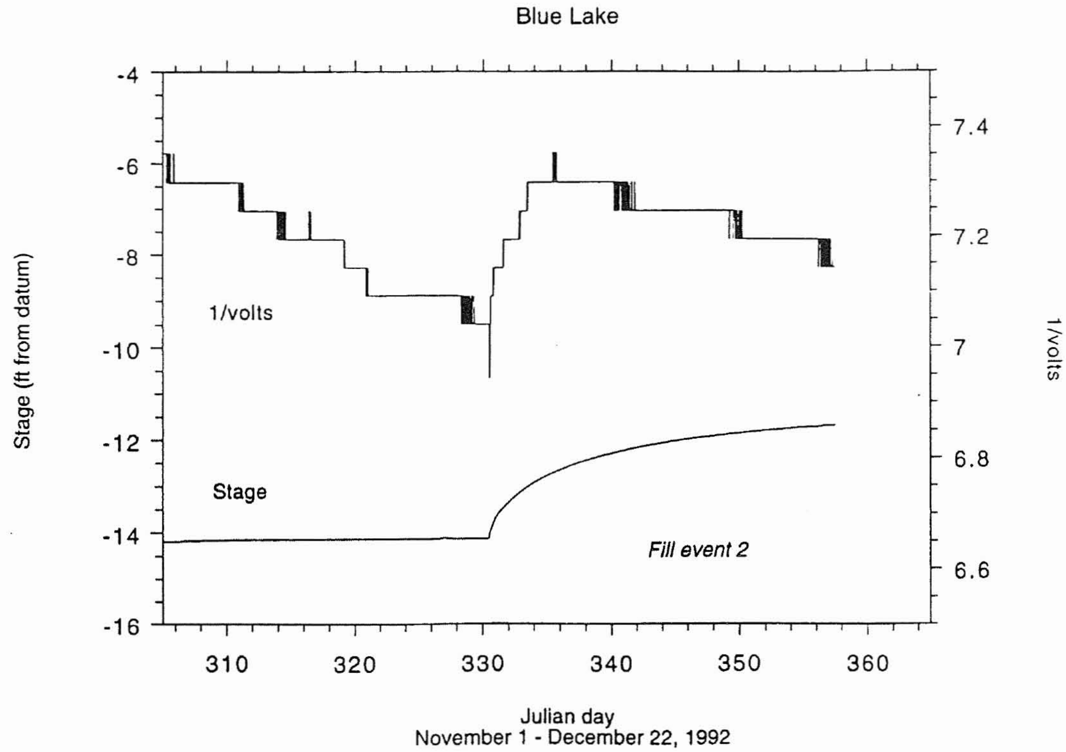


Figure 15. Stage, conductivity (as 1/volts) and water temperature at Blue Lake following the November, 1992, storm.



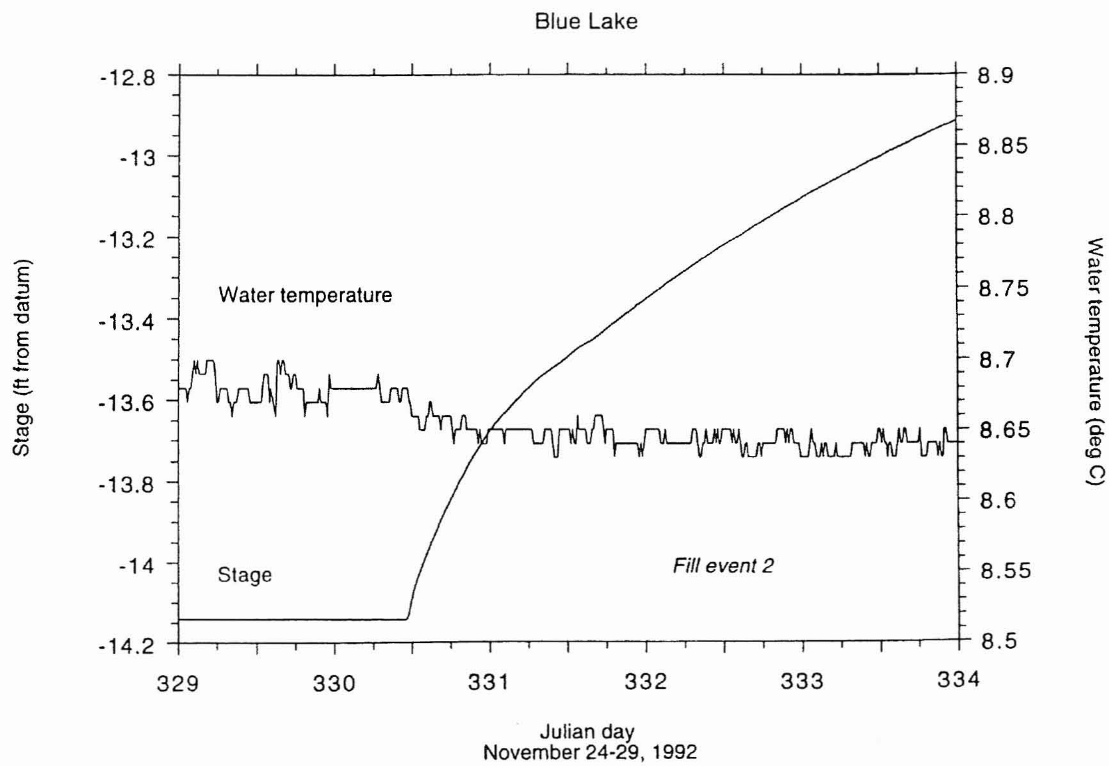


Figure 16. The record at Blue Lake from November through December, 1992, and detail of the water temperature drop between November 24 and 29.

Now dye some water red. Pour the red water (analogous to recharge) into the top of the tank, evenly over the sand surface. The water will infiltrate. If enough is added, water will eventually seep through the sand in the tank, flow through the upper part of the tube, fill the U-loop, and then flow out the end. Even after the red water is no longer applied, there should be leakage, as water drains under the influence of gravity, but eventually flow will stop. At this time, some red water will be left in the U-loop, and some will be left in the pore spaces between the sand grains; it is held in place by surface tension. This is stored water. Now add water dyed blue to the top. Again, it takes time for the water to seep in. Eventually, a small amount of red water comes out of the hole, followed by a larger quantity of blue water. We can say that the new recharge (blue water) has flushed out or *displaced* the stored water (red water stored in the U-loop and between the grains).

Now return to the distinction between pulse through time and flow through time. The pulse through time, as observed from the start of pouring of blue dye, is the time it takes until the small amount of red dye is displaced out the end of the tube. The flow through time is the longer time it takes before the blue dye first appears. Of course, there can be an added complication: the two dyes might mix somewhat, making it a little harder to distinguish the type of water reaching the observation point.

We can now return to our discussion of the observations at Blue Lake. The rise in conductivity at the onset of the second fill event suggests the following. Before the onset of the recharge event, subsurface waters were stored upstream of Blue Lake. This stored water could have been in the soil, the loess, the subcutaneous zone, and/or in fractures and conduits upstream of Blue Lake. These waters had a higher solute load, and a higher conductivity than the pre-storm waters in Blue Lake. These stored waters were displaced by the recharge. It took about 141 hours from the onset of the storm for the displaced water to first show up at Blue Lake. That displaced water most likely was the major component of water entering Blue Lake until the conductivity began to drop. By then, old stored water probably had begun to mix with new recharge water; this would cause the conductivity to decrease because the new water should be more dilute (fewer solutes). Also, as time progressed, newer recharge water began to make up a larger percentage of the total water flowing in, as well as the water stored in Blue Lake as water level rose.

The water temperature curves (Figure 11a and 17a) suggest that water temperature is close to normal cave temperature of 8.7°C throughout the study. But there are minor, abrupt offsets, and some fine structure is present. The manipulation associated with periodic maintenance of the probes is probably responsible for the offsets. The fine structure, however, does not correlate with the maintenance visits. It is possible to discern what we believe to be a real temperature response at the start of the second fill event. It is subtle, but it can be seen at the scale of Figures 11 and 15. More usefully, it can be seen at the scale of Figure 16b, which plots stage and water temperature for November 21-25. There appears to be a drop in water temperature of 0.03°C when the stage begins to rise. This is a small drop, barely bigger than the resolution of the thermistor wire, (0.01°C), but the drop appears to be real.

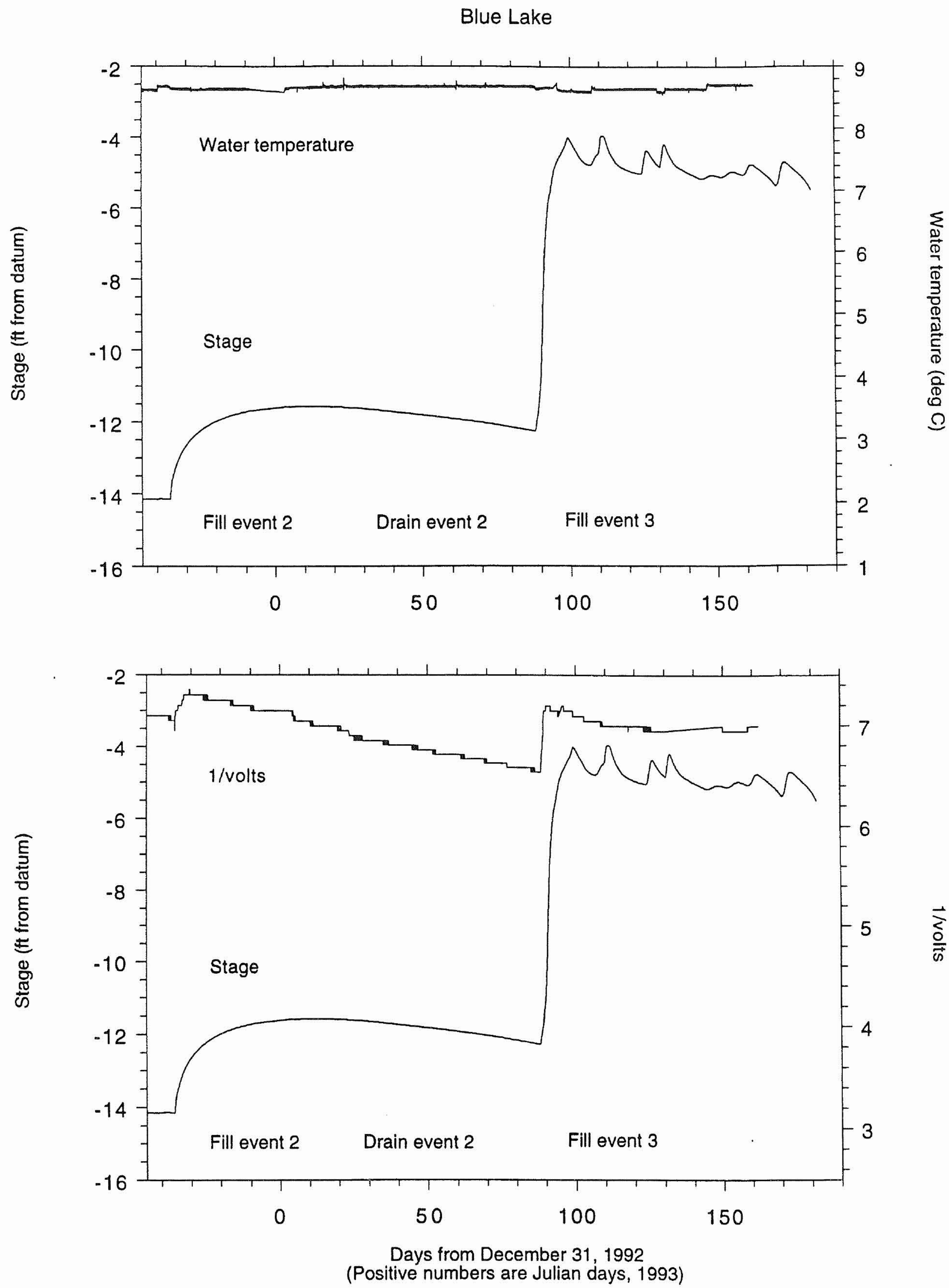


Figure 17. Stage, water temperature, and conductivity (1/volts) at Blue Lake.

The drop begins with the onset of the fill event; it probably indicates only that the water displaced into Blue Lake was barely colder than the water at Blue Lake. More importantly, it supports the interpretation that the initial water to arrive was displaced water. Had it been rapid run in water, it should have arrived sooner than 141 hours, and should have been colder (recall our estimate of the temperature of the recharge water was < 5°C).

Drain Event 2

Fill event 2 and the subsequent Drain event 2 were only partial. After the November storm, the surface above Mystery Cave froze, limiting recharge. We do not know if recharge to Blue Lake ceased totally during the winter, but many drip points in Mystery do cease or go to very low discharge in the period from roughly December to March. The water level rose to about -11.5 ft, then fell through the winter. Conductivity also fell during this period, as did calcium, magnesium, and bicarbonate (the first three data points in Figure 19a and 19b). As in the previous drain event, sulfate rose. For the very end of Drain event 1, at near-constant low stage with no visible influx of water, the suggestion was made that similar trends indicated precipitation of calcite in the small, isolated pools that made up Blue Lake. Here we have a single pool, just over a foot deep, extending upstream the full width of the tributary passage. Calcite rafts were not recorded in our field notes during that time period, but they could have been present.

One interpretation is that precipitation again occurred, but that is not the only possibility. Progressively more dilute water could have flowed into the lake most, if not all of the recession, producing a continually declining conductivity. However, there are difficulties with this alternative. As residence time of the incoming water increased, it should have become more concentrated, so there would be a tendency for conductivity to slow in its rate of decline. But the decline in conductivity is remarkably constant starting before the end of Fill event 2 and continuing throughout Drain event 2. (Compare the conductivity trend with that at the end of Drain event 1 between points a and b on Figure 11b).

No resolution to these problems will be offered here. The resolution of these problems -- if indeed one is possible -- will involve more technical chemical modeling that is beyond the scope of this interpretative report.

Fill Event 3

Fill event 3 is a response to a major recharge event, at the end of March and the beginning of April, 1993, that culminated in extensive flooding on the surface in southeastern Minnesota, both on the Root River and other surface rivers. The response in the cave was dramatic at Blue Lake. It was spectacular at Flim Flam Creek, which flooded for several days. It was traumatic on the Root River, and in the Mystery I commercial passages. Many of those passages flooded, in places clear to the ceiling. More extensive descriptions of the flooding are in a later section. To keep from being overly repetitive, and to preserve the continuity of explication of the in-cave responses to that flood, we shall not discuss the third fill event here. We note only that stage rose rapidly from about -12.3 ft to -4 ft, and that stage remained very high throughout the rest of the spring. Further, the third fill event displaced higher conductivity water into Blue Lake. Finally, a

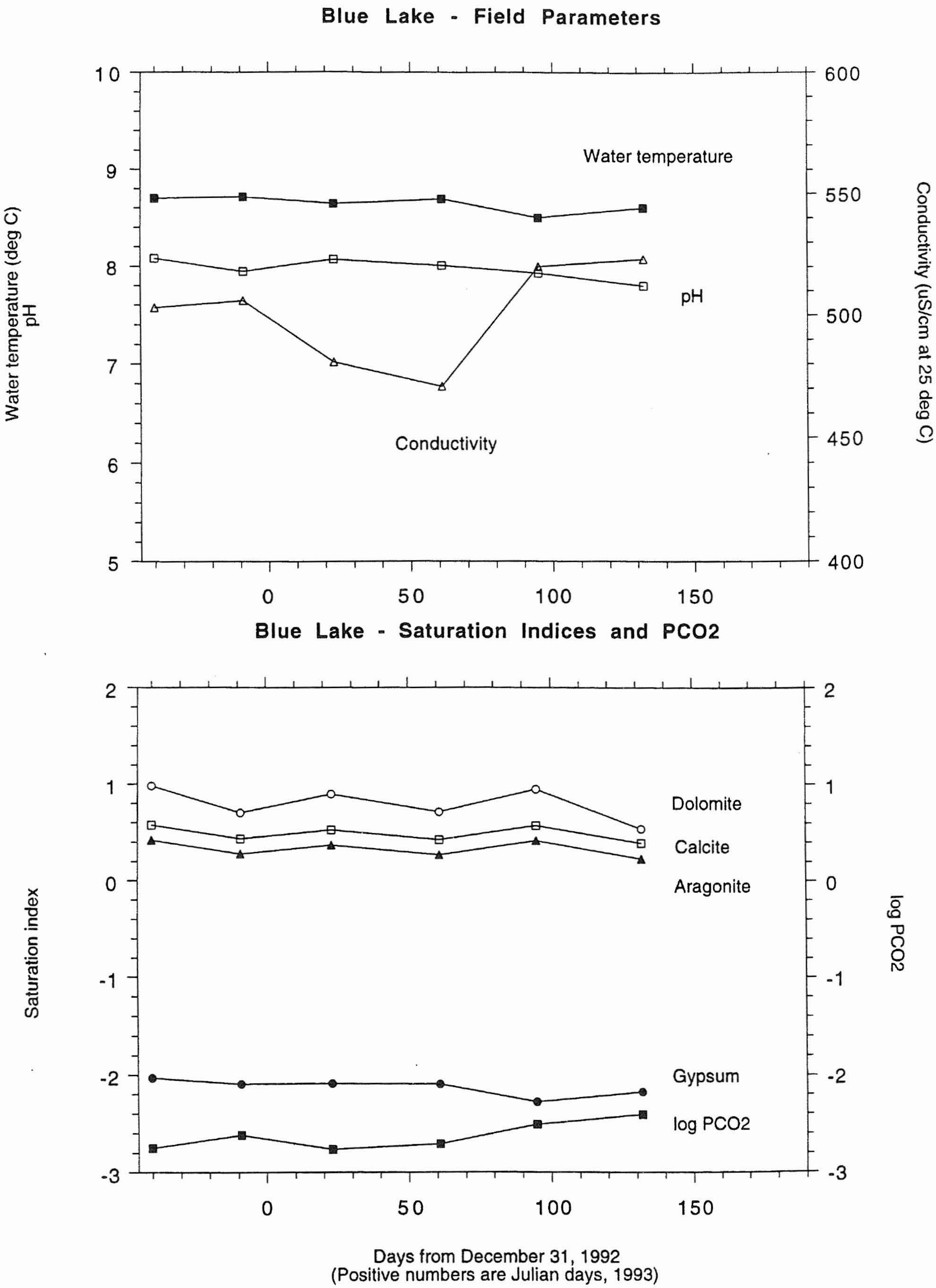


Figure 18. Time series of field parameters, saturation indices and log PCO_2 at Blue Lake.

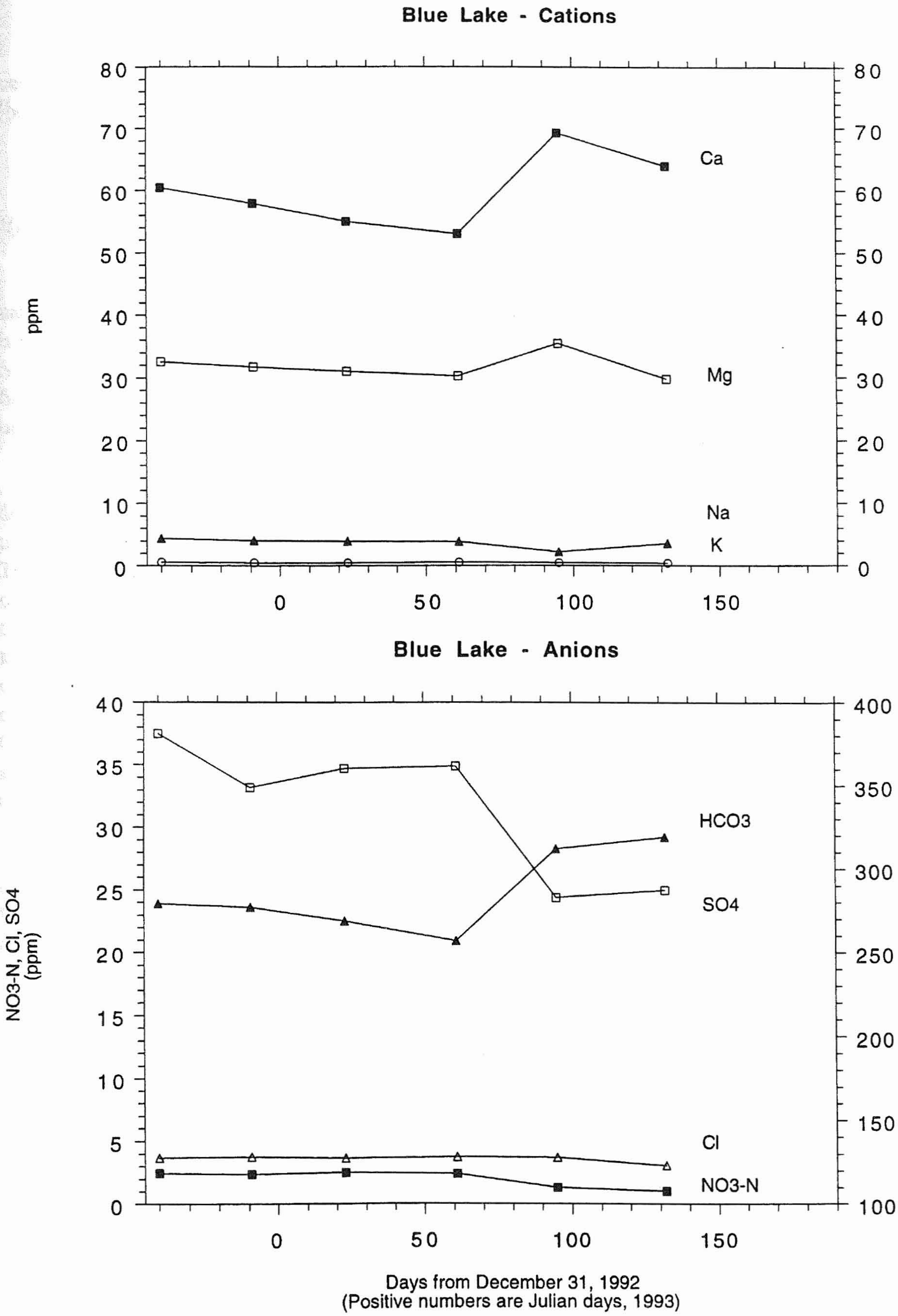


Figure 19. Time series of cations and anions at Blue Lake.

very small temperature drop, of similar magnitude to the one just discussed, was also observed (but is not readily seen in Figure 17a)..

Flim Flam Creek

Hydrologic Setting of Flim Flam Creek

Flim Flam Creek (FFC) is a perennial stream in the lower level of Mystery Cave. It is in a narrow fissure in the Stewartville Formation, about 45 ft below the Straddle Gallery. The fissure is on a cross joint, about 100 ft southwest of The Bar, near the Angel Loop of Mystery II. The Straddle Gallery consists of keyhole-shaped passages. They generally have a tubular top and deep fissures in the floor. One or both sides of each fissure has ledges that can be crawled or walked upon where the fissure is too wide to straddle.

Although not proven by dye tracing, most of the discharge of Flim Flam Creek must derive from sediment-filled fissures in the bed or banks of the Root River. Mohring (1983) dye traced Formation Route Creek in Mystery III to Flim Flam Creek and then to Seven Springs. This result demonstrates that Formation Route Creek is a major (and perhaps the major) connection route between the South Branch and Flim Flam Creek. A diagrammatic sketch of these flow paths is shown in Figure 20. The sketch uses the straight-line horizontal distance from the Root River at the bend closest to the west end of Mystery III (just downstream of the bridge over the Root River at the start of the Mystery I driveway) to the 1st Triangle Room. The distance is about 820 ft. The straight-line distance from the 1st Triangle Room to Flim Flam Creek is about 1740 ft. The straight-line distance from Flim Flam Creek to Seven Springs is about 3740 ft. These distances are short enough to expect relatively fast flow-through and pulse-through times.

Water from the South Branch is the dominant source of water in Flim Flam Creek most of the time. There is always, however, a component of infiltration water present in the streams. Under extreme conditions this infiltration component may temporarily become the dominant component.

Figure 20 shows the types of flow expected along these paths. Near the Root River, flow is in occluded (sediment-filled) fractures, and then in fractures that may be partially filled or full, depending on their size, geometry, and the discharge. The water then follows a course in which flow is usually in partially filled passages as vadose streams alternating with full (sumped) passages. Some of these flooded passages probably remain sumped even at low water levels while other stretches may alternate between sumped and partially filled conditions. At Flim Flam Creek, the water emerges from a sump, flows only 50 ft as a free surface stream, and then sumps again. Several major open joints cross what is presumed to be the downstream extension of Flim Flam east of the Straddle Galleries. Flim Flam is itself probably one of the major tributaries of the Disappearing River.

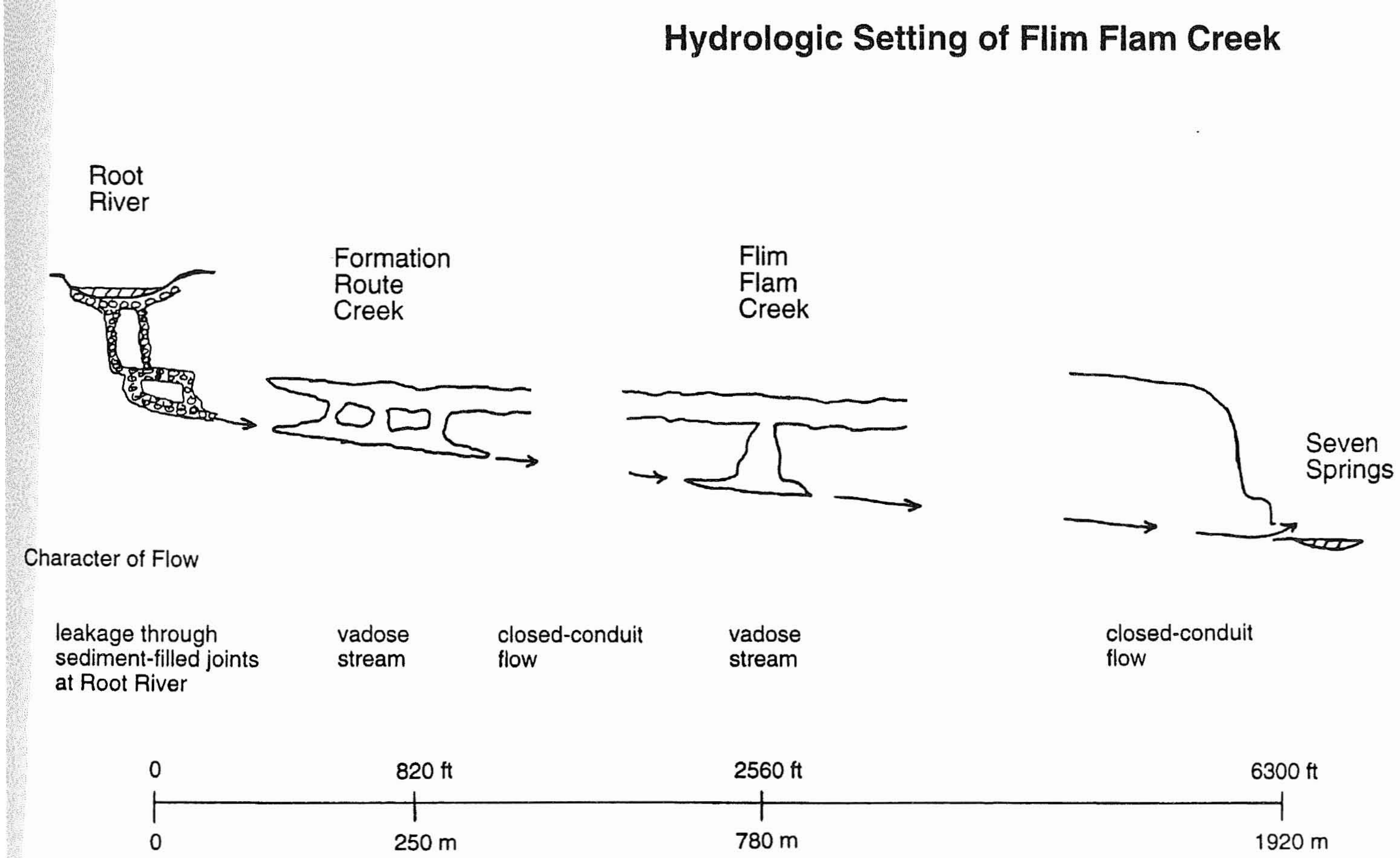


Figure 20. Hydrologic setting of Formation Route Creek and Flim Flam Creek.

Summary Plots, Scope of Discussion, and a Caution

Water level, water temperature, and conductivity were measured continuously beginning in late March, 1992 and continuing to early May, 1993. Summary plots for these parameters are in Figures 21 and 24. Figure 21 shows the data from 1992. Figure 24 shows the data for the first half of 1993. These figures are plotted for the same time periods as the summary plots for Blue Lake (Figures 11, 12, 13, and 15) to facilitate comparisons. Additional plots of the field parameters, anions and cations, and saturation indices are in Figures 22, 23, 25, and 26.

Flim Flam Creek responds to any changes in the stage, or the chemical and physical properties of the South Branch of the Root River. Consequently, signals are observed at Flim Flam Creek on several time scales. The various time scales can be divided into: 1) seasons, 2) mesoscale periods lasting a several days to a week or more, 3) individual storms lasting a couple of days, 4) daily cycles, and 5) events that last less than a day. The wealth of information in these complex signals can quickly become overwhelming.

To keep the discussion manageable for this interpretive report, we emphasize the major conclusions and provide typical examples. Further details are in the Technical Report. An account of the effects of the March 30-April 3, 1993 flood at Flim Flam Creek is in a later section.

A few cautionary words are in order. We are interpreting only the first year and a half of information from the digital data loggers. We almost certainly have not observed all of the phenomena Mother Nature has up her sleeves. Specifically, 1992 and 1993 were unusually wet. We have no data or observations from a significant dry period. We have seen some interesting phenomena only once. Murphy is alive and well. Everything that could go wrong, did -- usually at the worst possible times. Nonetheless, we have been lucky enough to observe a number of fascinating phenomena that tell us fundamental things about the hydrogeology of Mystery Cave.

The following discussion is greatly simplified and at several points we cautiously extrapolate. Some trends will be discussed as if we were interpreting a longer time span. This approach allows us to emphasize the major conclusions, but at several points the discussion will show particularly interesting shorter time-scale events. Many of these interesting events and phenomena need to be examined at shorter time scales than can be seen in the summary Figures 21 through 26 above. At the risk of overwhelming the reader we will zoom in on these events with expanded scale figures below. **Flim Flam Creek is not a boring place.** [As always, we reserve the right to revise any or all of our conclusions and interpretations as new data are obtained in the future. We hope the observations themselves will not change, however.]

Trends in Water Temperature

Water temperatures at Flim Flam Creek range about 1 to 20°C through the annual seasonal cycle (Figures 21 and 24). Over mesoscale periods (corresponding to 5-10 or 15 day weather trends), water temperature varies as much as 7°C during the summer and as much as 2°C in the winter (Figure 27). Within stable mesoscale periods, water temperature varies 1-3°C depending on surface weather conditions (air temperature, amount of sunshine, etc.). Over

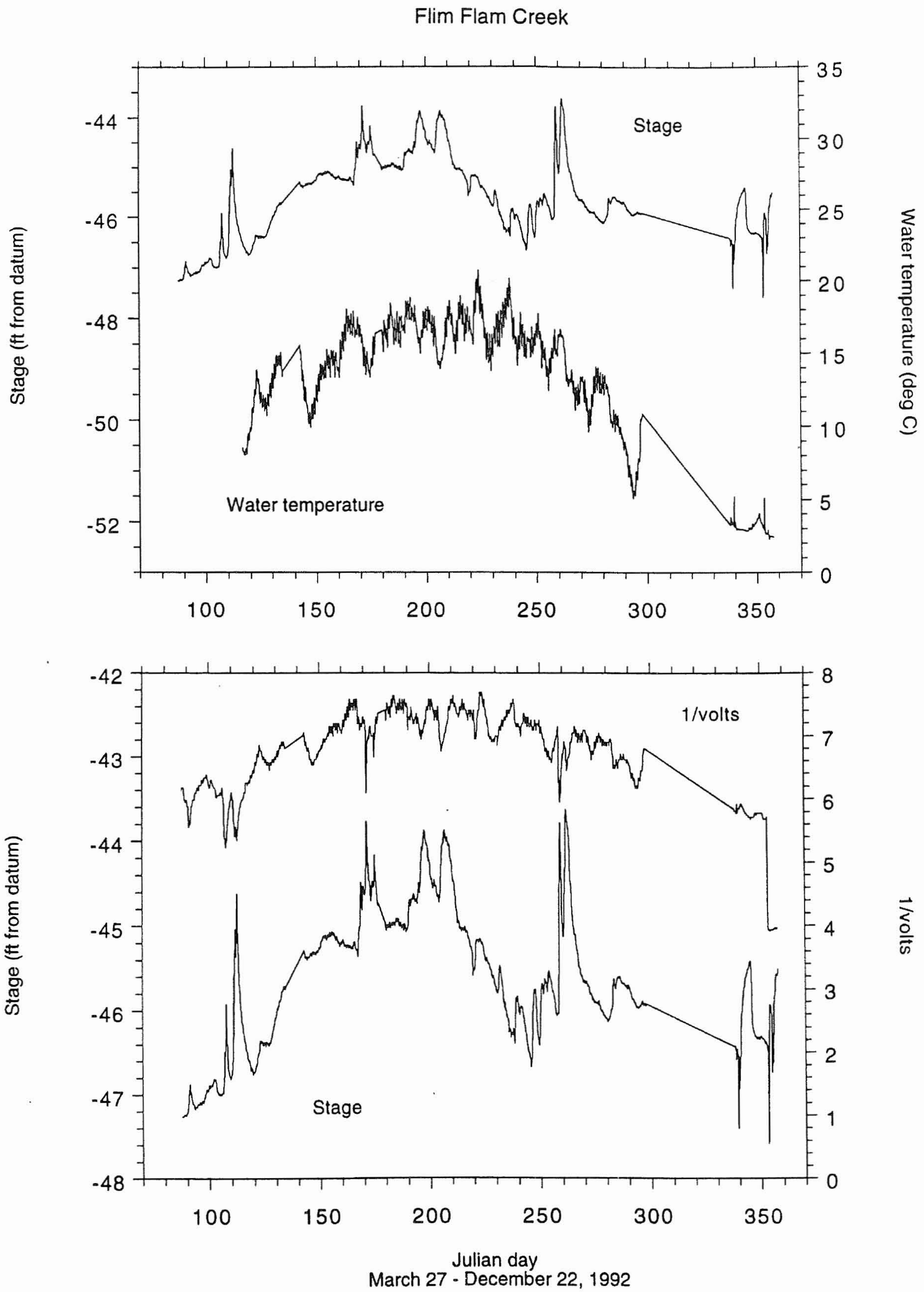


Figure 21. Stage, water temperature, and 1/volts, Flim Flam Creek, 1992.

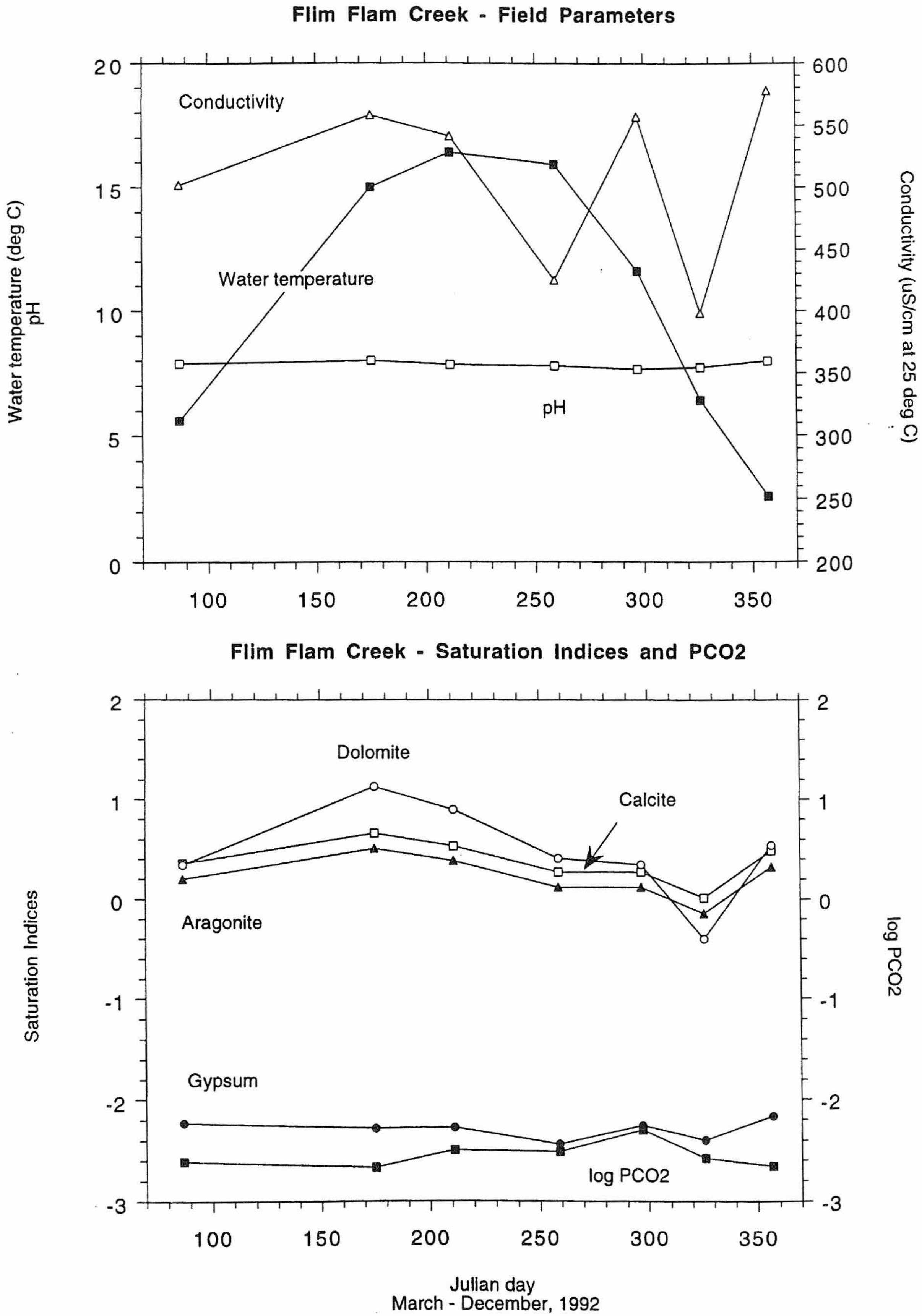


Figure 22. Field parameters and saturation indices, Flim Flam Creek, 1992.

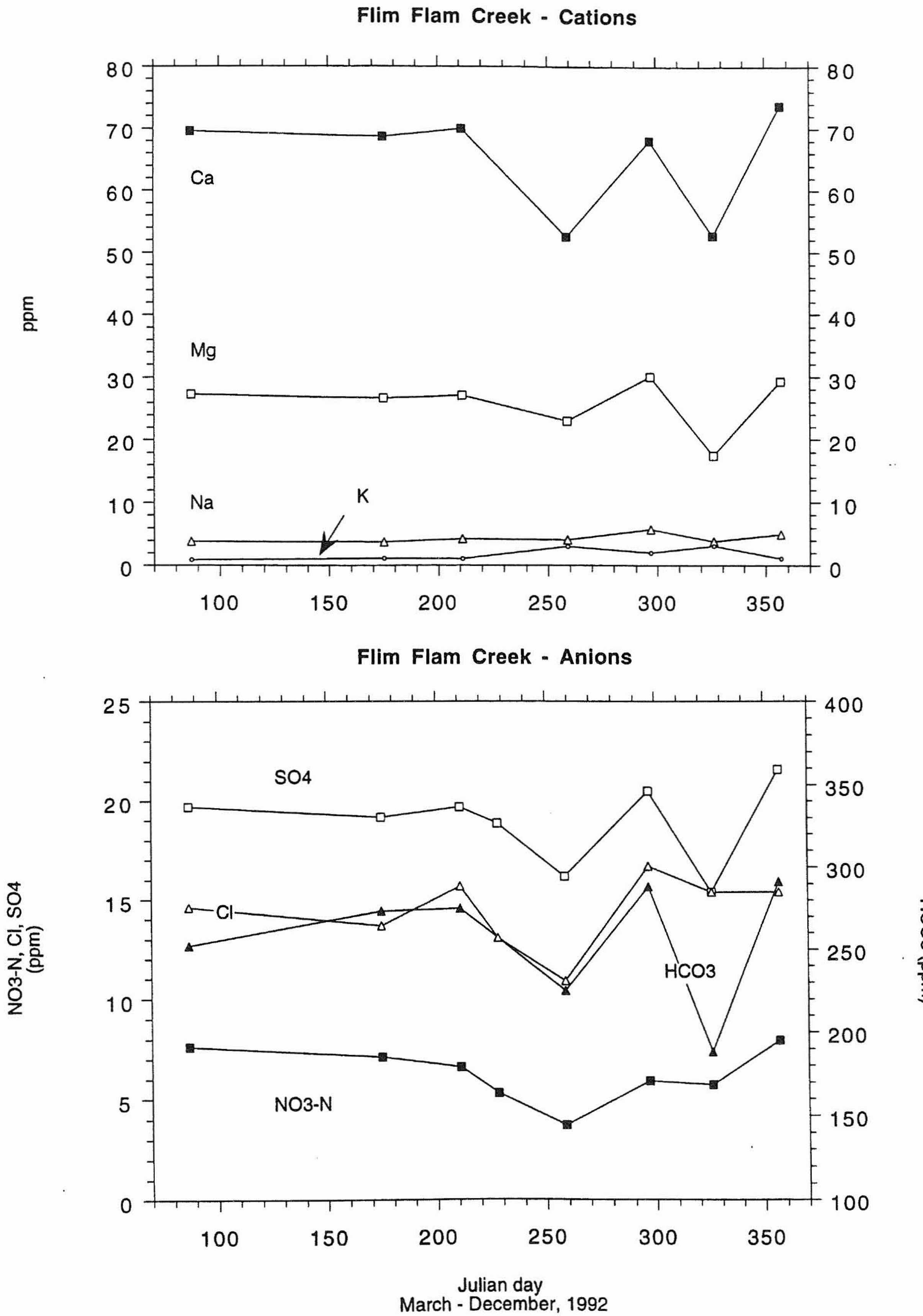


Figure 23. Cations and anions, Flim Flam Creek, 1992.

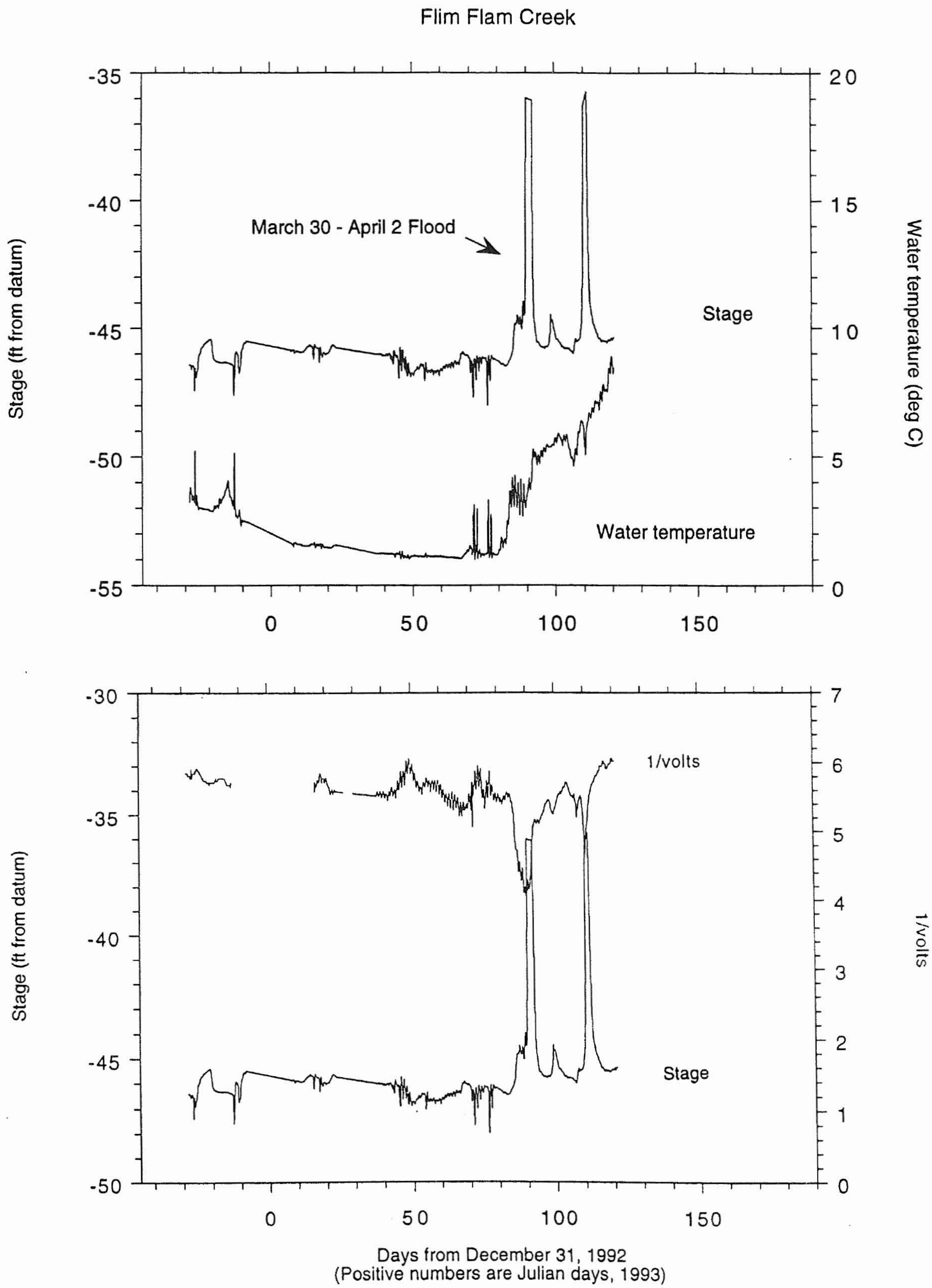


Figure 24. Stage, water temperature, and conductivity (1/volts) at Flim Flam Creek.

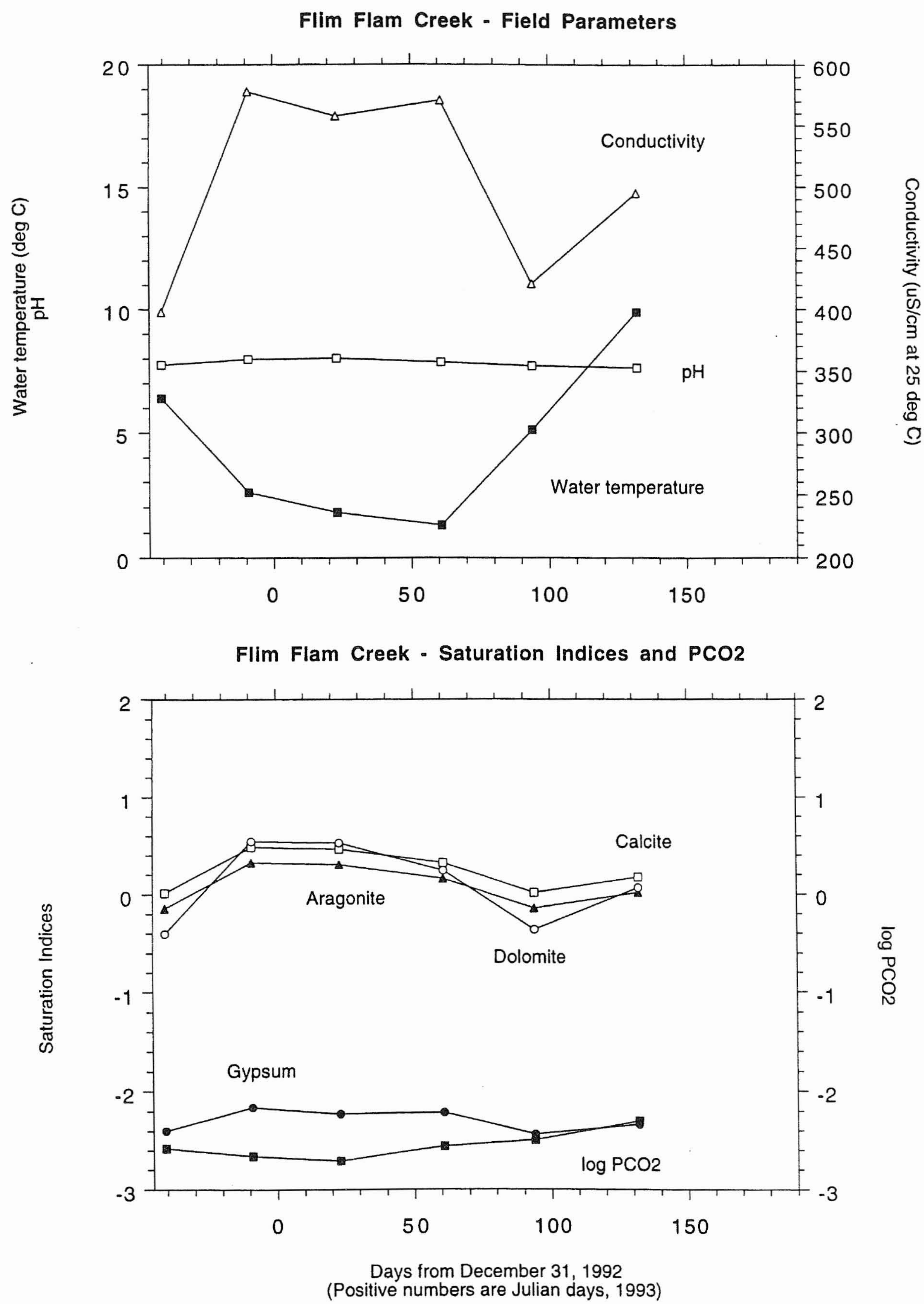


Figure 25. Field parameters, saturation indices, and PCO_2 at Flim Flam Creek.

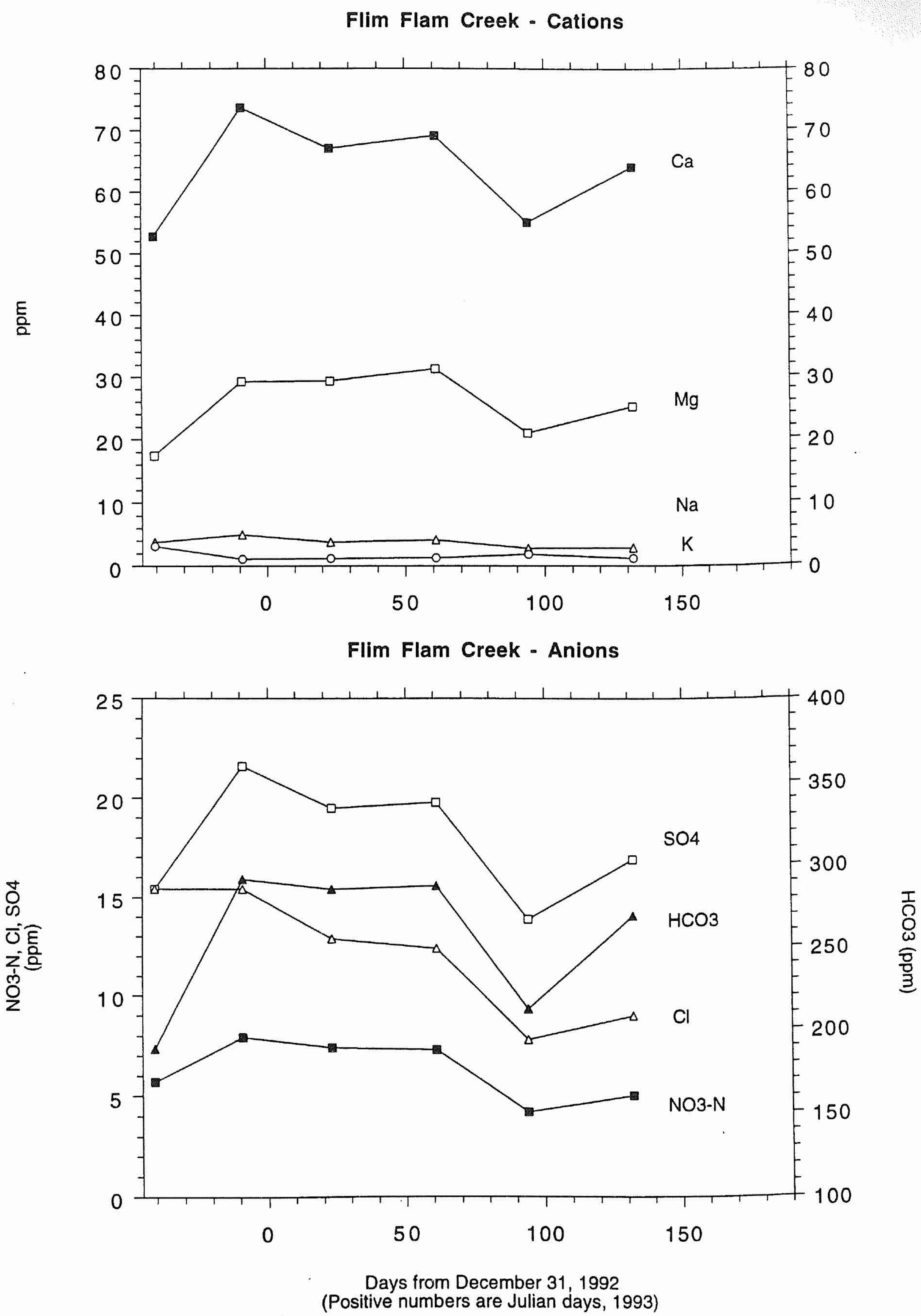
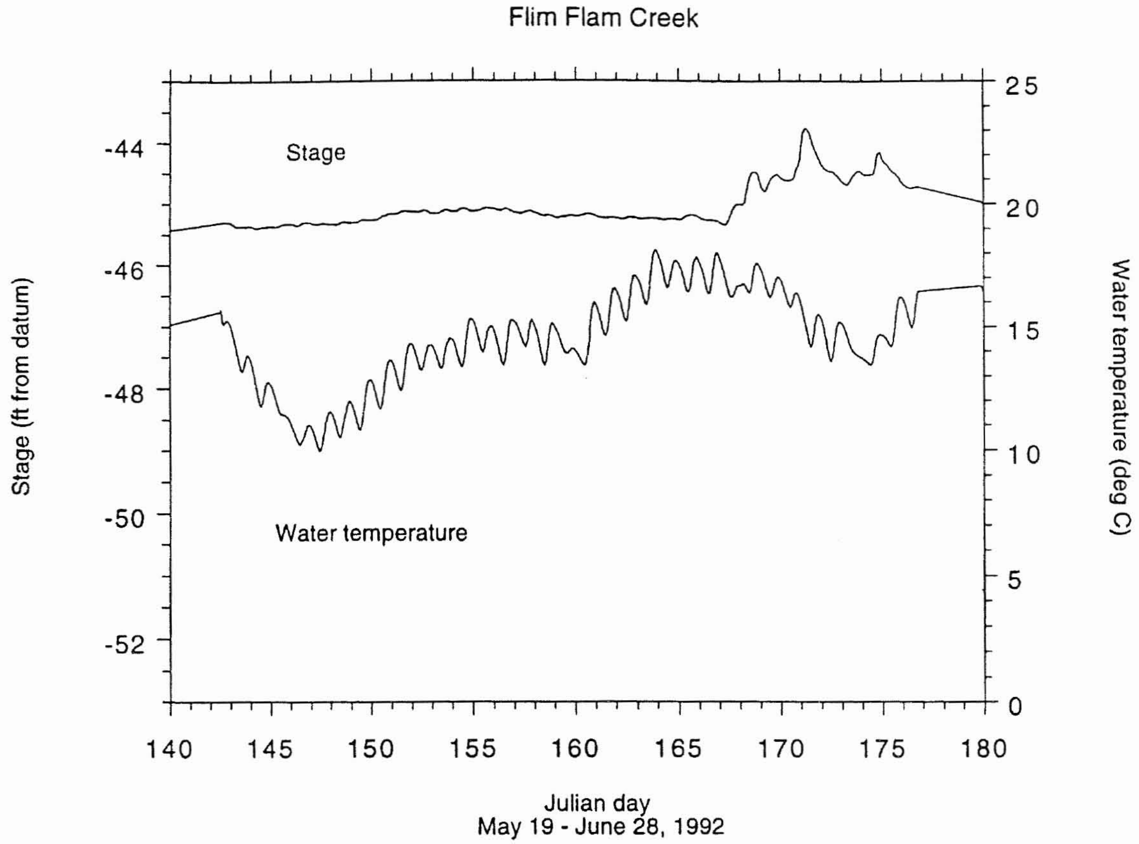


Figure 26. Cations and anions, Flim Flam Creek.



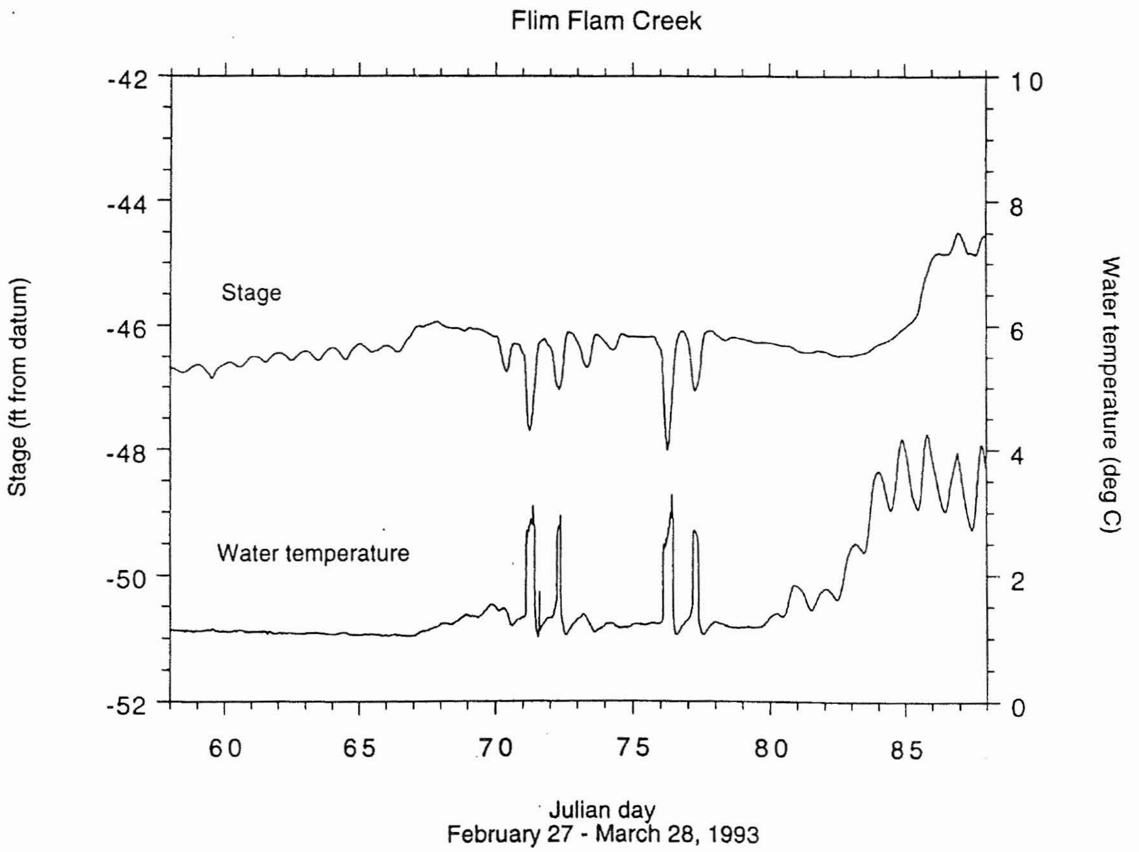


Figure 27. Mesoscale variations in temperature and transitional periods.

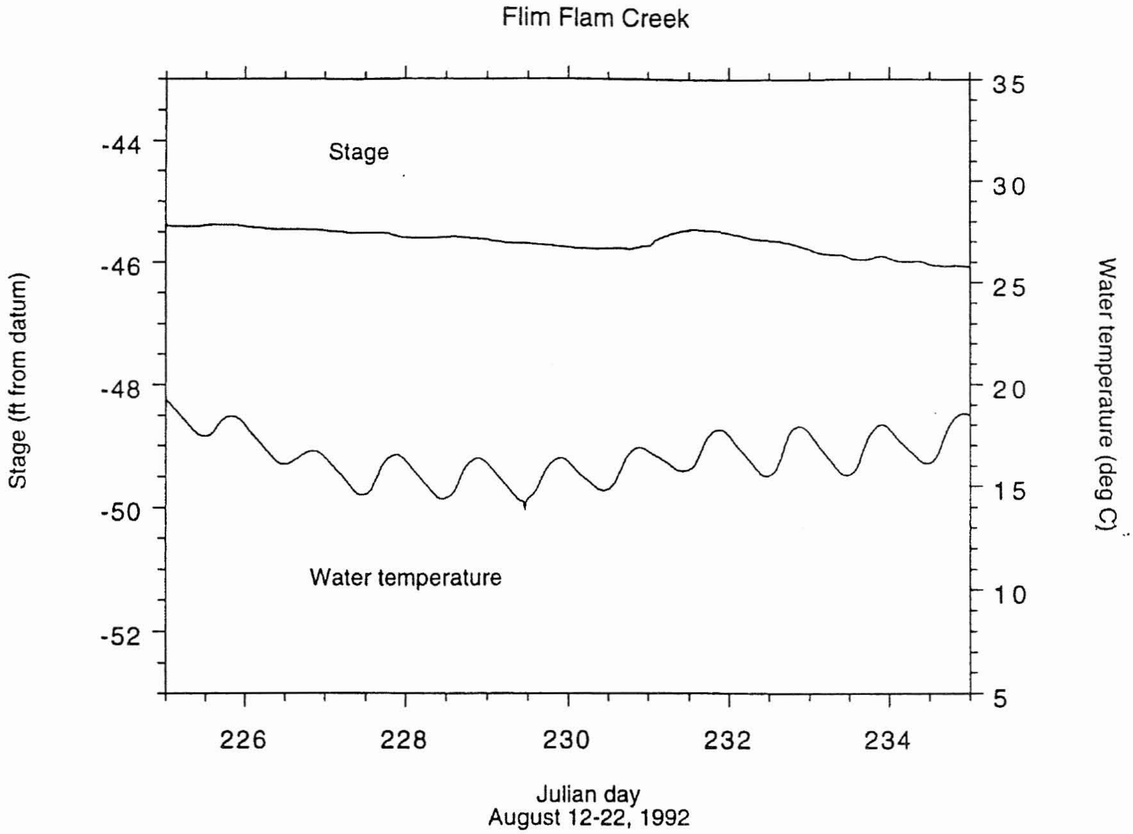
transitional periods, (about 1-5 days; Figure 27) water temperatures may rise or fall as much as 5°C. Storms produce waters warmer or colder than those already present, depending on the season and on variations in air temperature during the storms.

Much of the year, but especially in the summer, there is a daily temperature variation of 1 to 3°C (Figure 28). The daily temperature cycle disappears during the winter when the Root River is iced over and air temperatures are below freezing (Figure 28). The daily temperature cycle is driven primarily by solar radiation heating of the river. Bright cloudless days, even if the air temperature is cool, produce larger daily cycles than to do warm but cloudy days. The biggest effects are observed on hot, sunshiny days.

The primary source of water to Flim Flam Creek is the Root River, but some contributions come from cave waters that have longer residence times. Such waters have temperatures close to 8.7°C. Therefore, we see a dampening of the temperature signal from the Root River that depends on the relative contribution of Root River water and the other cave waters. Additional dampening of the temperature signal arises from heat exchange with cave air, bedrock, and sediments. The water temperature at Flim Flam never gets as hot in the summer or as cold in the winter at does water in the South Branch. The temperature response of Flim Flam to changes in the South Branch is a **muted** version of the surface temperature changes.

We were surprised to observe short time-scale events occurring in the middle of winter. During extremely cold periods in the late fall and winter, the already low stage in Flim Flam Creek sometimes abruptly falls but the water temperature rises (Figure 29). Although a complete quantitative interpretation for these events is not yet available (there are additional complications), the outlines of an explanation is possible. When the river is frozen over, the water flowing beneath the ice and sinking is close to 0°C. If a sudden cold snap freezes the river to the bed, either at the sink points or at some shallow point upstream, the input of cold surface water can be temporarily halted. The water level in Flim Flam drops. As the water level drops the fraction of groundwater infiltration left in the stream increases. The temperature in the creek, therefore, increases toward 8.7°C. When the pressure of the water flowing beneath the ice reopens the sinkpoints, very cold water again flows into Flim Flam, the flow increases and the temperature drops. The additional complications involve the heat exchange between the rock walls of the creek and the very cold water.

One of the more important aspects of the temperature variation is the amount of time water temperatures are significantly above or below mean cave temperature. The water flowing in the lower streams either cools or warms the cave depending on the season. During the winter, cave passages adjacent to the underground streams tend to dry out. During the summer, these passages tend to become more moist, in part because of condensation effects. This time is important because of the effects the lower level streams may have on cave meteorology. Lively (1993) has found that Mystery Cave seems to have two air circulation patterns, a summer pattern and a winter pattern. During the summer pattern, the radon levels in the cave air are higher on average than during the winter pattern. During 1992, the transition from winter to summer patterns occurred during March and April (Lively, 1993, Fig. F15 and F16). The transition from summer to winter conditions occurred October 9 to 12 (Lively, 1993, Fig. F18 and F23). For



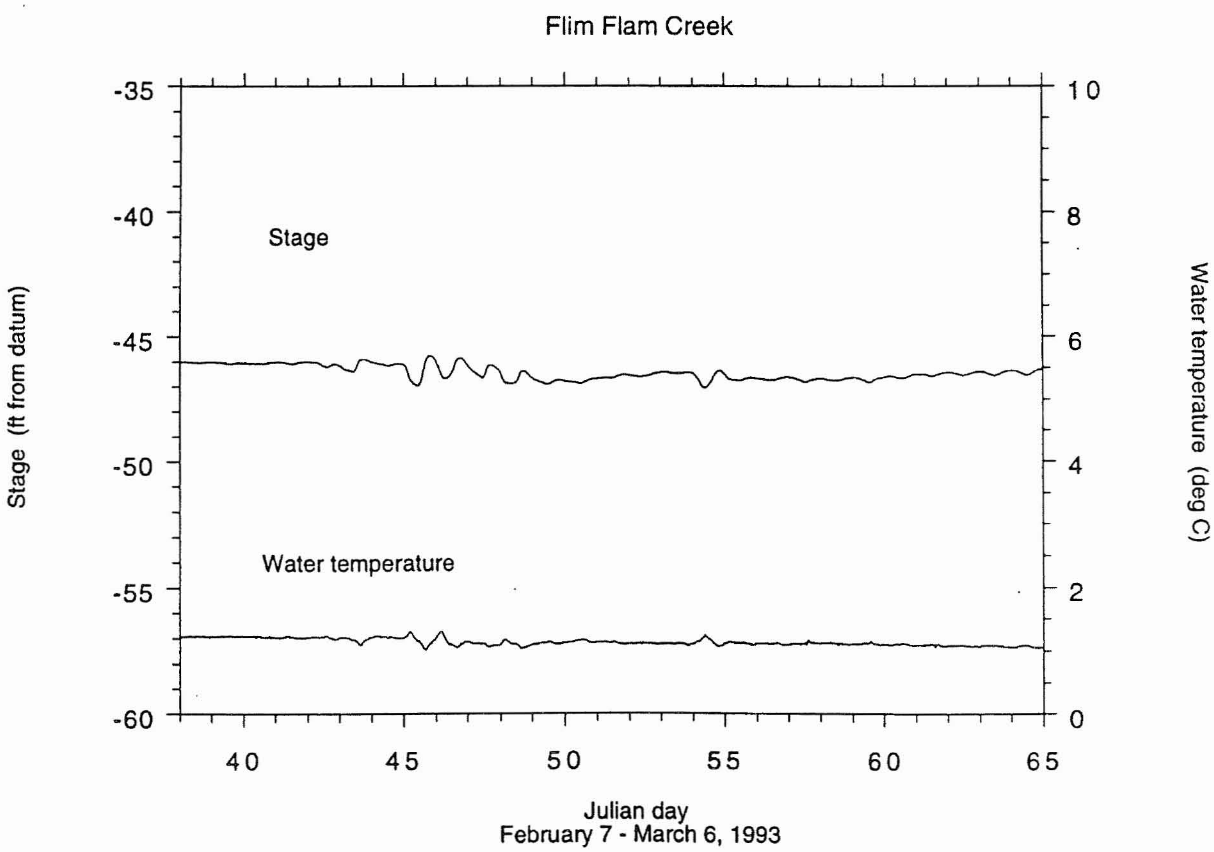
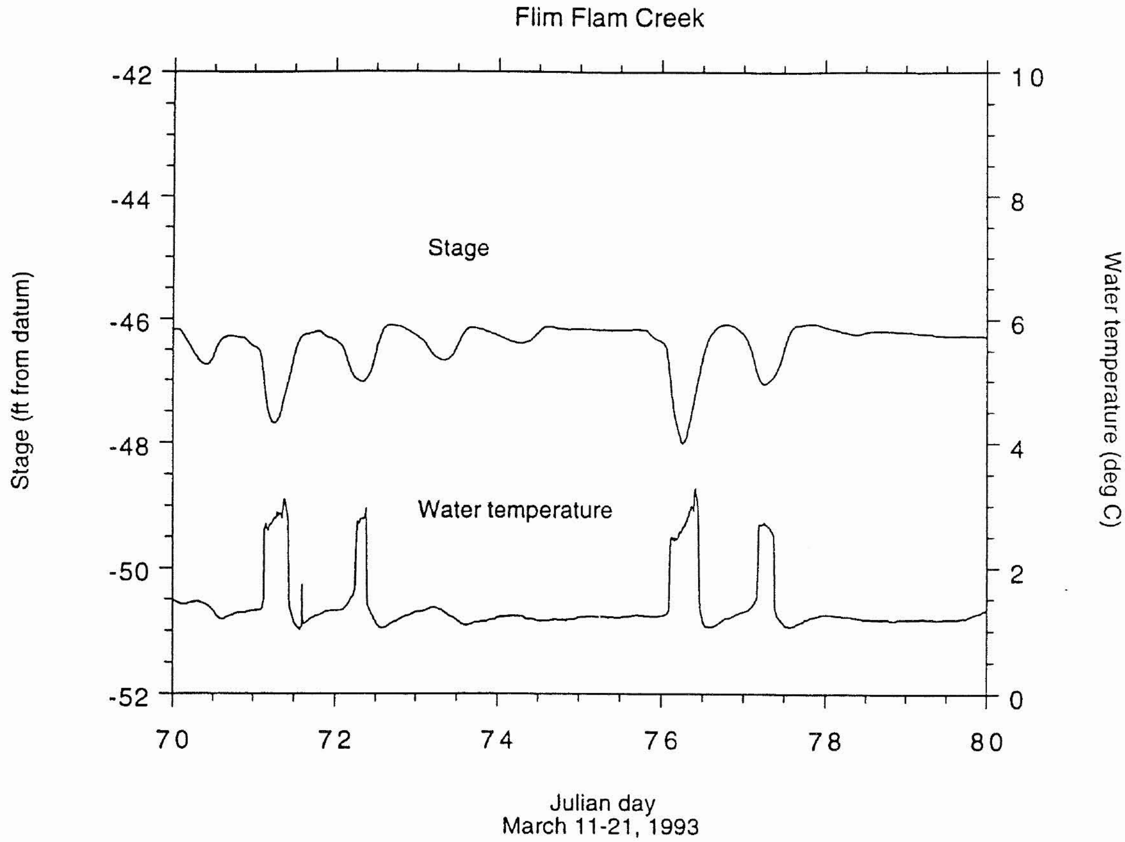


Figure 28. Daily cycles in temperatures.



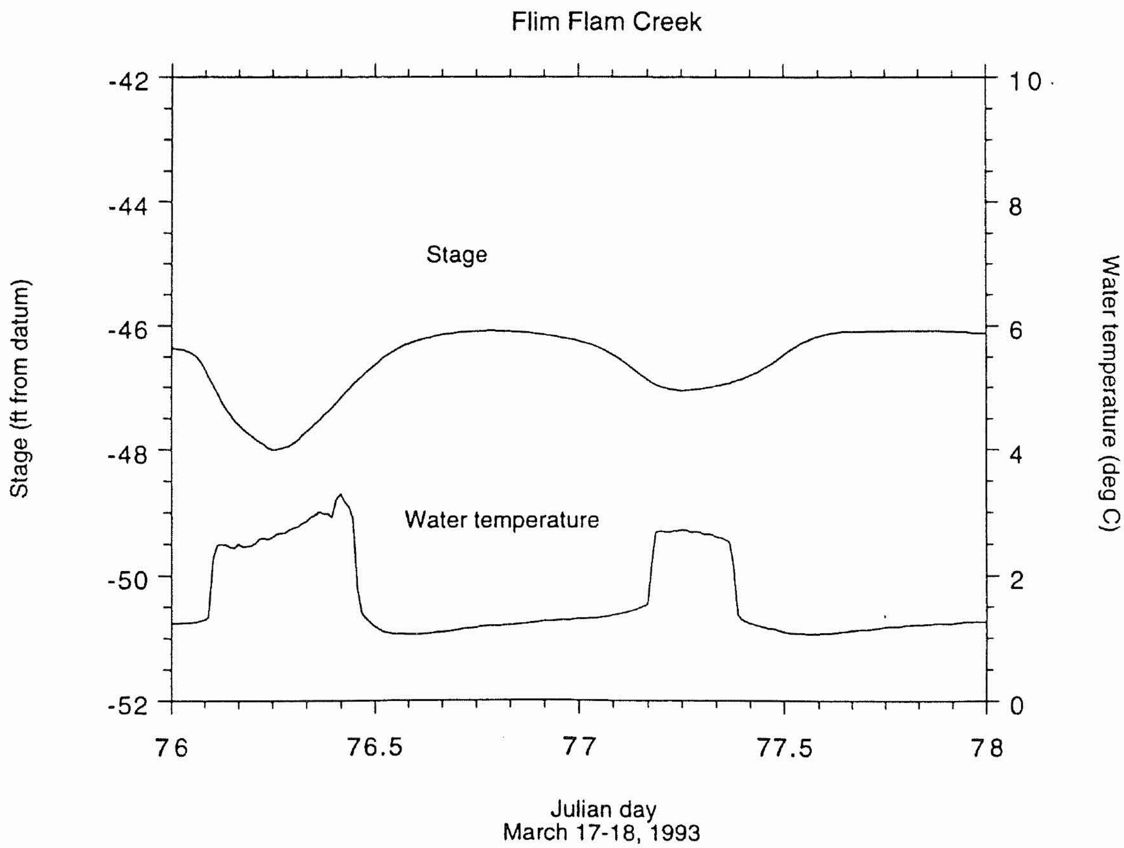


Figure 29. Short-term variations in stage and water temperature in the winter.

comparison, water temperatures during 1992 were above mean cave temperature (8.7°C) from about April 24 (day 115) through October 16 (day 290).

When water temperatures are higher than mean cave temperature, fogging can occur. Water vaporizes from Formation Route Creek and Flim Flam Creek, increasing local humidity. Water condenses on colder cave walls, releasing latent heat. The water itself is warm, so several factors combine to produce a rise in local air temperature. Air circulation patterns may change. All of these effects are noticeable during the summer in the vicinity of the Bar and in part of the Angel Loop along the commercial trail.

Stage or Water Level

Hydrologists prefer to work with the flow volume rather than simply with stage or water level. Stage is what is normally monitored and then it is converted to flow volume through an empirically determined relationship, a rating curve. Rating curves are determined by measuring the flow of a stream under a variety of flow conditions. Unfortunately, Flim Flam Creek is relatively inaccessible at the base of a 45-ft deep narrow fissure. The enterable passage is low and wet, ends in sumps both upstream and downstream , and is cold much of the year. The geometry at low flow is not conducive to stream gauging. Storms typically induce a one to two foot rise in stage from a low-flow water depth of about a foot. The largest storms (three in 1993) produce rises of over 20 ft in stage. During the early summer of 1993, water level rose high enough so that water was visible at the Bar, according to tour guides. The conditions during high flow make flow measurements impossible. In the absence of a rating curve for Flim Flam Creek, the following discussion of flow is in terms of stage.

At Flim Flam Creek, stage is lowest during the winter, rises somewhat during wet springs, and shows sharp responses to rises on the Root River. Such responses are clearly visible in Figures 21 and 24. The stage in Flim Flam is a **multiplied** version of the surface stage changes. A rise of a couple of feet in the South Branch can cause a 20 foot rise in the stage in Flim Flam if stage in the South Branch is already high. The importance of this observation can not be overemphasized. The multiplier effect produces a major, life-threatening danger to exploration of the lower levels whenever there is any possibility that the surface water level may increase. At times when the stage in the South Branch hiccups, Flim Flam Creek belches.

There are some additional responses -- for example, abrupt, sharp drops in stage -- that deserve mention. Stage is generally low during the coldest part of the winter. Water in the Root River is in contact with ice. For two or three months there is an ice cover on the river. If there are recharge points on the bank margins, they may be iced over, lowering the surface recharge to Flim Flam Creek. At such times, water temperature in the underground river may rise (Figure 29), as discussed above. However, the response is not universal. Sometimes as stage falls there is a fall in water temperature that lags behind the fall in stage. These events are very cryptic.

Response Times

The *flow through time* from the Root River to Flim Flam Creek is rapid. The flow through time clearly varies with stage in both the Root River and at Flim Flam Creek, but is difficult to precisely quantify with the available data. Flow through times can in principle be measured directly by dye traces but the appropriate sink points in the South Branch have not been identified and it will be difficult to sample Flim Flam every few minutes for several hours to pin down the transit times.

Part of the difficulty in making precise estimates arises because the Root River weather station is about 3800 ft upstream of the postulated sinkpoints. The signal measured at the Root River at the weather station has to pass downstream before transmission into the subsurface and we have only stage data for the Root River. Only one data logger was available for both weather parameters and measurements on the Root River during this study. It was not possible with available channels to monitor conductivity or water temperature.

Nonetheless, correlations can be made between surface air temperatures and cave water temperatures. Comparisons can be made for time periods in which air temperatures fall rapidly several degrees, because the water temperature then responds most quickly (Figure 30).

Comparisons can be made for daily cycles in air temperature (Figure 31). Correlations can also be made for periods of intense precipitation, if air temperature during precipitation is significantly different from that of the Root River (Figure 32). Such correlations give flow through times on the order of a couple of hours to 5 or 6 hours. The shorter flow through time estimates are more consistent with Mohring's (1983) dye trace measurement of 6 hours flow through time from the 1st Triangle Room in Mystery III to Seven Springs.

The *pulse through time* is at least partly a function of pre-existing stage. It can be extremely rapid if stage is already high. At high flow a nearly completely connected network of submerged conduits transmits the pressure pulse. Under these conditions, an increase in leakage at the sinkpoints (from rapid flooding, for example) produces a rapid rise in stage at the upstream end of the flooded conduits, and stage can rise rapidly at Flim Flam Creek, long before the water can flow from the Root river to Flim Flam Creek. If stage is low, then some water must flow through parts of the network to raise water levels to a point at which there is a complete hydrologic connection of flooded conduits, before a pressure pulse can transmitted.

Conductivity and Water Chemistry

It was not technically or economically feasible to monitor the chemistry of the waters in Flim Flam Creek on a continuous basis. Conductivity was monitored instead as a crude proxy of the total dissolved load in the stream. Conductivity is shown on Figures 21 and 24 as 1/volts. The conductivity records shown in Figures 21 and 24 have lots of structure. Conductivity, however, is a function of water temperature as well as solute load. In Flim Flam Creek this voltage was measured at water temperatures ranging from 1 to 20°C. The size of the temperature effect is as large or larger than the variations caused by changes in the solute load. Normally,

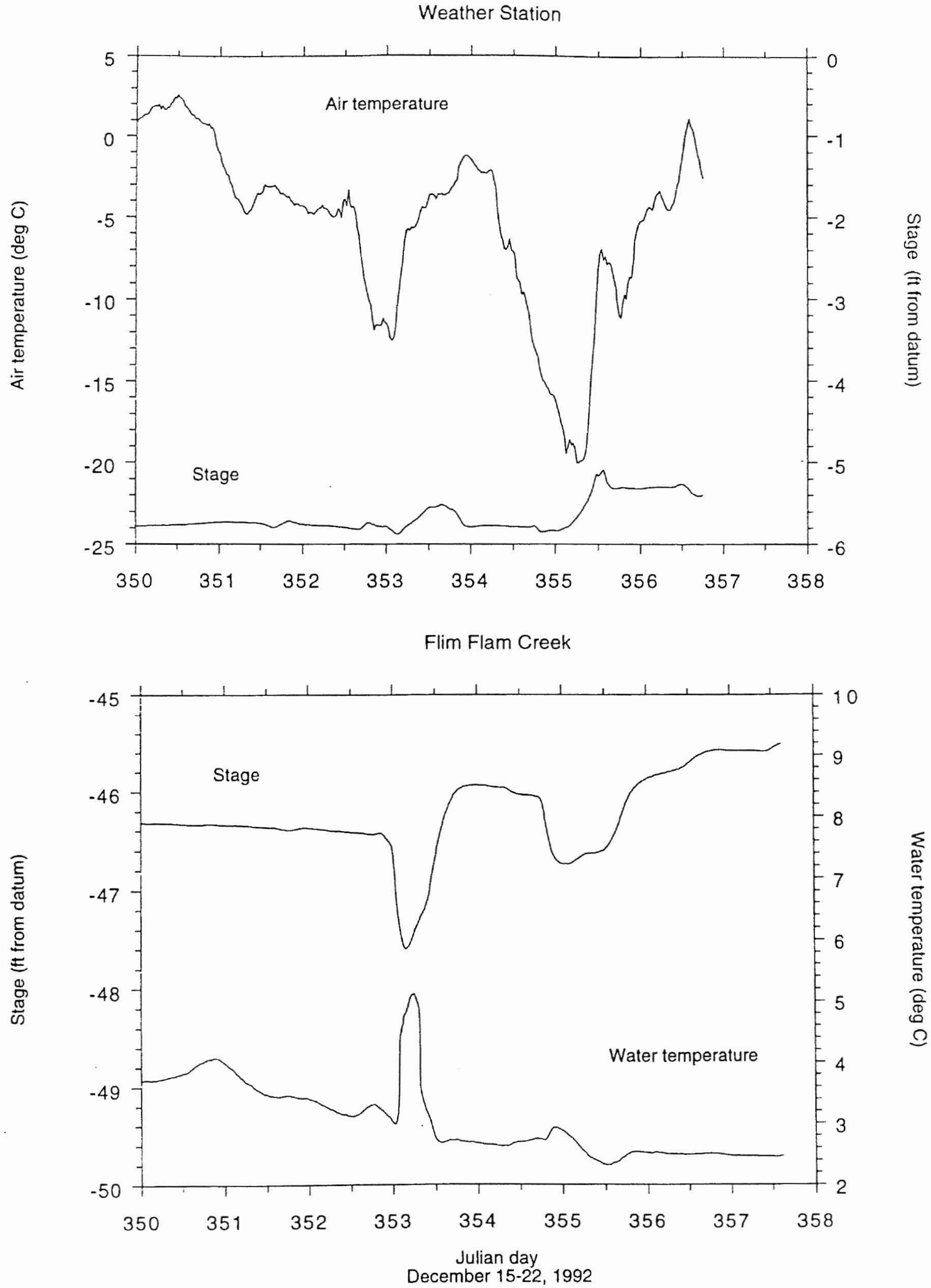
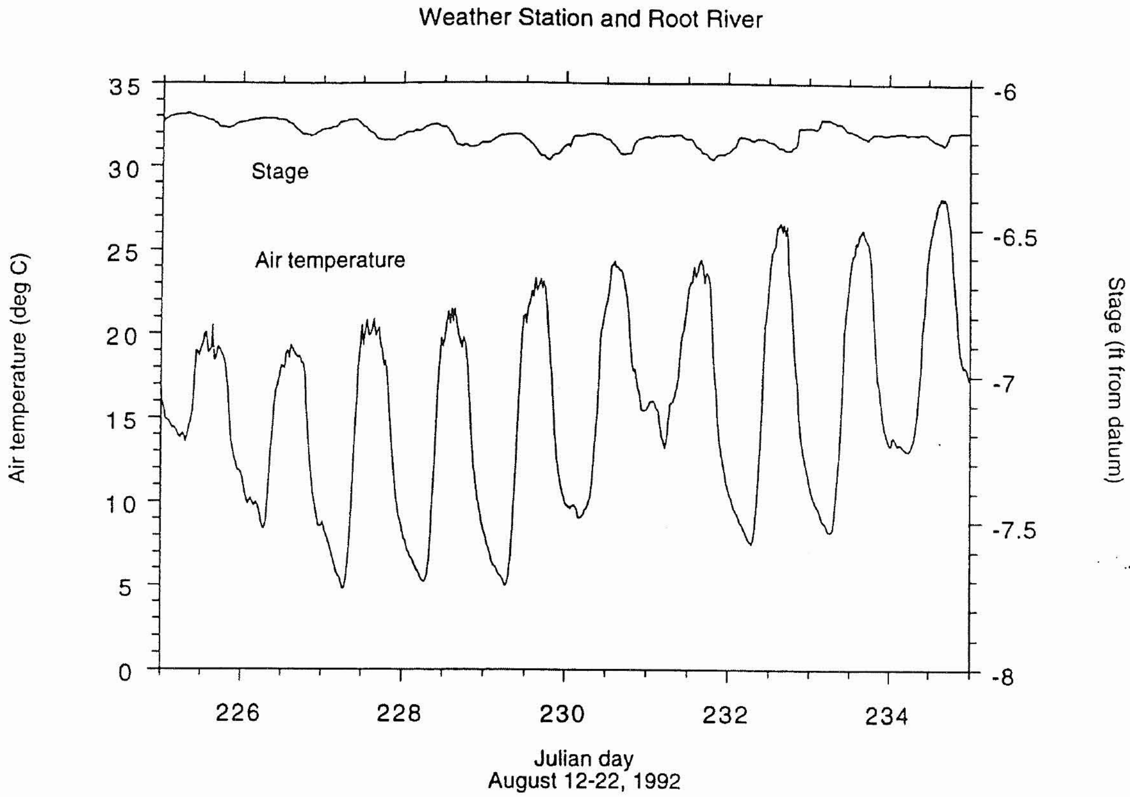


Figure 30. Correlation between surface air temperature and cave water temperature at Flim Flam Creek when air temperature falls abruptly.



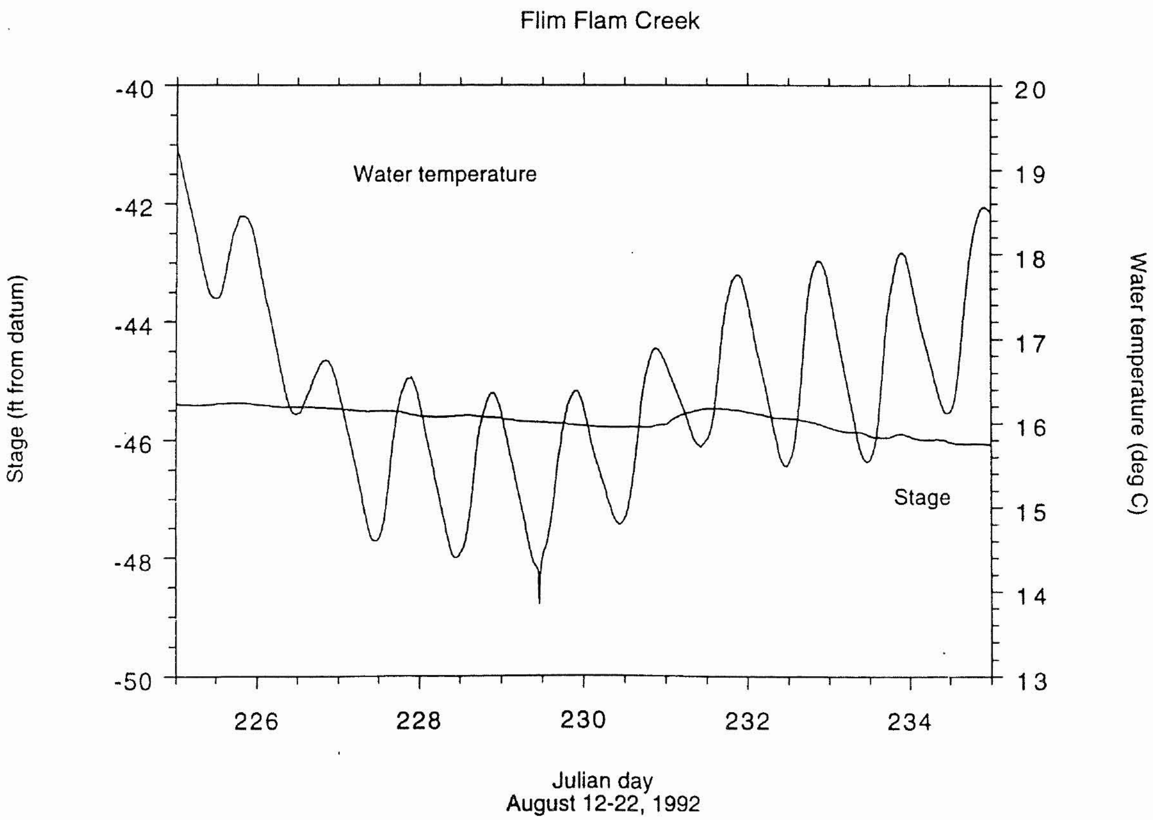
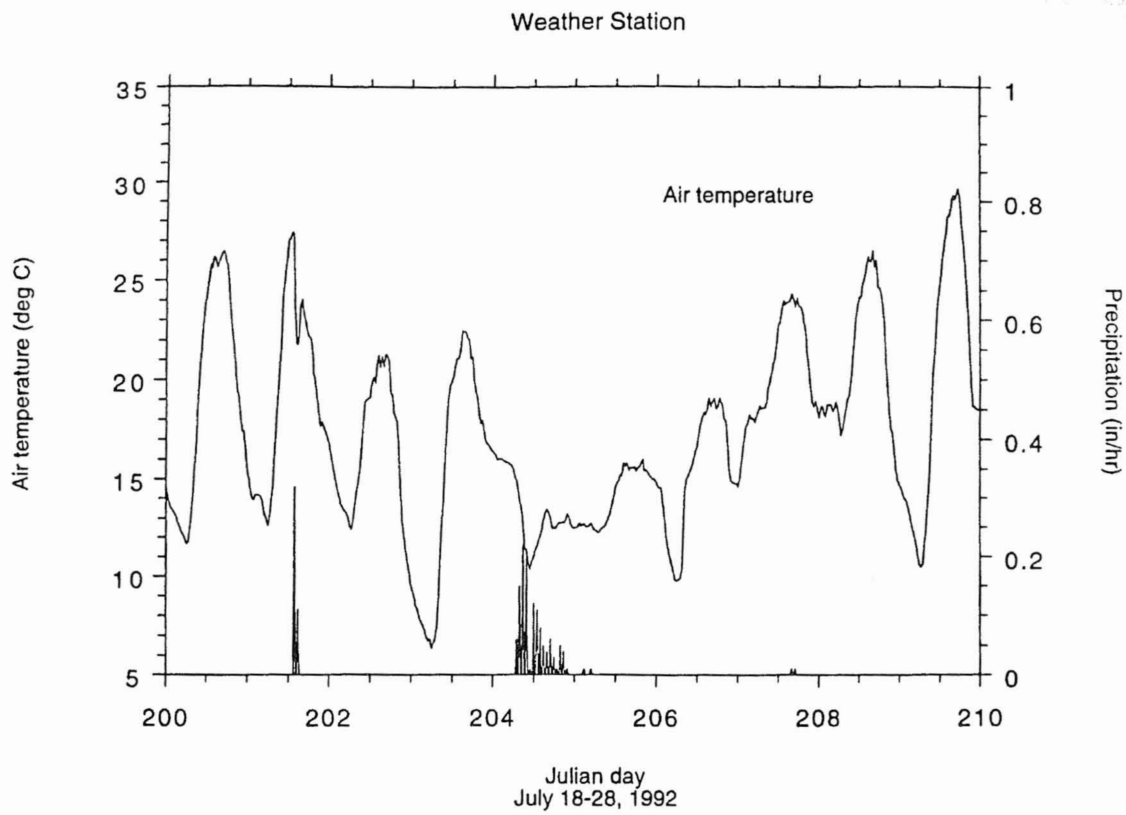


Figure 31. Comparison of surface air temperature and cave water temperature at Flim Flam Creek during times of maximum daily variations in air temperature.



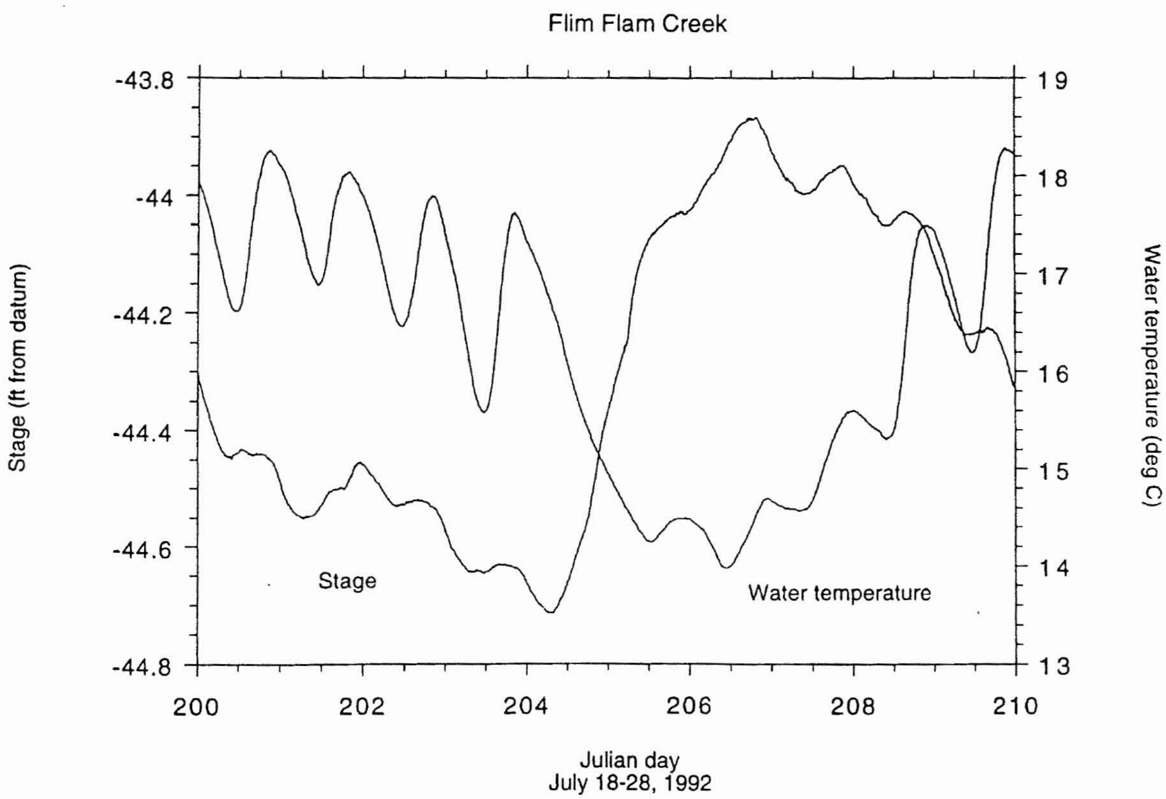


Figure 32. Correlation between cave water temperature and air temperature during periods of intense precipitation.

conductivity is corrected to a standard temperature (usually 25°C) before comparisons are made. This temperature correction may not be possible for this data set and interpretation of conductivity at Flim Flam Creek as 1/volts must proceed with caution. The qualifications and detailed discussion of this problem can be found in the Technical Report. [We were able to use 1/volts more extensively in the discussion of Blue Lake, because Blue Lake water temperature was nearly constant and the temperature effect was not significant.]

The arched overall trend of 1/volts on Figure 21 is primarily due to the temperature effect. The field measurements of conductivity (Figures 22a and 25a), where the appropriate temperature corrections were made, do not unambiguously support a seasonal trend in the conductivity. Neither do the measured concentrations of the major ions calcium, magnesium and bicarbonate (Figures 23 and 26). A seasonal effect should be present in the system, however.

Most of the abrupt rises and falls in 1/volts in Figure 21b are primarily due to changing water temperature. Some reflect changes in solute load correlated with peaks in stage. During these times, precipitation dilutes river water, causing drops in conductivity. However, because water temperature usually falls during these events, some of the drop in the values of 1/volts can be attributed to the change in water temperature. In Figure 24b, the values of 1/volts decline at times of the introduction of snowmelt.

The results of the cation and anion analyses of Flim Flam Creek waters are shown in Figures 23 and 26. The saturation indices calculated from these data are shown as part of Figures 22 and 25. Most of these waters are close to saturation for calcite, aragonite and dolomite. The ion concentrations in Figures 23 and 26 are spiky, much more so than those of Blue Lake or most other cave waters. The levels of cations and anions respond to events on the Root River.

The plots of the anions (Figures 23 and 26) are revealing. Note that the levels of nitrate and chloride in Flim Flam are significantly higher than the levels of these two ions in Blue Lake (Figures 13b and 19b). Nitrates and chlorides are indicators of human impact. Conversely, the level of sulfate in Flim Flam is about half that found in Blue Lake. Sulfate is produced naturally by oxidation of sulfides in the bedrock and shows the influence of infiltration waters. This distinction is also backed up by the coliform bacteria and pesticide analyses. Flim Flam Creek typically contained coliform bacteria and pesticides. Blue Lake did not.

The overall picture is very consistent. The water in Blue Lake is dominated by recharge from infiltration sources that have only low levels of human induced pollutants. Blue Lake can fill rapidly, but most of the time it is a stable bath tub for days, weeks or months. Flim Flam Creek, in stark contrast, is dominated by direct recharge from the South Branch. The water in Flim Flam shows all of the human pollutants that affect the South Branch. The water quality and level in Flim Flam Creek changes dramatically on time-scales that can be as short as minutes.

Coon Lake Drips and Coon Lake

Description of the Site

Coon Lake Drips (CLD) is in 5th Avenue of Mystery II. The site is on the north side of the passage, across from **Coon Lake**, several hundred feet west of the Garden of the Gods. The water drips from flowstone covering the north wall. Some of the water drains from fissures in the ceiling and spreads out on the flowstone. Some issues from small stalactites set in the flowstone. The water drips onto a flowstone- and silt-covered floor.

Coon Lake Drips feeds Coon Lake, a shallow pool (usually about 4 by 10 by less than 1 ft deep) whose size varies with the discharge rate at Coon Lake Drips. Water from Coon Lake slowly seeps into floor sediments or evaporates. During the winter the pool nearly dries up as the discharge declines at Coon Lake Drips.

Topographic Setting

Coon Lake Drips apparently lie beneath a grass-covered hillslope, just south of the driveway to the Mystery II entrance. The precise position of CLD beneath the hill has not been located by surveying. Superposition of the cave map on a topographic sheet suggests that the elevation of the surface directly above CLD is about 1300 ft. The elevation at Coon Lake is approximately 1205 ft. The ceiling at CLD is at about 1220 ft, so the spot where water enters to feed Coon Lake Drips is approximately 80 ft below the surface.

Immediately west of CLD the surface is a forested hillslope leading into a re-entrant valley. A few tens of feet east of a point directly above CLD, the grassy hillslope flattens into a gently rolling plateau. Most of the immediate plateau is a pasture, but to the south of the pasture is a field planted in corn in recent years. Seismic work by Palmer and Palmer (1993a) nearby above the Garden of the Gods gave a depth to bedrock of 22 ft. This was interpreted above (see Geomorphic Setting) to indicate a 22 ft thickness of soil, loess, and possibly additional glacial material. The grassy hillslope above the driveway has been carefully checked for open drains, sinkholes, or other indicators of concentrated recharge. The only features found were mounds (several feet in diameter) of sandy material with adjacent holes apparently dug by gophers. In all probability, there are additional macropores on the hill. Along the driveway itself, near the east end close to the Garden of the Gods, a few linear depressions extend across the roadbed.

Drip Rates During Periods of Snowmelt

Coon Lake Drips appear to be perennial. A data logger and drip rate recorder (rain gage) were installed on February 26, 1993, to measure drip rates. The low flow in the winter, when the surface was frozen and covered with snow, was about 0.2 l/hr (Figure 33). The drip rate was constant until late March and can be considered a type of baseflow.

On March 18 (Julian day 77) a warming trend began following a few days with lows below -20°C (Figure 34). From noon March 18 through noon March 23 (day 82) the air

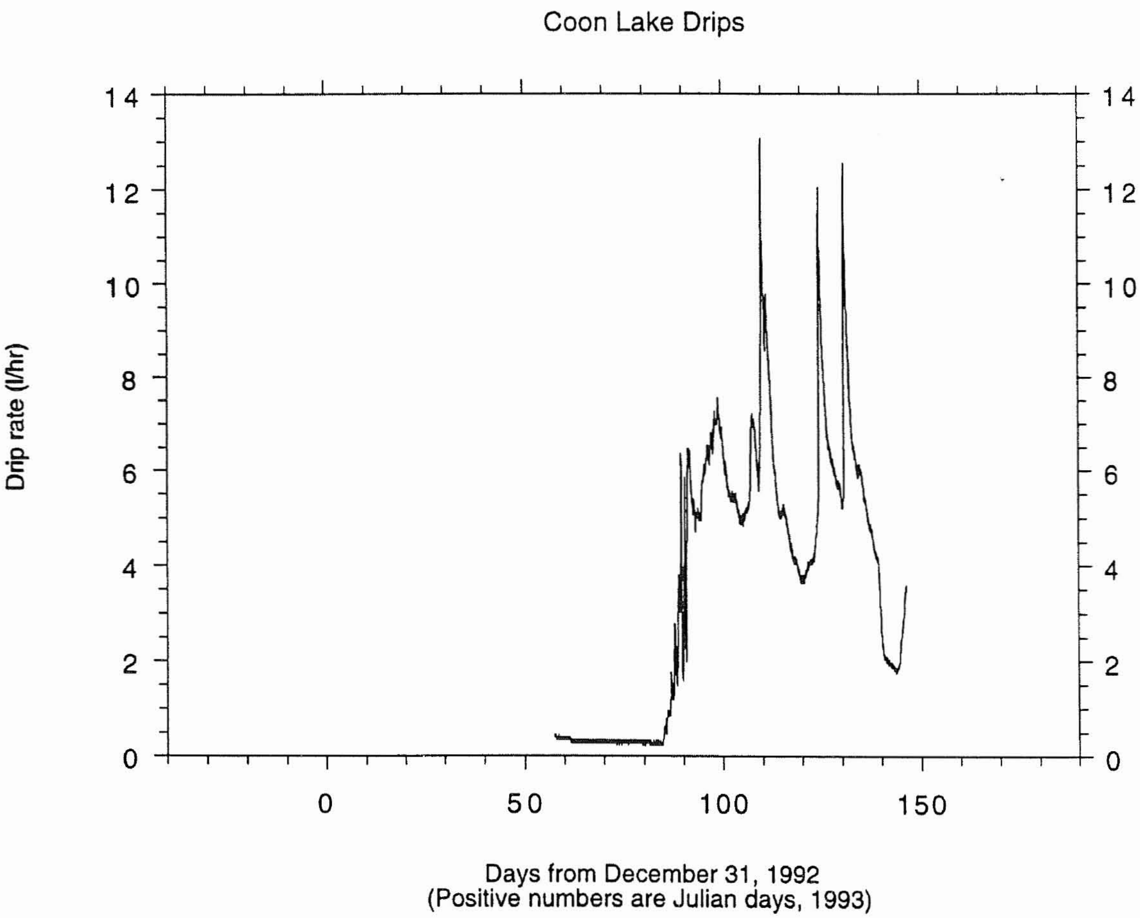


Figure 33. Drip rate, Coon Lake Drips, 1993.

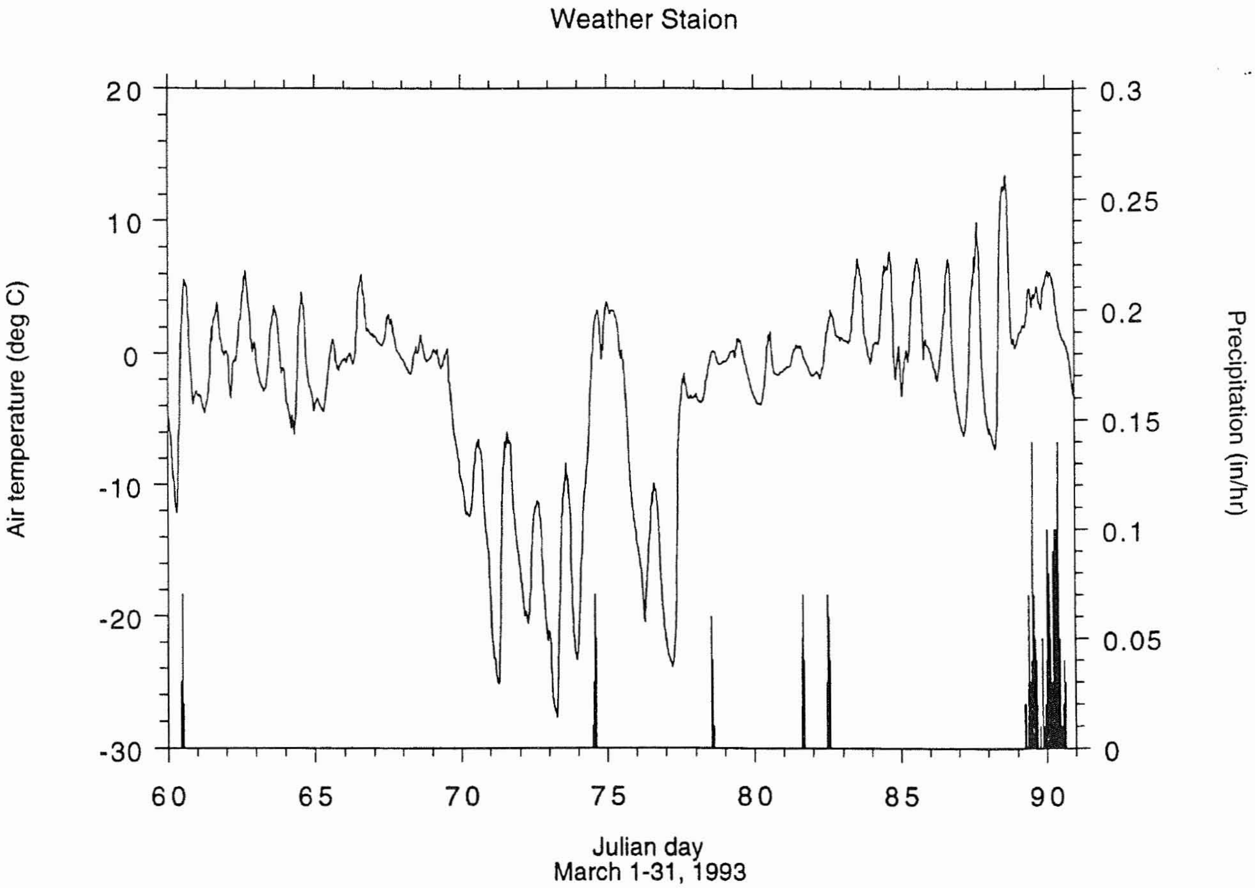


Figure 34. Air temperature and precipitation, Mystery I weather station, March, 1993.

temperatures remained near zero. These temperatures warmed the top of the snowpack, preparing it for the melting soon to come. From noon March 23 through the start of March 27 (day 86), air temperatures were mostly above freezing, with a daytime high of 6°C and temperature ranges of about 6°C (Figure 35). Over the following days, daytime high temperatures rose progressively, reaching about 14°C on March 29.

The snowpack must have begun to melt and induce recharge by March 25 (day 84), because late that day the drip rate began rising at Coon Lake Drips (Figure 35). Over the next several days, as daily air temperature rose and fell, sufficient snow melted to produce daily cycles in drip rates. The first cycle, marked by a peak late on March 26 (day 85) is poorly developed, but the three following ones are clear. Just as high air temperatures progressively increased, so did the drip rates. Late on March 29 (day 88), the drip rate reached about 4 l/hr.

Response Time from Snowmelt

The daily temperature cycles and corresponding drip rate cycles allowed the calculation of response times. The response times were calculated both from the peaks of the air temperature to the peaks of the drip rates and from the minima of the air temperatures to the minima of the drip rates, as shown below.

Julian day 1992	Time between peaks	Time between minima
86	7 hr	---
87	4.5 hr	9.5 hr
88	7.5 hr	7 hr
89	---	6.5 hr

These data show a rapid response time for Coon Lake Drips. Similar or more rapid responses have been obtained for recharge events driven by precipitation. During these events, no temperature responses have been recorded, even during times in which recharge water was significantly colder than mean cave temperature. The temperature data (Figure 35) and the chemical analyses (Figures 36 and 37) suggest that these responses do not represent flow through times. Coon Lake Drips are similar to Blue Lake, but with a much faster time scale. Recharge moves rapidly through the surface materials and displaces pre-existing groundwater from the loess, the subcutaneous zone (insofar as one is present above the site), and/or fissures that lead to cave. Drip rates respond rapidly to storms, reaching a maximum observed discharge of nearly 15 l/hr.

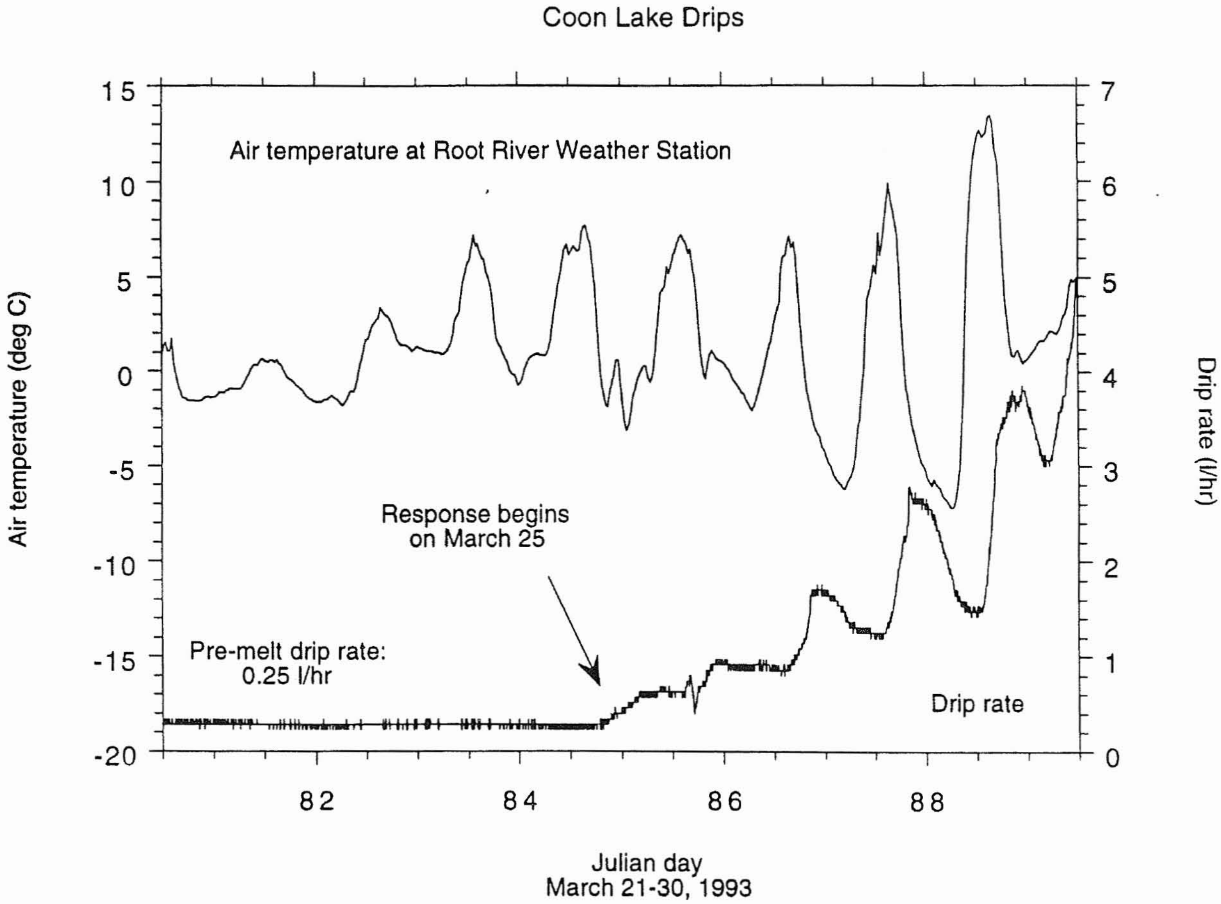


Figure 35. Coon Lake Drips drip rate and air temperature at weather station, March 21-30, 1993.

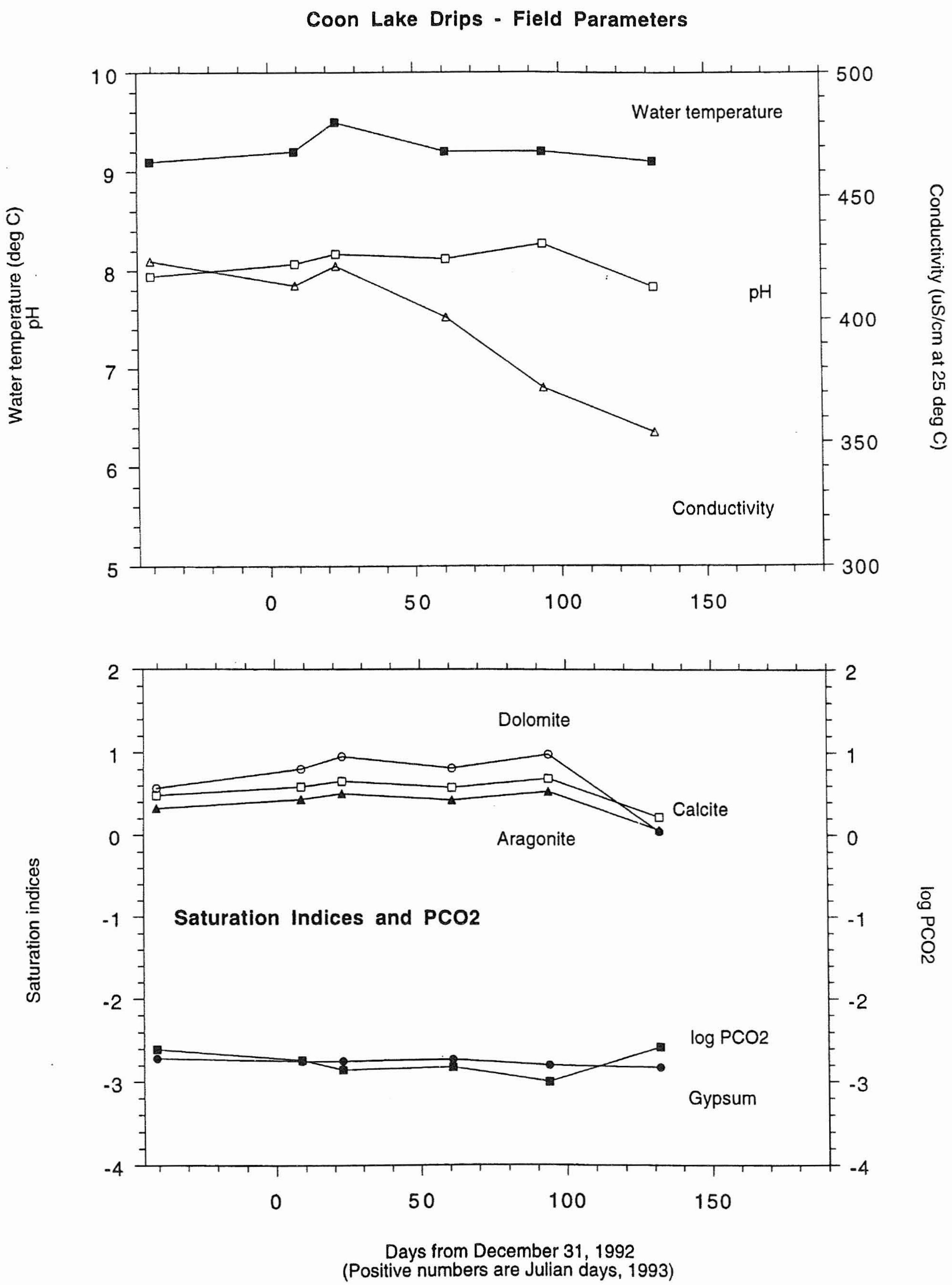


Figure 36. Field parameters and saturation indices, Coon Lake Drips, 1993.

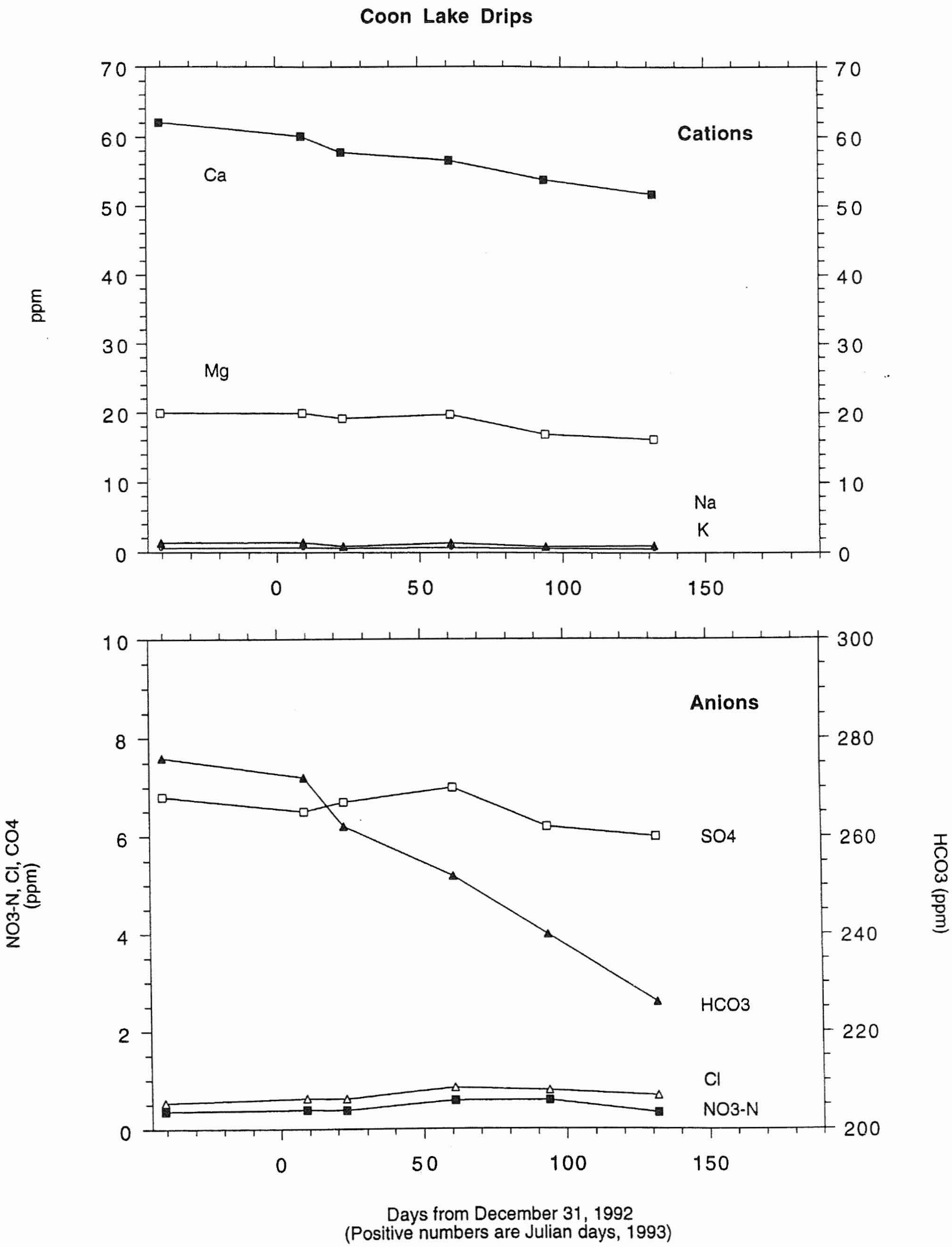


Figure 37. Cations and anions, Coon Lake Drips, 1993.

FLOODING AT MYSTERY CAVE: THE MARCH 30-APRIL 2, 1993 FLOOD

Scope of the Discussion

The spring and summer of 1993 were unusually wet in the midwestern U.S., resulting in a series of flood events throughout the region. In southeastern Minnesota, the flooding began on March 30, as a cold front dumped several inches of rain on an extensive snow cover. Flooding began rapidly on the Root River. At Mystery I, water crested the banks by late on the 30th or early on the 31st. Water was above the banks most of the time until the end of the 31st. Commercial passages in Mystery I were inundated on the 31st and possibly on the first of April. At Flim Flam Creek, water rose over 20 ft and apparently stayed at least 10 ft above normal for over 48 hours beginning about midnight on March 31. Although the effects of the flooding lasted longer, it is convenient to refer to the flood as the March 30-April 2 flood.

Three other major but less intense flood events occurred at Mystery Cave in 1993. One was in May and one was in July. In August, the Root River briefly left its banks (for about one hour, according to Mystery Cave staff) but this did not result in flooding of commercial passages. For brevity, these floods can be termed the first, second, third, and fourth floods. Only the first flood will be discussed here.

We have organized our discussion around four interrelated questions: 1) What conditions led to the flood? 2) What happened on the Root River? 3) How high did waters get in Mystery I, and what were the flow patterns? 4) How did the waters at instrumented cave sites respond to the flood?

Summary diagrams for the flood are in Figures 38 through 41. Figure 38 shows data from the Root River weather station and the Root River. Figure 39 shows data from Flim Flam Creek. Figure 40 is for Blue Lake, and Figure 41 shows data from Coon Lake Drips. A plot of precipitation and cumulative precipitation is in Figure 42.

Pre-flood Conditions: Surface

Before a snowpack contributes to runoff, it must undergo a process called *ripening*. During ripening, the snowpack warms to 0°C and changes to a state in which it cannot hold any more water (Brooks and others, 1991). Warm air temperatures, solar heat (insolation), conduction of heat upward from the ground, and rainfall can add heat to the snowpack. Some of the snow melts, infiltrates under the influence of gravity, and fills open spaces between the snow crystals. When all of the spaces are filled, and the snow is at 0°C, it is ripe. Any further melting will produce runoff.

Of course, some water may infiltrate from the base of the snowpack before the pack is fully ripe, if it can get past ice lenses and frozen soil. The infiltration that led to an abrupt rise in drip rates at Coon Lake Drips on March 25, 1993, probably occurred before the snowpack above Mystery II was fully ripe. Over the next few days, the pack must have fully ripened for short periods over much of the surface basin of the South Branch of the Root River. We can infer this

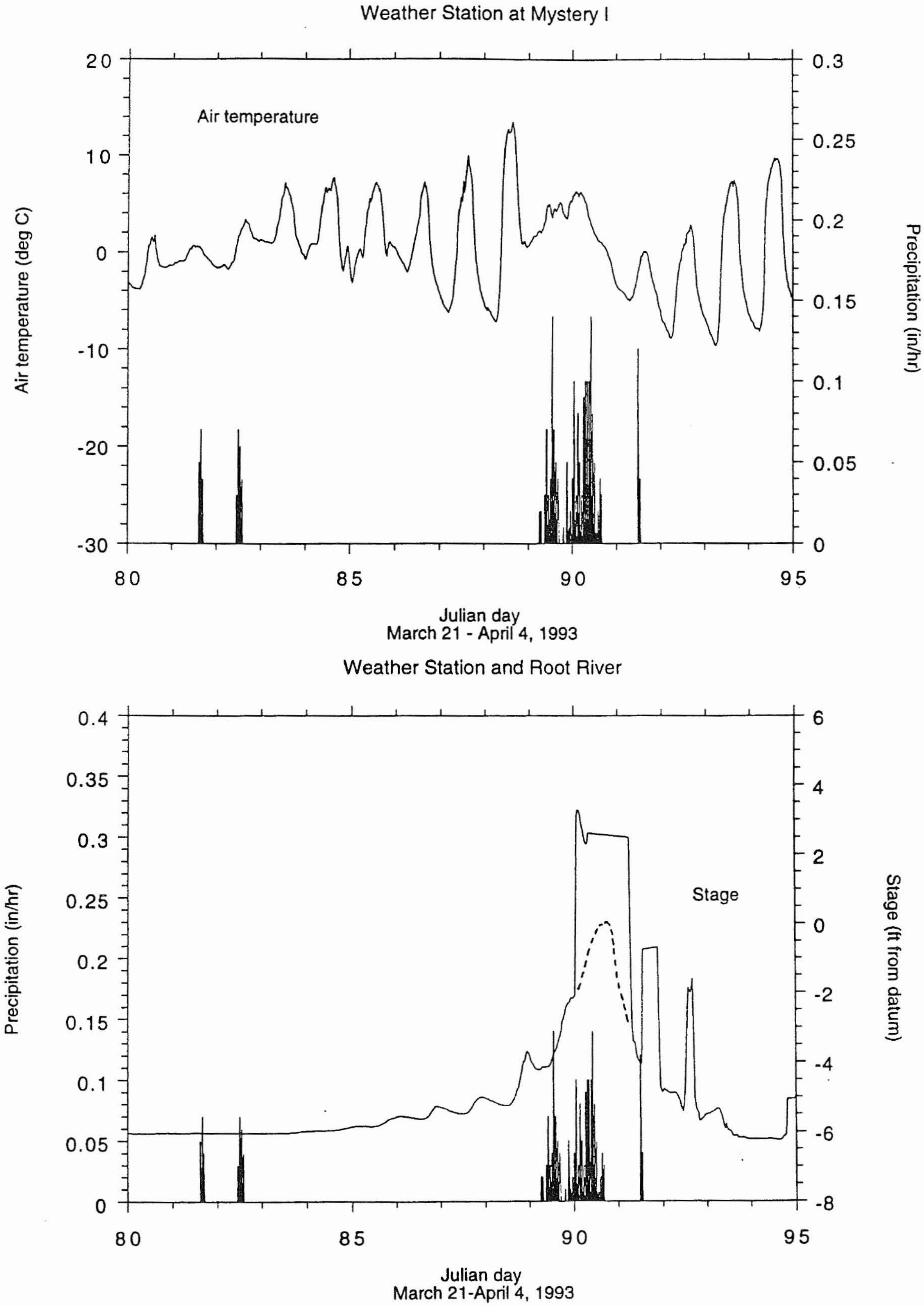
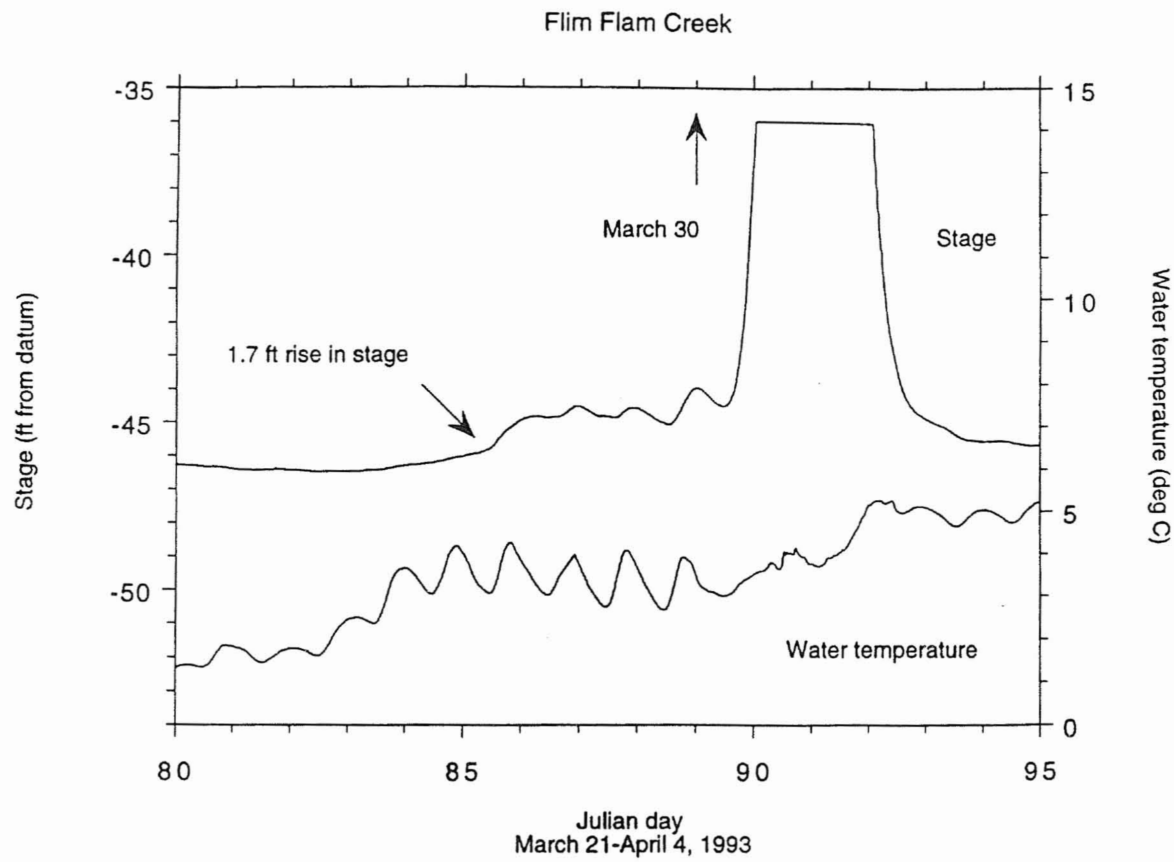


Figure 38. The weather station and Root River records at the time of the March flood.



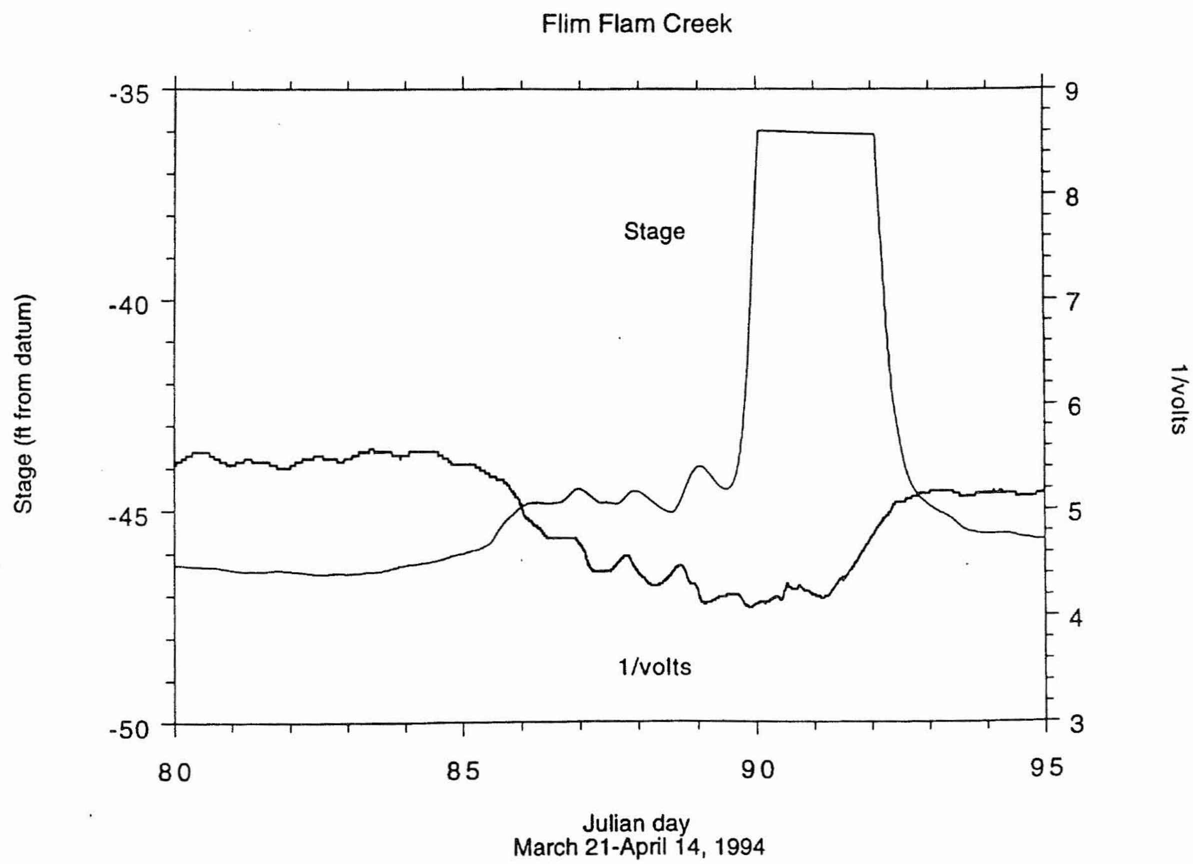


Figure 39. The record at Flim Flam Creek of the March flood.

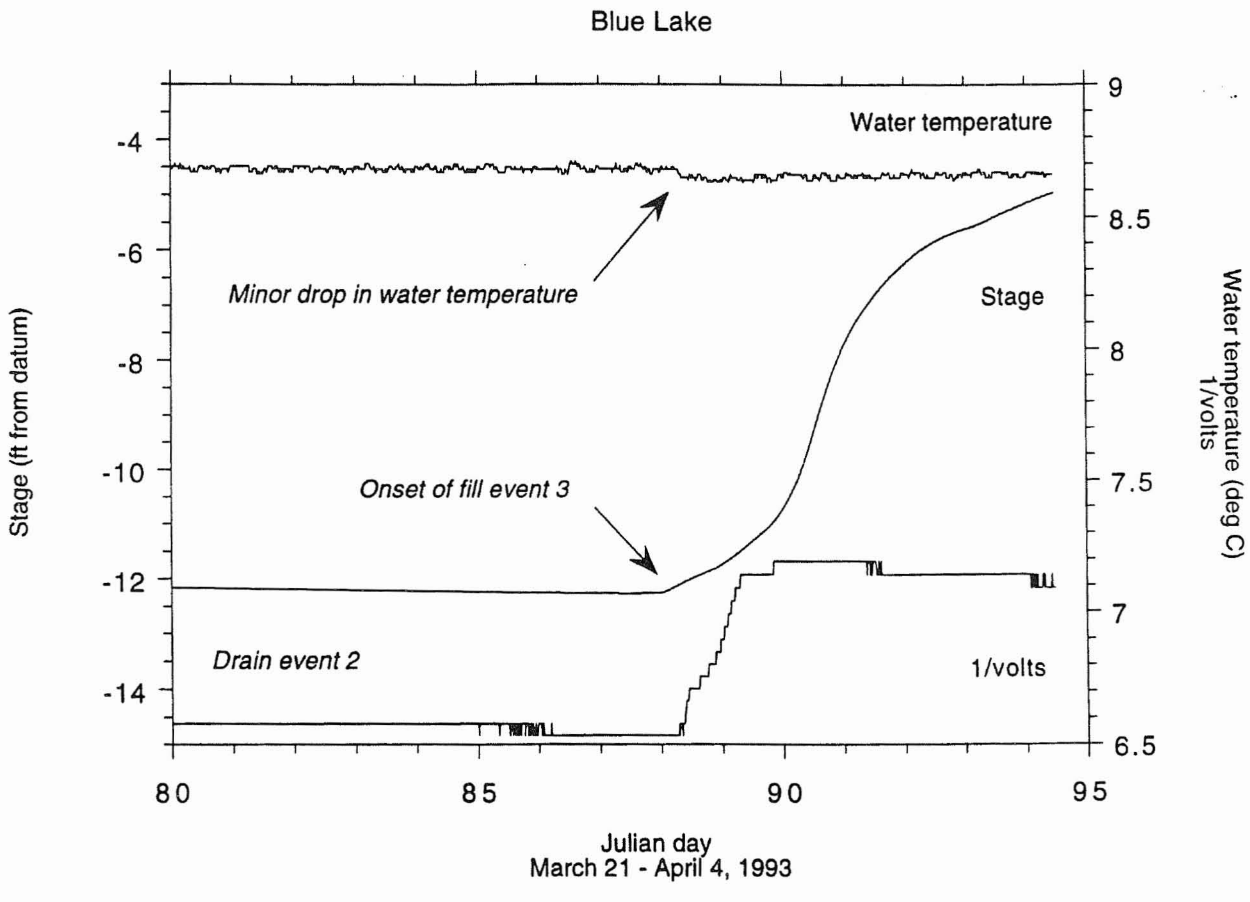


Figure 40. The record at Blue Lake of the March flood.

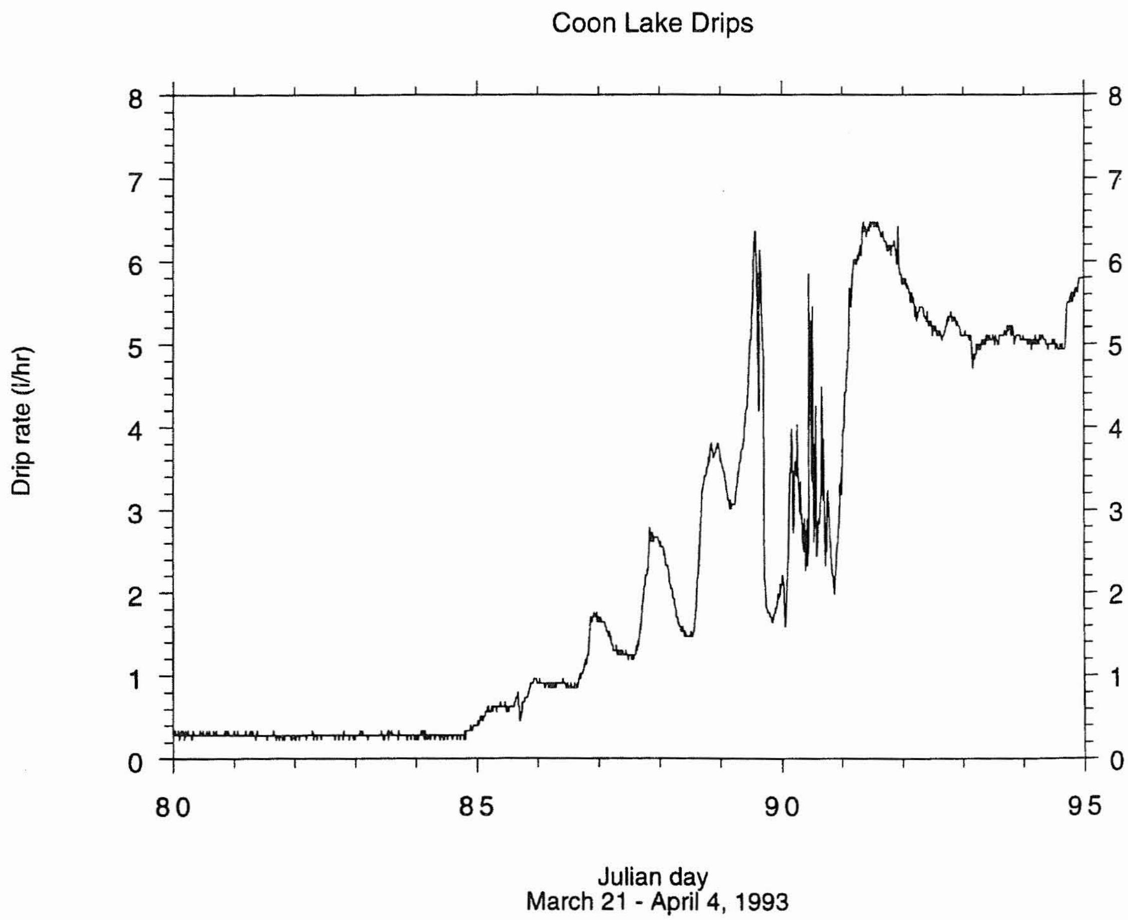


Figure 41. The Coon Lake Drips record of the March flood.

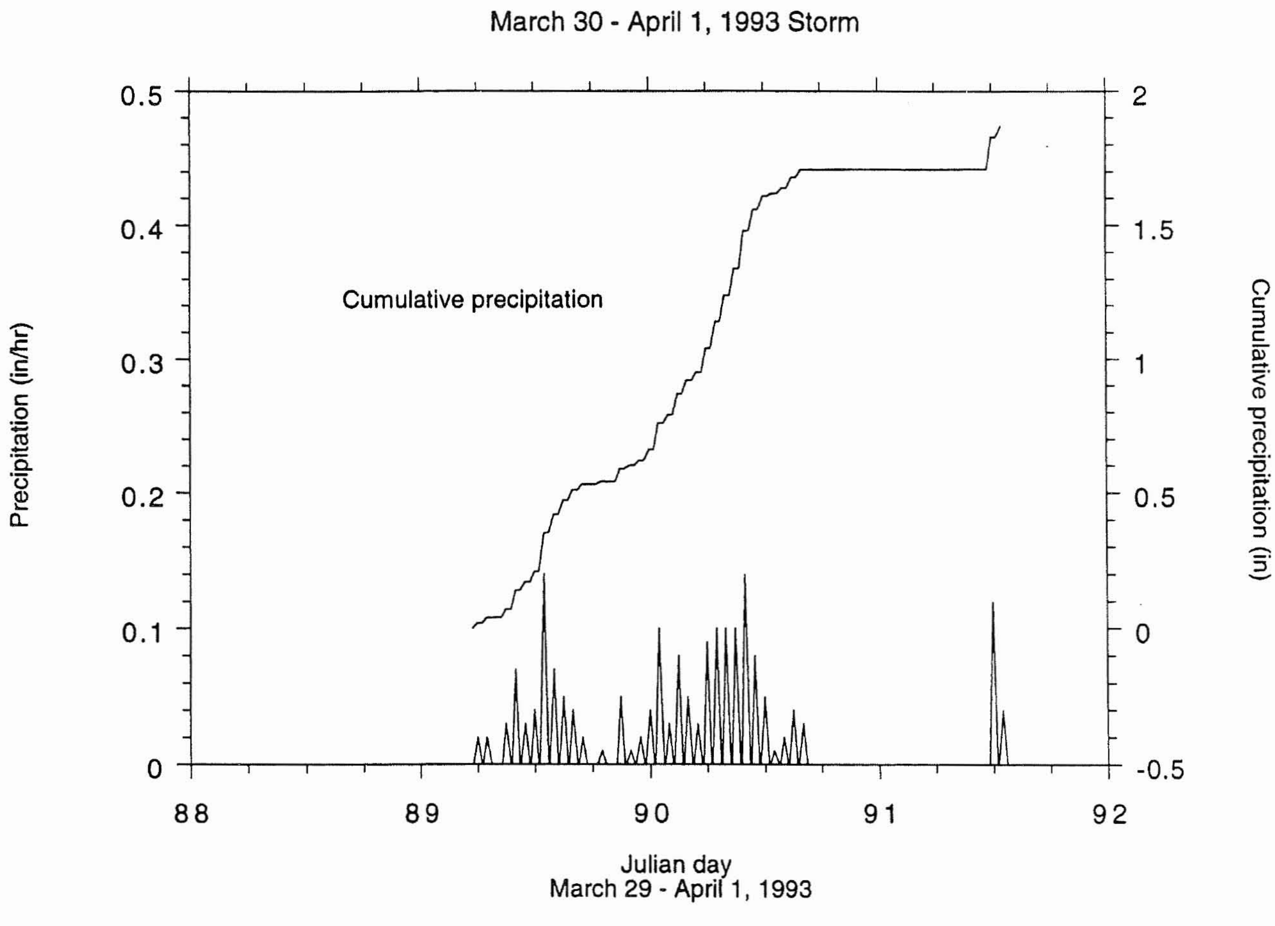


Figure 42. Precipitation and cumulative precipitation for the March 30-April 1, 1993, storm.

directly from cyclic rises and falls of about 0.3-0.5 ft in stage on the Root River, and an overall rise in stage of about 2 ft from March 25 to March 30, before the onset of precipitation (Figure 38).

The eleven days leading up to the flood, beginning on March 18, directly contributed to the intensity of flooding. It did this by bringing the snowpack close to a state of ripeness, primed for runoff during the warmer parts of the day, or for runoff once rain began. Minor rains earlier in the month (Figure 34) produced no noticeable response in stage on the Root River; the rain simply infiltrated the snow, adding to its water content.

Pre-flood Conditions: Blue Lake and Flim Flam Creek

The pre-flood melting produced a response at Coon Lake Drips (Figure 34), as discussed above. At Blue Lake (Figure 40) there also was a pre-flood response. This response begins Fill event 3.

Stage started rising at about midnight at the start of March 29 (day 88). Conductivity (as 1/volts) started to rise at about 6:45 am. Water temperature began a 0.02°C drop from 8.68°C at about 7:15 am; the drop was reasonably complete by about 8:30 am. Conductivity, in contrast, fluctuated until 9:15 am, then began a steady rise that lasted over 24 hours (until 7:15 am, March 30) before flattening out. During this period, stage rose from about -12.23 ft to -11.50 ft.

These observations can be interpreted as follows, recalling our model for fill events at Blue Lake (see p. 24-26 and 33-36). Infiltration, induced by pre-flood snowmelt, displaced higher conductivity water stored upflow from Blue Lake, which slowly started to fill the pool. At the start of Fill event 3, Blue Lake was already about 2 ft deep, as a result of Fill event 2 and Drain event 2. The displaced water was slightly colder than the water at Blue Lake, so water temperature fell slightly. The incoming water was *not* rapidly infiltrating snowmelt; such waters would have started near 0°C, been very dilute (thus had a low conductivity), and should not have been able to thermally or chemically equilibrate rapidly enough to produce the observed responses at Blue Lake.

For Fill event 2, it was possible to calculate a response time of 141 hours (almost 6 days) from the onset of a 2.18 inch November, 1992, storm to the arrival of displaced water at Blue Lake. It is harder to calculate a response time for displaced water for Fill event 3, because it is not clear which surface event(s) (air temperature, Root River daily melt cycles, or Coon Lake Drips drip rate cycles) to use.

Air temperatures consistently rose above 0°C beginning on March 23 (day 82; see Figure 34). At Coon Lake Drips, a displaced water response of about 5-10 hours was inferred, but this assumes some melting had already occurred to open flow paths and establish a more-or less continuous hydrologic connection. As a rough approximation, we can consider the onset of cyclic response in stage on the Root River (Figure 38) and the onset of the rise in drip rate at Coon Lake Drips (Figure 35). Both of these can be placed on March 25 (day 84). We also can consider the rise in water temperatures at Flim Flam Creek on March 23 (day 82; see Figure 39).

On that day, water temperature, which already showed a cyclic response, rose from about 2 to 3°C. From March 25 to the onset of the flood on March 30, the water temperature shows a daily cycle fluctuating about 3.5°C. Whichever events we use for correlation, we get a response time on the order of at least four days for the displaced water at Blue Lake. There, stage rose on March 28 (day 88).

Characteristics of the March 30-April 1, 1993 Storm

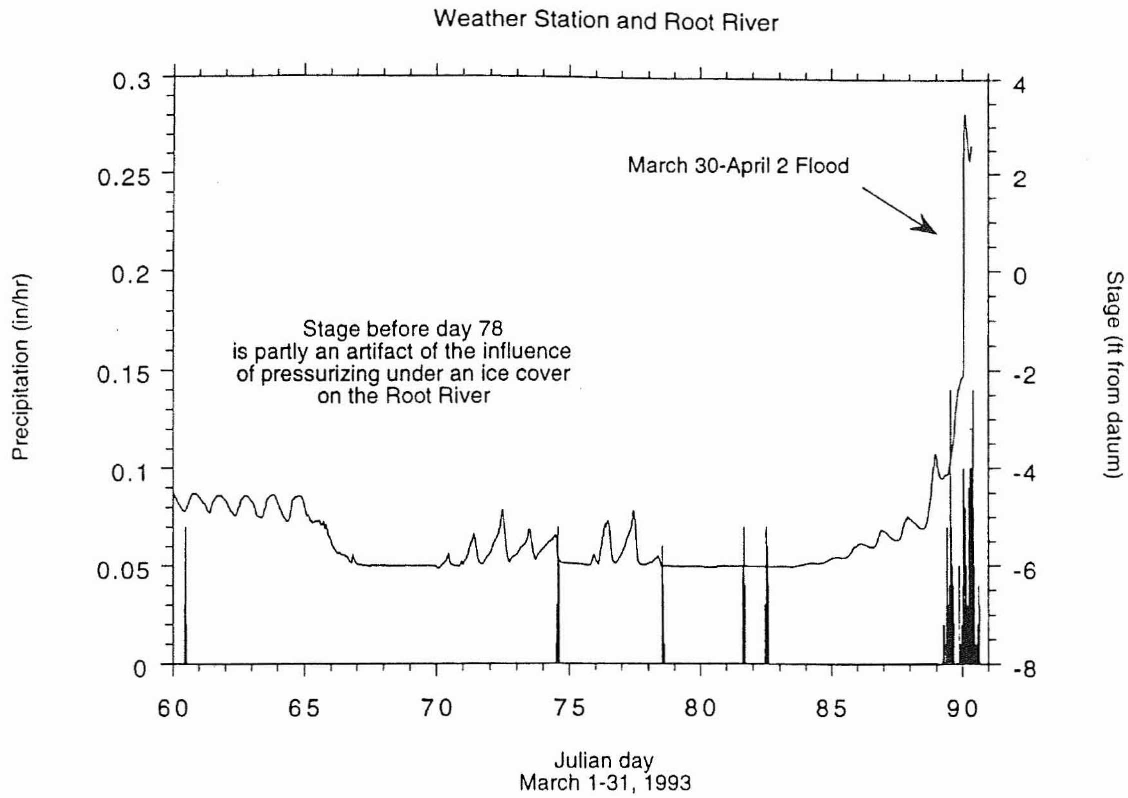
Figure 42 shows the precipitation record for the storm, as precipitation over one-hour periods. It also shows cumulative precipitation. The storm left 1.71 inches in two waves on March 30 and 31. An additional 0.16 in fell about midday on April 1, 1993, for a storm total of 1.87 inches.

Response on the Root River

The stage record must be interpreted cautiously because the capacity of the pressure transducer was exceeded during the storm. If stage exceeds a threshold value, the pressure transducer ceases to record physically meaningful values and may be permanently damaged or broken. After removing data that clearly are due to over pressuring, we obtain the plots of Figures 38 and 43. The higher parts of these plots -- those parts with positive elevations above datum -- are also problematic, because stage is recorded as rising to 3.28 ft above the top of the stilling well that contains the pressure transducer. This is impossible. Had water risen that high, it would have inundated the weather station and overturned it. The top of the stilling well is only one foot below the bottom of the weather station. During the flood, the water level rose to less than six inches of the base of the box, according to Mystery Cave and DNR staff who were on the scene. Valiant efforts by these people saved the weather station from being turned over and destroyed. Had they not done so, we would have had no stage record, because the data logger would have become wet and would have short circuited. (One data logger in the Bomb Shelter of Mystery I, used by Richard Lively for recording radon and meteorological measurements, did flood and short circuited. The data logger was damaged and all of the data on it lost.)

In addition, the pressure transducer cable has a tube that extends alongside the wires that lead to the data logger. The transducer uses atmospheric pressure as a reference. The tube must remain open to the atmosphere for the pressure transducer to yield accurate values. If the tube is blocked or no longer open to the atmosphere, then the readings become suspect. The pressure transducer used at the stilling well had sufficient cable for the tube to extend only to near the top of the stilling well. The end of the tube was covered with a plastic bag along with a desiccant package, but to maintain contact with the atmosphere, the bag was taped so that an opening was present at the top. The bag hung about 1 ft below the top of the stilling well, above and to the side of a light bulb hung even lower in the well. The light bulb was used as a heat source to keep the water from freezing during the winter; an inverted bucket was used to cover the stilling well. When examined on April 3, after the flood, the plastic bag was partially filled with water.

With these cautions in mind, we note the following. The initial response at 6:30 AM on March 30 began shortly after the onset of rain. The initial stage was at -4.2 ft, which is within the



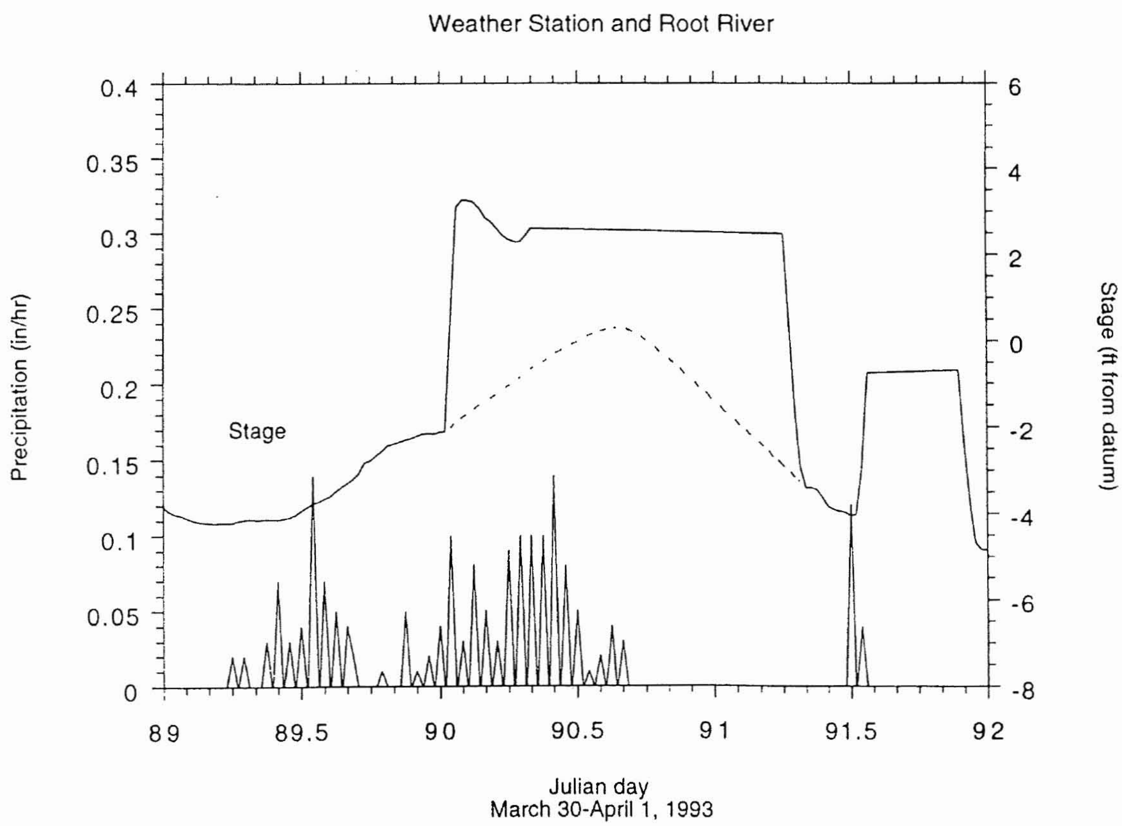


Figure 43. Stage and precipitation on the Root River for March, 1993.

banks but high. Stage rose 0.1 ft between 6:30 and 10:00 AM on March 30 (rate of rise = 0.03 ft/hr). Between 10:00 AM and about 30 minutes after midnight on March 30 (00:30 on March 31) the river rose 2.1 feet to a stage of -2.1 feet. That corresponds to an average rate of rise of 0.14 ft/hr. This part of the record is plausible.

The stage plot in Figure 43 next shows an abrupt rise of 5.38 ft from -2.1 ft to +3.28 ft from 00:30 AM to 2:00 AM on March 31. That corresponds to an average rate of rise of 3.6 ft per hour. A rise that fast is difficult to believe, however, given the abuse the pressure transducer suffered and the physical implausibility of the highest numbers.

The elevation at the top of the stilling well (0 datum) is 1230.86 ft (Palmer and Palmer, 1993a). On the Mystery I entrance door, the highest debris line indicated a high water level of about 1231 ft. The Mystery I entrance is about 100 yards downstream of the stilling well. Although we do not know what the gradient was during flooding, it was not reversed -- the water must have reached higher than the top of the stilling well. It could not have gone much higher, certainly not 3.28 ft higher, because the weather station is only one foot higher than the top of the stilling well.

A plausible interpretation is that the bag floated and partly protected the tube from becoming filled with water, but water eventually covered the bag, at which point stage readings became unreliable. We do not know at what stage the unreliable data began. Based on our estimate that the plastic bag was 1 foot below the top of the stilling well, all data above -1 ft stage must be considered suspect. We do not think the pressure transducer was permanently damaged, however, because the system gave reasonable responses to stage variations in the days and month following the flood. The wet bag was replaced on April 3, and at that time the plastic tube appeared to be free of trapped water. Later calibrations of stage made by filling the stilling well with water and recording falling water level in the well gave consistent results that differed little from earlier lab calibration of the pressure transducer before installation.

Reasonable stage readings resumed, perhaps, at about 8:00 AM on April 1, when stage was at about -3.5 ft. The dashed lines in Figures 38 and 43 show one estimate of the stage during the flood. This interpretation derives some credence from the rapid response of stage to precipitation recorded on April 1 shortly after 12 noon. (Other more complex scenarios are also possible, however.) Stage is seen in Figure 38 to rise to about -0.7 ft before the reading again went off scale. Readings remained off scale until about 9:30 PM on April 1, when they fell to about -0.7 ft.

A third sharp peak in stage was recorded during the afternoon of April 2 (Figure 37). Assuming this was real (it had no overpressure component), it can be interpreted as the passage of a runoff pulse from some upstream tributary to the South Branch of the Root River -- from either the March 30-31 rain or the April 1 rain.

Response in Mystery I

Water did not enter the cave through the Mystery I entrance, but the flooding was high enough to have done so were the entrance not gated. As previously noted, the water level at the Mystery I entrance crested at about 1230.4 ft. This level is about 2.3 ft above the cement floor at the entrance floodgate. The floodgate in fact prevented water from entering the entrance and running into the cave. However, inside the cave water rose up out of lower level fissures and flowed east through the cave away from the Root River. DNR and Mystery Cave staff entered the cave before and after the flood crest, and observed flow along the main tour route. Water rose from fissures near the entrance, flowed past the Pipe Organ, the Frozen Falls area, and Turquoise Lake en route to the Bomb Shelter and the rest of the Door-to Door route.

A polyethylene beaker used for water sampling left at a drip point across from the Pipe Organ (a few days before the flood) was found on a ledge 50 ft past Turquoise Lake after the flood on April 3. A canoe and large wooden planks used at Turquoise Lake and left by DNR staff on the walkway at the lake were moved. The planks were left in Turquoise Lake and the canoe was moved up on a ledge. Considerable sediment was eroded from several banks. Many of the light bulb holders floated up out of their moorings but remained attached by connecting wires. Some cracked and filled with water. Other light bulb holders were wet but appeared little the worse for wear. The lighting system sustained considerable damage although the computer-driven control system at the entrance was not flooded and functioned normally after the water receded.

Monitoring equipment used by Richard Lively at the Bomb Shelter was washed farther into the cave. Before the flood, some of the equipment was on a table about 1.5 ft high; after the flood, the equipment was stretched out down the passage, still attached by electrical cords. An evaporation pan and basket cover was installed a few days before the flood at the Bomb Shelter. After the flood the pan was 30 ft farther in, submerged in a new pool left by the floodwaters.

The rising water was turbulent and turbid. Existing sediments along the trails were rearranged by erosion and redeposition. A fine silt covering was ubiquitous on railings. Cement walkways were covered by mud, silt, sand, and in a few locations, small breakdown fragments eroded from overhanging walls in the relatively weak beds of the Dubuque Formation. However, in comparison with floods in other eastern U.S. caves that receive direct surface flood waters from sinking streams, this flood did surprisingly little re-arrangement of sediments -- at least along the trails. Much of the surface debris and large sediment was filtered by the occluded joints through which the food waters entered the cave. Only the finest sediments could be lifted by the flood water up to the commercial level to be deposited as thin coatings on rails and on cement floors. The thicker accumulations on the trails were sediments with local sources within the upper level.

The heights reached by floodwaters can be estimated by observing locations of such features as (1) sediment deposited on passage walls, on railings, and on floors; (2) sediments deposited in pools or small indentations; (3) areas of erosion or collapse of bedrock; (4) disturbed light fixtures; or (5) disturbance of equipment or materials left in the cave.

At the Formation Room in Mystery I, water rose barely to the level of the cement pad above the steps leading into the room. A sandbank next to the steps was severely eroded. The cement pad, which is nearly, but not quite level, had a thin coating of silt on its lower section near the steps. A radon detector a few inches away on the pad barely escaped inundation.

Confirmed heights reached by floodwaters at locations near leveling stations listed by Palmer and Palmer (1993a) are as follows:

Entrance Floodgate to Mystery I ..	1230.4 ft
Turquoise Lake	>1220 ft
Bomb Shelter	>1220 ft
Formation Room pad	1218 ft

A rise in stage on the Root River increases the pressure head on the sediments of the streambed thereby increasing infiltration rates. Water is injected into every available opening. Some of those openings probably do not transmit significant amounts of water until threshold pressures are reached. Other fractures are probably above low-flow stage on banks or along the cliff near the Mystery I entrance. Such fractures cannot transmit water from the river until stage is high. The net effect is that a given increase in stage injects a greater amount of water per unit time as the flood stage increases.

The capacity of the lower levels of Mystery Cave to accept this water is not infinite. Some sections of passage are of smaller diameter than others. There are constrictions. As the flood waters pour into the lower levels the capacities of these constrictions are exceeded. The result is backflooding. The water level rises. If the flood is of sufficient magnitude and duration, water rises completely out of the lower levels and enters the commercial trails of Mystery I.

It is important to note that most of Mystery I is below the level of the bed of the Root River, but adjacent to it (Sheets 1 through 4, Palmer and Palmer, 1993a). Passages in Mystery I trend east away from the Root River (Figure 1). Therefore, water from the flood had a strong component of flow to the east, into the cave.

Response at Blue Lake

The pre-flood response at Blue Lake (Figures 40) raised stage from -12.23 at the end of Fill event 2 to about -11.50 ft, increasing water depth from about 2 ft to about 2.7 ft at the time conductivity leveled out on March 30, 1993 (day 89).

What happened next? Stage continued to rise, but when did Blue Lake respond to the March 30 flood? And what was the nature of that response? Is it unequivocally present as a distinct point in the plots of stage, water temperature, or conductivity?

We believe that the March 30-April 1 storm induced infiltration which induced another pressure pulse. The pulse displaced additional stored water (rather than directly transmitting a rapidly arriving batch of recent snowmelt and rain) into Blue Lake. This is suggested by the unchanging water temperature and conductivity that continued long after the storm. The 0.02°C drop in water temperature at the start of Fill event 3 was interpreted above to reflect minimally colder displaced water. A similar temperature drop followed the March 30-April 1 storm as shown in Figure 40.

Eventually, of course, water that infiltrated during the storm should have arrived at Blue Lake. The question is, when did it arrive, and did it carry a signal that clearly marks its arrival? The longer the flow-through transit time, the more time the cold, dilute infiltrate would have had to thermally and chemically equilibrate, or so mix with other waters that they would be difficult to discern as different from water present in Blue Lake.

The arrival time *of the start of the response (however expressed) at Blue Lake to the March 30-April 1 storm* is, in fact, not clear. The difficulty could arise in part because of the nature of the surface conditions that led to the pre-flood response. We saw previously (pg. xx) that it is difficult to correlate the onset of Fill event 3 with a specific surface event. However, signals at several surface and cave sites (air temperature at the Root River weather station; rise in stage on the Root River; water temperature rise at Flim Flam Creek; and the time of the change from winter base flow at Coon Lake Drips to higher drip rates) suggested a response time on the order of at least four days.

There is also the difficulty of deciphering the structure of the system of flow path(s) that feed into Blue Lake. If there are several major tributaries that combine upflow of Blue Lake, then arrival times from the same surface signal could vary. Arrival times would depend on travel times of through-flow and pulse-through components along the separate tributaries. Total response time would be the sum of through-flow and pulse-through times. Further, even if average response velocity was identical for each component, then total response time could be different, if flow path lengths (tributary lengths) were different.

A final difficulty arises because of the structure of Blue Lake itself. It is, we said, a leaky bathtub with at least two sets of drains. The lowest are into the sediment in the floor. The highest drains consist of the routes that feed Blue Lake Springs. These drains have to be higher than Blue Lake Springs (but not by much) to induce flow out the springs. The highest of the seeps and holes that constitute the springs are at an elevation of 1233.28 ft (Palmer, personal communication, 1993). The next lower are at 1233.12 ft. The water level in Blue Lake must rise higher than -5.62 ft relative to datum to create a head difference and induce flow out Blue Lake Springs. The water level reached this elevation after the storm early on April 3 (day 93). At that time, were discharge into the lake approximately constant, then the addition of an extra drain should have slowed the rate of rise in stage. Instead, the rate of rise of stage increased shortly after the critical elevation was reached. The stage continued to increase until April 9 (day 99). In all probability, discharge into Blue Lake increased throughout this time period.

Response at Flim Flam Creek

At Flim Flam Creek (Figure 39), stage rose about 1.7 ft during the pre-flood interval from a low at about -46.5 ft on March 23 (day 82) to about -44.8 ft on March 26 (day 85). Between

March 21 (day 80) and this rise in stage, the water level showed no daily cyclicity that could be attributed to daily snowmelt cycles. After the rise, daily melt cycles are reflected in stage cycles at Flim Flam Creek.

In contrast, daily *temperature* cycles were evident at FFC before the 1.7 ft rise in stage (Figure 39a), but were subdued, with amplitudes of about 0.5°C. After the rise in stage, the temperature cycles intensified, with amplitudes of 1°C or greater. The conductivity (expressed as 1/volts) was nearly stable as long as stage was stable (with minor daily cyclicity due to variations in temperature), but dropped sharply with the 1.7 ft rise in stage. Because water temperature rose correlative with the stage rise but temperature declined, the rise in stage reflects a significant increase in the dilute snowmelt flow component derived from rapid run in from the Root River.

The flood response began on March 30, within about 11 hours of the onset of precipitation at 5:30 am. A minimum in stage of -44.5 appears at about 11:30 am. A gradual rise to -44 ft was completed at 4:00 PM. Thereafter, stage rose rapidly. By 1:00 AM on March 31, stage had risen to -36 ft, an 8.5 ft rise. At this point, the capacity of the pressure transducer was exceeded. From the height of silt and sand deposited on chockstones in the FFC fissure, and silt deposited on wall indentations even higher, we know that stage rose to at least -19 ft (Palmer, written communication, 1993). This represents a rise of 27.5 ft. Stage readings began again about 49 hours later, at about -36 ft, the same elevation recorded just before readings were first lost. By 4:30 PM on April 2 (day 92), stage fell back to the pre-flood minimum stage recorded on March 30. Thus the primary flood response at Flim Flam Creek can be estimated at three days and five hours. The duration of the response is longer, by more than a day, than the duration of the initial peak on the Root River (which ended by about 7:00 AM on April 1). A second peak in stage on the Root River, from roughly noon to about 10:00 PM on April 1, no doubt is partly responsible for the long duration of the primary response in stage at Flim Flam Creek. Other factors involved may include the time it takes for waters to drain past constrictions downstream of FFC. For the subsurface upstream of FFC, there would be a variation in arrival times for incoming water from various sources, so the response at Flim Flam Creek can be expected to be spread out longer than flooding on the Root River under most circumstances.

The cyclic variation in water temperature that immediately preceded the flood was lost during it, but re-established rapidly starting April 2, after water returned to about -43 ft, well above the pre-flood minimum of -45.5 ft. (Two minor fine-structure rises and falls with short periods less than a day during the flood probably represent periods during which water from a particular tributary became dominant, or at least modified the temperature of a larger volume of floodwaters with which it had mixed.) During the flood response, water temperature rose from a 3.5°C mean temperature (within daily cycles) to about 5°C. The conductivity (as usual, expressed as 1/volts without temperature corrections) initially exhibited fine structure at a low level, through the middle of April 1, but then rose as soon as water temperature increased.

Response at Coon Lake Drips

The drip rate, which was recorded over five minute intervals, shows considerable fine structure (Figure 41, 44 and 45). In the pre-flood period of March 25-30 (days 84-89) daily drip rate cycles became established; they are associated with daily snowmelt cycles. The minima in drip rates were broad (at least 4 hours) on March 28 and 29 and occurred about noon each day. On both days, the rise from the minimum was abrupt, beginning about 2:00 PM.

We do not believe that the data imply rapid transmission of melt water to Coon Lake Drips. Instead, pulses of stored water were being displaced, in response to surface infiltration of snowmelt, into the cave passage. Both through-flow time and pulse-through time were involved.

The storm began at 6:00 AM on March 30. Had no storm occurred, there would probably have been a minimum in drip rate on March 30 in the early afternoon. That minimum would have been higher than the minimum observed on March 29, but lower than the actual minimum observed on March 30 (point X, Figure 44). The actual minimum came about 5:00 AM, when the drip rate was 3.l/hr. The rise in drip rate began about 5:45 at the onset of the storm. This suggests a nearly complete hydraulic link from the base of the snowpack to Coon Lake Drips. The snow pack would have been ripe, even at night (air temperatures were above freezing (Figure 41) the night of March 29-30). As soon as rain fell, infiltration increased beneath the snowpack. Water was immediately displaced to fall at Coon Lake Drips and begin a rise in drip rates. Such a model for the response is tempting, especially for the onset of the storm. However, the response at Coon Lake is too variable (and too complex) to fit this explanation throughout the storm.

Drip rates rose to a maximum of about 6.4 l/hr at 2:00 PM on March 30, fell to about 4.2 l/hr at 3:30 PM, then rose rapidly again by about 3:50 PM to 6.4 l/hr (Figure 45a). Next, drip rates rapidly declined to just over 2 l/hr by 6:00 PM, declined slowly to 1.7 l/hr, and rose to 2.2 l/hr until about 1:30 AM on March 31. A consistent rise to about 3.5 l/hr at 4:00 AM is followed by chaotic behavior. For the next 14 hours, drip rates fluctuate wildly from 2.2 to 6.1 l/hr. It is tempting to try a correlation of these drip rates with rainfall (Figure 45b). To a first approximation, such a correlation appears to work, assuming a complete hydrologic connection.

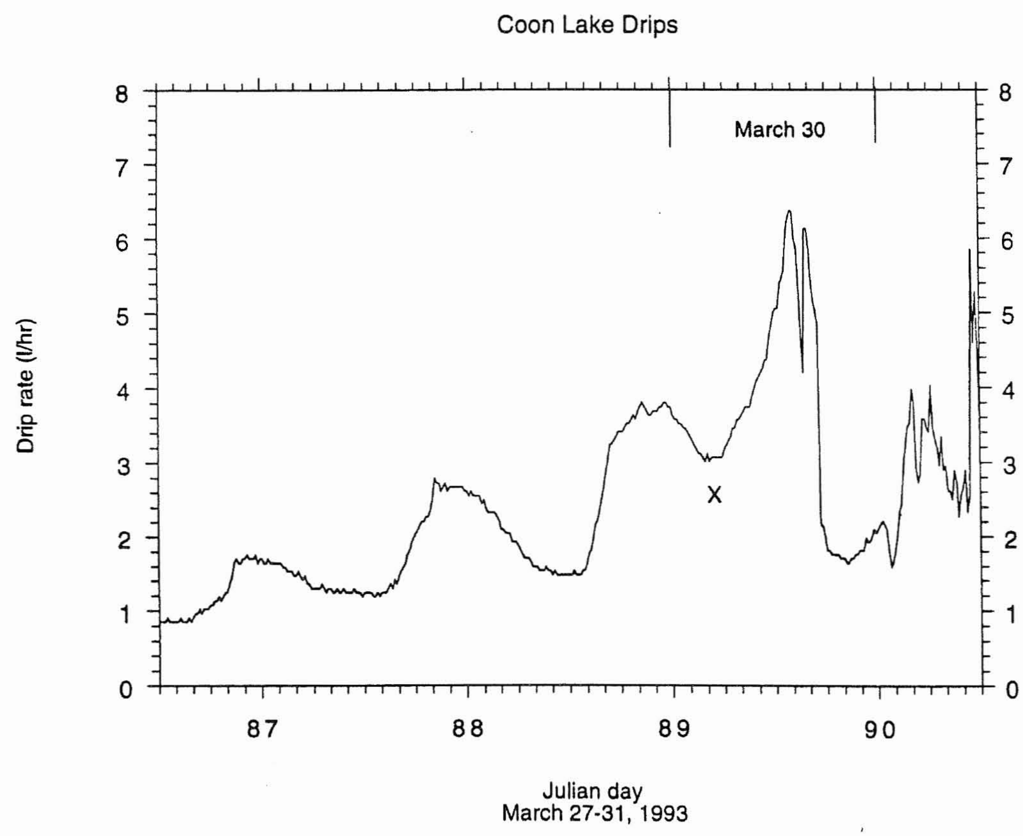


Figure 44. Coon Lake Drips drip rate, March 27 to March 31, 1993.

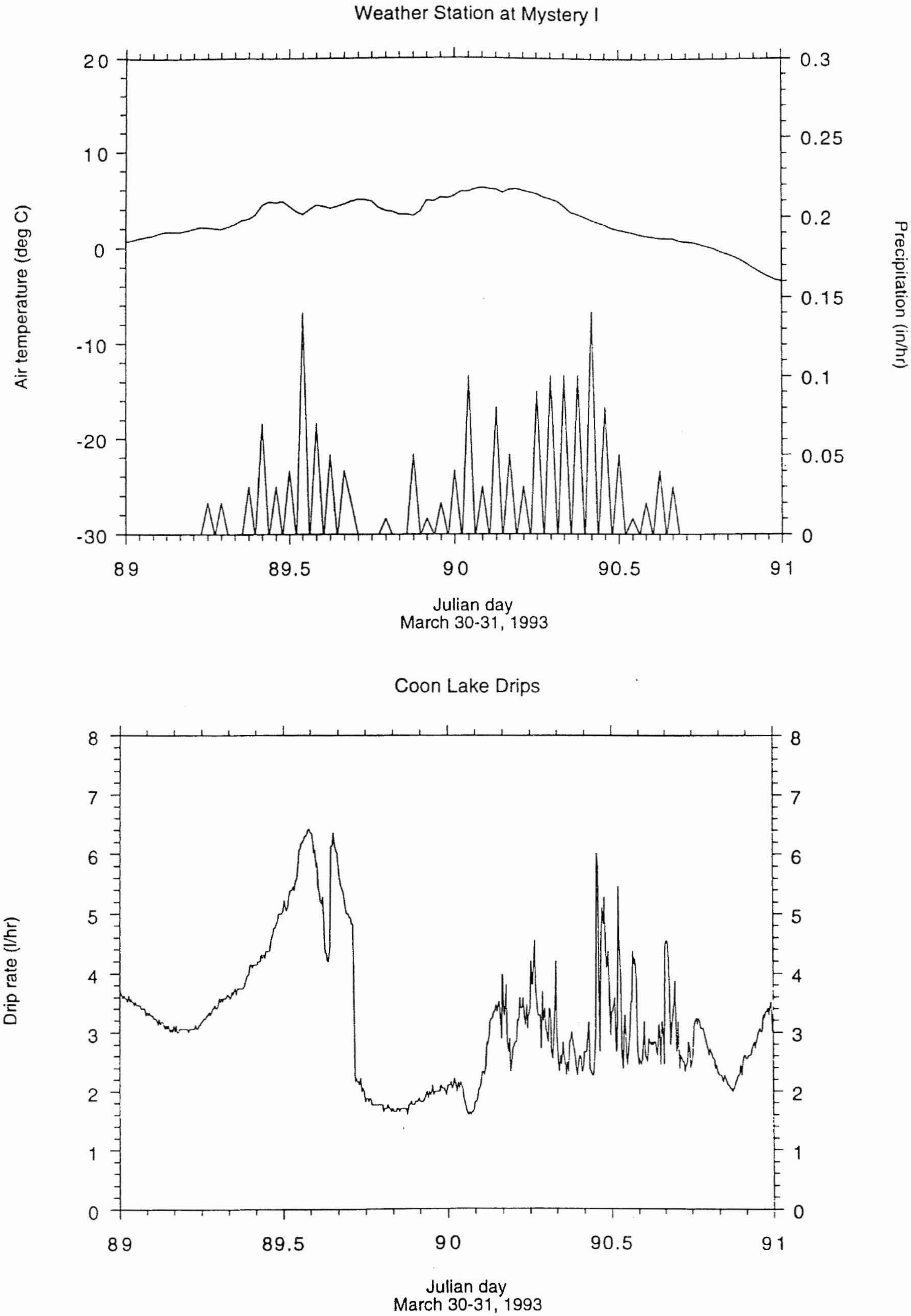


Figure 45. Fine-structure of drip rates at Coon Lake Drips, and precipitation and air temperature at the weather station, March 30-31, 1993.

MYSTERY CAVE: SELECTED COMPARISONS WITH OTHER CAVES

Region

Mystery Cave is one of the two longest mapped caves in the upper Mississippi Valley. Mystery Cave is the largest commercial cave in the upper Mississippi Valley karst and is the longest mapped cave in Minnesota by over a factor of two. Mystery Cave is the largest of a group of flood-water maze caves developed in the Dubuque and Stewartville Formations. Other significant caves developed in similar hydrogeologic settings include Spring Valley Caverns, Goliath, and the Forlorn River Complex. All of these caves are found within a few miles of each other in Fillmore County.

The second major class of caves in the upper Mississippi Valley karst are the dendritic river caves that develop upstream of major resurgence springs at the Cummingsville/Decorah contact. Cold Water Cave south of Harmony in northern Iowa is the largest known example of this type of cave. Significant Minnesota examples of this type of cave include Pine, Tyson's, Deep Lake Cave, and Bat River Caves. All of the Minnesota examples are in Fillmore County.

Niagara Cave, the second commercial cave in Minnesota, is a transitional form between the flood-water maze caves and the dendritic river caves. The entrance of Niagara is a sinkhole through the Dubuque and takes flood waters after any significant recharge event. The cave cuts down through the entire Stewartville Formation into the underlying Prosser Formation.

The third major group of caves in the upper Mississippi Valley karst are the dry maze caves that develop in the Prairie du Chien Group. Crystal Cave, a commercial cave near Spring Valley, Wisconsin, and many other caves in southwestern Wisconsin are developed in the Prairie du Chien Group. In Minnesota, significant Prairie du Chien caves include, Hiawatha Caverns (in Wabasha County), Hiawatha Cave (in Winona County), and Priest's Cabin Hollow Cave.

Chemistry and its Influence on Speleogens and Speleothems

Once a cave has formed, the chemistry of entering waters has a direct influence on the features that develop. If the waters are saturated with respect to calcite, then they may deposit speleothems. If they are undersaturated, then they are solutionally aggressive: they can dissolve bedrock or existing speleothems. If bedrock is dissolved, then various solutional forms -- known as speleogens -- may form. In Mystery Cave, speleogens include rounded ceiling and wall pockets, joint spurs, and scallops. Scallops are rare, but the other forms are ubiquitous along the tourist routes.

In many temperate zone karsts, the bulk of the entering water is from concentrated recharge. The water comes from drainage at sinkholes and sinking streams. Much of the time, these waters are undersaturated when they arrive at the cave. The passages that transmit the water are actively enlarging, because the solutional capacity of the water has not been exhausted. Where the waters have a strong vertical component of flow, they may dissolve vertically oriented solutional forms such as vertical shafts and flutes or rills. Where aggressive floodwaters are injected into bedding plane partings, following floods much of the water drains back out. In some caves, vertical rills or flutes form on bedrock below the bed partings.

Such vertically-oriented features are nearly absent from Mystery Cave. Niagara Cave, the other commercial cave of Minnesota, has a vertical shaft that has been eroded headward by a waterfall to form a solutional canyon, but no such features are present in Mystery Cave. Yet Mystery Cave has abundant sites of vertically descending water. Why are there few, if any shafts, rills, or other vertical speleogens?

The key may well be the calcareous composition of the soil and loess above the cave, its large thickness, and the long transit times for vadose waters to infiltrate and arrive at the cave. Much of the solutional capacity of the water is simply used up outside of the cave. Consequently, even though abundant vertically descending water is available, and sufficient relief is available for the development of large vertical shafts, the water has only a limited capacity to dissolve the dolomite and limestone.

QUESTIONS

The cave specialist and the 1993 interpretative staff submitted questions they are commonly asked by cave visitors. This part of the Interpretative Report is arranged as answers to those questions. The submitted questions are in italics below.

Cave Water Quality -- Natural

1) Given an "average" cave water drop, what are percentages of what chemicals/molecules?

This is a fundamental question and a good place to start. It is simpler to use an actual chemical analysis of Mystery Cave water rather than talk about an "average" water. Table 1 lists the composition of a water sample collected from Turquoise Lake on July 28, 1992. Turquoise Lake is typical of the waters in the cave and is along the commercial tour. There are detailed tables of similar data in the Technical Report for a number of different waters in Mystery Cave.

The waters in Mystery Cave are mostly water. This sample of water from Turquoise Lake was 99.92% water by weight. The waters in Mystery Cave typically range between about 99.90 and 99.95% water.

The total of all of the dissolved solids (TDS) in this sample was 0.0773% or 773 parts per million (ppm) or 773 milligrams per liter (mg/l).. These dissolved solids come from a variety of sources. Much, but not all, of these dissolved solids are in the form of ions. Ions are electrically charged atoms or molecules.

The various waters in Mystery Cave have dissolved solids dominated by calcium (Ca^{+2}), magnesium (Mg^{+2}), and bicarbonate (HCO_3^-) ions. These compositions are produced by rainwater and snow melt absorbing carbon dioxide to form carbonic acid and then dissolving the limestone and dolomite bedrock. The basic chemical equations that describes the dissolution of limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) can be summarized as:

$$\mathbf{CaCO_3 + CO_2 + H_2O \longleftrightarrow Ca^{+2} + 2\,HCO_3^-}$$

limestone + carbon dioxide + water yields calcium ions + bicarbonate ions

and

$$\mathbf{CaMg(CO_3)_2 + 2\,CO_2 + 2\,H_2O \longleftrightarrow Ca^{+2} + Mg^{+2} + 4\,HCO_3^-}$$

dolomite + carbon dioxide + water yields calcium ions + magnesium ions + bicarbonate ions

The reactions proceed to the right as the limestone or dolomite dissolves to create caves in the bedrock. The upper reaction proceeds to the left in the cave as calcite ($CaCO_3$) speleothems are deposited. Dolomite is not known to precipitate in cave to form speleothems.

Table 1. Chemical composition of Turquoise Lake, July 28, 1992

Component	chemical formula	units	conc.	% of TDS
water	H_2O	wt %	99.92	
calcium ion	Ca^{+2}	ppm	107	13.8
magnesium ion	Mg^{+2}	ppm	49.4	6.4
sodium ion	Na^{+}	ppm	9.8	1.3
potassium ion	K^{+}	ppm	0.84	0.1
iron	Fe	ppm	<0.01	----
manganese ion	Mn^{+2}	ppm	0.005	----
strontium ion	Sr^{+2}	ppm	0.098	----
barium ion	Ba^{+2}	ppm	0.144	----
aluminum ion	Al^{+3}	ppm	0.004	----
bicarbonate ion	HCO_3^{-}	ppm	465	60.2
nitrate ion	NO_3^{-}	ppm	50.0	6.5
sulfate ion	SO_4^{-2}	ppm	27.4	3.5
chloride ion	Cl^{-}	ppm	32.2	4.2
bromide ion	Br^{-}	ppm	0.04	----
fluoride ion	F^{-}	ppm	0.15	----
dissolved silica	SiO_2	ppm	31.0	4.0
Total Dissolved Solids (TDS)	----	ppm	773	≡ 100
pH	H^{+}	-log [H^{+}]	7.83	
dissolved carbon dioxide	PCO_2	log atmos.	-2.29	

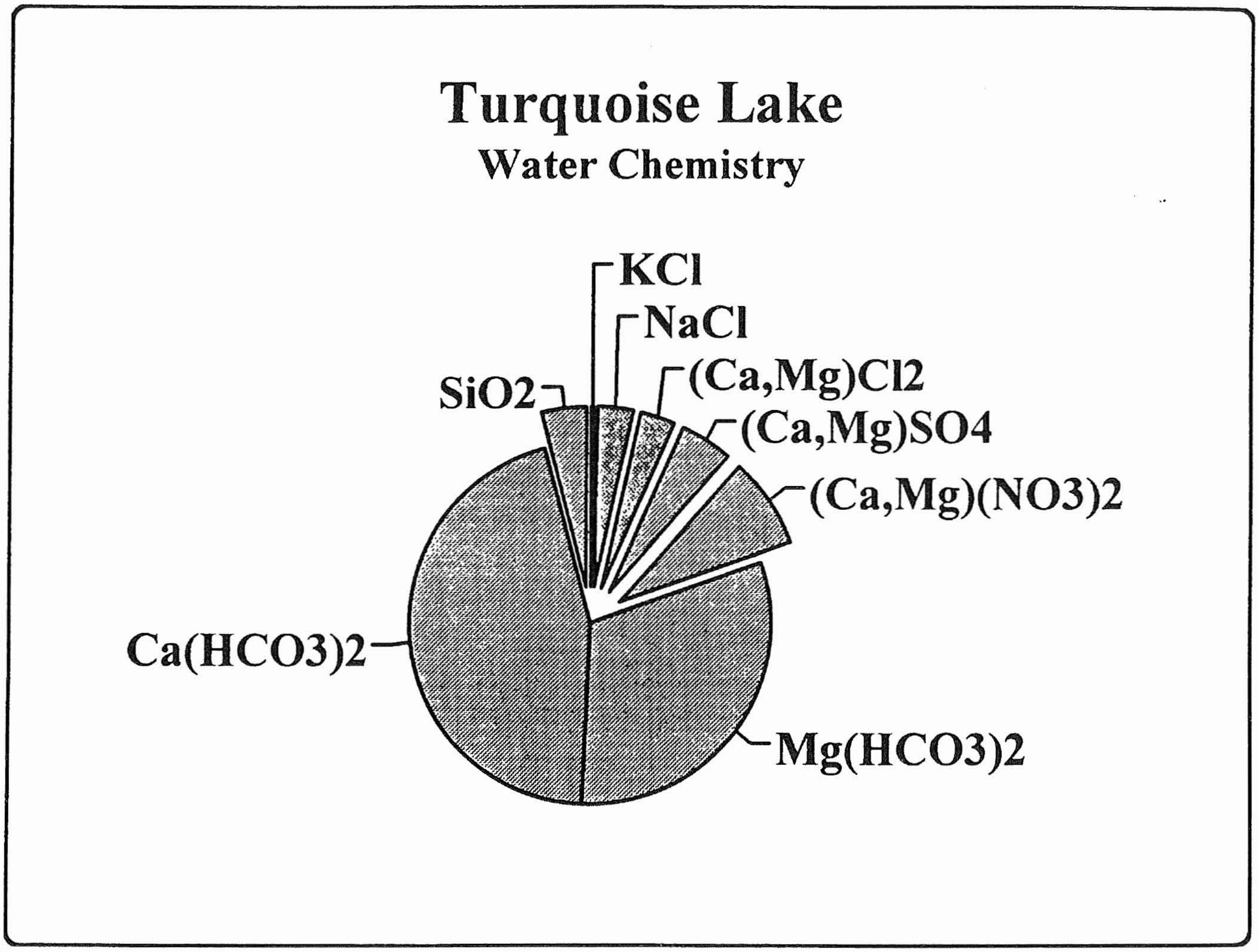


Figure 46. Chemical composition of the dissolved solids in the July 28, 1992 sample of Turquoise Lake.

The largest fraction, 60.2%, of the TDS is bicarbonate. Calcium is second at 13.8%. Magnesium and nitrate are nearly tied for third at 6.4 and 6.5% respectively.

Figure 46 shows the TDS of this water sample recast as the equivalent dissolved chemical compounds. Calcium bicarbonate and magnesium bicarbonate make up 76.4% of the dissolved solids. Calcium magnesium nitrate, calcium magnesium chloride, and sodium chloride all of which are probably products of human activities over the cave, make up 14.5% of the dissolved solids.

Another way of expressing this same chemical composition is to ask how much limestone, dolomite, and other chemicals would need to be dissolved in a gallon of distilled water to produce a gallon of Turquoise Lake water. One gallon is 3.7854 liters, therefore, the recipe for Turquoise Lake water is:

Ingredients:

1 gallon of distilled water.
1,139.7 mg of dolomite
193.9 mg of calcite.
239.7 mg of calcium magnesium nitrate
139.5 mg of calcium magnesium sulfate
91.1 mg of calcium magnesium chloride
94.1 mg of sodium chloride
5.9 mg of potassium chloride

Instructions:

Mix the rock and chemicals into the water. Bubble in carbon dioxide until the dolomite and calcite dissolve. Place in a lovely pool in the largest cave in Minnesota. Light appropriately. Show to visitors.

A couple of additional notes may help to explain this recipe.

The distilled water, limestone, dolomite and carbon dioxide are all natural components of the cave environment.

The calcium magnesium sulfate is also natural. It can be produced in the cave by oxidation of the pyrite, FeS_2 -- which occurs as a minor component in the bedrock, to sulfuric acid followed by the reaction of the sulfuric acid with dolomite. The sulfide oxidation is probably promoted by bacteria.

The calcium magnesium nitrate, calcium magnesium chloride, sodium chloride, and potassium chloride are due to human activities on the surface.

The nitrates come from the nitrogen applied to the fields both in the form of manure and from commercial fertilizers. The nitrogen in manure is the ammonium ion (NH_4^+) or in a reduced organic form. The commercial nitrogen fertilizers include "anhydrous" (a short hand version of anhydrous ammonia or NH_3) and urea. In the soil all of these forms of nitrogen can be oxidized to nitric acid. The nitric acid reacts with dolomite to form calcium magnesium nitrate. Nitrate is the form of nitrogen plants can utilize to grow. Part of the nitrate not utilized by the plants is carried by infiltrating waters into the cave.

The most significant source for chlorides is the "potash" fertilizer applied to the fields. Although the potassium is reported as weight per cent K_2O on the fertilizer bags, the potassium compound actually used is sylvite or KCl. The KCl dissolves in the soil. The plant roots efficiently exchange calcium and magnesium ions for the potassium ions and the resulting calcium magnesium chloride leaches through into the cave. Other potential anthropogenic sources of chloride include human and animal waste, water softener salt, and road deicing salt. Some of the sodium content of the cave waters may come from these latter sources.

2) *I need some way to get across parts per million or ppb to the visitors. Could you relate this to the number of water drops in a gallon of water or drops in the portion of the river seen from the foot bridge?*

A drop of water is about 0.04 milliliters. A gallon of water therefore contains roughly 100,000 drops. **One part per million is roughly one drop in 10 gallons**. A part per billion is roughly one drop in 10,000 gallons. Ten thousand gallons is probably too large for most people to envision easily, however.

The flow in the South Branch of the Root River beneath the foot bridge varies dramatically. The flow at the Mystery I bridge gets down to about 5 cfs (cubic feet per second) in drought years. At that flow, the terminal sink of the river is upstream from the end of the driveway. During flood the flow may reach thousands of cfs. One cfs is equal to 448.8 gallons per minute or 1699 liters per minute. One cfs therefore corresponds to about 42.5 million drops per minute. One billion drops per minute would correspond to a flow of 23.5 cfs. That is a common flow for reasonably wet conditions. In a wet year like the summer of 1993, 23.5 cfs would probably been a normal flow. If 1994 turns out to be a dry summer, then a typical flow might be closer to half that value. When the water flow is medium to high, you can say that **one part per billion corresponds to one drop into the river every minute**. If the flow gets low this summer it is probably more realistic to say one drop in the river every couple of minutes.

3) *Does the [mineral] content of the water in the cave differ from when it enters? Is it "purified" in the cave? What are some probable/possible effects of chemical change in the groundwater on the cave?*

If "purified" means the removal of contaminants or pollutants, then very little purification occurs in the cave. Concentrated pollutant inputs from, for example, an overlying septic system or feed lot might be diluted in the cave by waters from other sources. But the cave has few natural defenses against pollutants or methods for removing those that reach it. Protection of the cave water quality rests firmly on the shoulders of those who live over and around the cave and those who visit it.

Natural changes in the water chemistry do occur in the cave. Water enters the cave in a variety of ways. Changes in the waters' chemical composition depend on the path the waters take through the cave. Some of the waters that enter the cave precipitate part of their dissolved solids to form speleothems. Such waters are in one sense purified, but this is not the normal usage of "purified". The major removal of dissolved solids in the cave is by deposition of $CaCO_3$ as calcite and aragonite speleothems. The deposition of $CaCO_3$ is described by the first chemical equation in the response to *question 1)* above. That deposition can be driven by the degassing of CO_2, the evaporation of water, or both processes acting at the same time. Deposition of soda straw stalactites is mostly driven by CO_2 degassing. The formation of the aragonite needles on the lower wall of 5th Avenue in Mystery II is primarily driven by water evaporation (although CO_2 degassing of necessity occurs during evaporation). The formation of the raft cones and other pool formations probably occur due both to CO_2 degassing and evaporation.

Other waters may dissolve additional bedrock in the cave. The lower level streams, particularly during periods of high flow, bring waters into the cave that are unsaturated with limestone and dolomite. "Unsaturated" in this context means containing less than their maximum levels of dissolved calcite and dolomite. Such water are referred to as "aggressive" waters in the karst and geochemistry literature. Ceiling drips that respond rapidly to surface recharge events may also introduce unsaturated waters into the cave. As these waters dissolve additional material in the cave, the cave is enlarged. This process is most active today in the lower level streams.

4) What is the temperature of the water in the cave?

The temperatures of most of the cave waters are relatively constant and are usually in the 8° to 9° C or about 46° to 48° F range.

The temperature of cave waters that are directly affected by surface waters can vary on a variety of time scales. In the winter, cold water in surface streams is barely above freezing. Cold water sinking in the streambed of the Root River reappears in Mystery Cave in the lower level streams, for example at Flim Flam Creek in Mystery II. The water temperature of Flim Flam Creek in the winter can be as low as 1.4 °C. In the summer, it is much warmer, as high as 20 °C. The water carries a temperature signal from the surface into the cave. The water temperature signal can be complicated, for there are daily temperature signals as well as seasonal ones. In the summer, the Root River can warm and cool over a range of about 3°C on days of sunshine. The maximum temperature is in the afternoon. The minimum is in the morning, about sunrise. A subdued version of this temperature cycle appears at Flim Flam Creek. There, temperature may vary about 1-2°C. The maximum is often about 4-6 hours after the maximum on the Root River; the same is true for the minimum.

Cave Water Quality -- Human Impacted

5) What chemicals are in the water and what is their point source?

The chemicals in a representative Mystery Cave water are outlined in Table 1. Of the major dissolved chemicals, calcium, magnesium, bicarbonate, sulfate and silica and most of the iron, manganese, strontium, barium, aluminum, and fluoride are natural and come from the interaction of recharge water, soil carbon dioxide, and bedrock. The nitrate, chloride, sodium and probably the potassium ions in the cave waters result from human activities on the surface.

Dye tracing has demonstrated direct connections between a drain field over the cave and the tributaries to the Disappearing River. There are several other drain fields that probably contribute to specific areas in the cave. Agricultural activities on the surface over and adjacent to the cave are major contributors to the nitrates and chlorides in the cave waters.

The nitrates come from the nitrogen applied to the fields both in the form of manure and from commercial fertilizers. The nitrogen in manure is the ammonium ion (NH_4^+) or in a reduced organic form. The commercial nitrogen fertilizers include "anhydrous" (a short hand version of anhydrous ammonia or NH_3) and urea. In the soil all of these forms of nitrogen are oxidized to from nitrate ions. Nitrate is the form plants can utilize to grow. Part of the nitrate not utilized by the plants is carried by infiltrating waters into the cave.

The most significant source for chlorides is the "potash" fertilizer applied to the fields. Although the potassium is reported as weight per cent K_2O on the fertilizer bags, the potassium compound actually used is sylvite or KCl. The KCl dissolves in the soil and the chloride leaches through into the cave. Other potential anthropogenic sources of chloride include human and animal waste, water softener salt, and road deicing salt. Some of the sodium content of the cave waters may come from these latter sources.

The herbicides atrazine and alachlor have been detected in Mystery Cave waters. Atrazine was detected in 62% of the 45 samples analyzed. Alachlor was detected in about a third of the samples analyzed. Atrazine is one of the major herbicides used in corn production and alachlor is widely used in soy bean production.

A limited survey for volatile organic compounds (VOCs) in Mystery Cave found no evidence of these compounds. Contamination from industrial sources does not appear to be a problem. Any type of spill, leak, or other contamination source which reaches the South Branch upstream from Mystery Cave will be quickly carried by the water into the lower stream levels of the cave, however.

6) Is it safe to drink the water in the cave?

Usually, **but we do not recommend drinking the water anywhere in Mystery Cave**. Most of the waters in Mystery Cave are actually below the relevant drinking water standards most of the time. This water is by definition "safe to drink". Almost any of the waters can, however, contain nitrate, coliform bacteria, or both above the drinking water standards in any specific analysis. One can not tell by looking which water is contaminated and which is not. Therefore, none of the water can be safely considered a potable supply.

Water in the lower level stream passages, the pools, and a few of the drips show the most evidence of surface contamination. These waters are very directly connected to the surface.

Drinking from them is equivalent to drinking from the South Branch or from the runoff from a field. **Not Recommended**.

7) *If some of the cave water is not fit to drink, why not? What will it do to you if you did drink it? Have there been any people get sick from bad water around here? What causes the most problems?*

The atrazine and alachlor levels detected in the cave are all below the drinking water standards. The only contaminants that exceed the drinking water standards are nitrate and coliform bacteria. Again, the waters most directly connected to the surface show the highest and most persistent levels of contaminants.

None of the pollutants detected in Mystery Cave waters are acutely toxic. These waters are not dangerous to be around or to have on you. A water drop falling on a visitor is not going to make the visitor sick. The dangerous components are most likely biological -- bacteria and viruses -- but are very difficult to measure. A common health effect from drinking this type of contaminated water is diarrhea or other "flu-like" symptoms (Mills, 1978) particularly in children. Other infectious agents may also be present.

There are a couple of documented examples of acute illnesses related to water quality in Fillmore county. Mills (1978, p. C-63) reported that in Fillmore County:

> "Children exposed to drinking water containing greater than 2.2 fecal coliform have greater than two and one-half times the chance of developing a severe diarrheal illness infection than do children not so exposed. Similarly, children drinking water containing greater than 10 mg/l nitrate have more than two and one-half times the chance of developing such an illness."

The earliest recorded use of dye tracing in Fillmore County is Kingston's (1943) account of eleven cases of typhoid fever with one death that occurred in and adjacent to Harmony in the fall of 1939 and the spring of 1940. A fluorescein dye trace of the sinkhole that received 60,000 gallons per day of partly treated sewage from Harmony was positive to a private well in Harmony. The Health Department indicated that "the eleven typhoid fever cases probably were water-borne and that infectious organisms had been transmitted through the cavernous and fissured limestone formations."

It is much more difficult to demonstrate a cause and effect relationship between water quality and human illness for chronic or long term illnesses such as cancer. There are simply too many confounding exposures.

Cave Water Quantity and Flow

8) *How have the groundwater levels changed at the Mystery Cave area over time (pre ice-age -- ice age --after ice age -- present)? Has anyone made "theoretical" computer images/maps depicting the topography/river flow into the past -- say at intervals of every thousand years?*

The South Branch of the Root River is slowly eroding its valley downward and upstream. Regionally the water table is lowering as the river incises the landscape. Mystery Cave is an important part of that process. Milske and others (1983) found that about 11,000 to 12,000 years ago the Door-to-Door gravels were deposited along a flow path that did not involve the lower level streams. The Door-to-Door underground river may not have resurged at Seven Springs but at some location east of the current resurgence. As the water level lowers, new areas of the cave system are drained and older, higher levels may be filled by sediments or destroyed by erosion.

The ice-age/interglacial warm period cycle that has repeated itself about 100 times in the last 2.5 million years also has a profound effect on the cave. During most of the ice-ages, Mystery Cave is not covered with glacial ice. However, Rich Lively's (1983) speleothem age dating work indicates that much of the area was affected by permafrost and that the speleothems stopped growing during the glacial advances. The truly enormous volumes of water released as the glaciers melt may be the major factor in shaping the river valleys of southeastern Minnesota. We talk about "10 year floods" and "100 year floods". The melt back of the glaciers cause "10,000 year floods", which are correspondingly larger.

No one to our knowledge has yet attempted to construct a detailed computer model of the evolution of the Root River basin and of Mystery Cave. We are probably years to decades from having enough knowledge to construct such a model. It would certainly be an instructive tool to have, however. Milske (1982) constructed maps showing the routes that paleo rivers of the cave flowed at selected times in the past. These maps represent an initial step in such a detailed reconstruction and modeling.

9) During the floods of 1993 how high did the water get in the cave and how fast did it fill up and drain out of the cave?

We have better high-water information for the first flood at the end of March 1993 than we do for the later floods. Figures 47 and 48 show the water level records for the South Branch at Mystery I and for Flim Flam Creek. Both floods exceeded the overpressure capacity of the automated stage recorders at Flim Flam Creek and in the South Branch. *Neither recorder was able to measure the peak stage.* We are therefore restricted to post-flood observations of "high-water marks" in various places. Warren and Mark can give additional detailed observations since they cleaned up the resulting mess.

The high-water mark during the March 30-April 2 flood on the outside of the Mystery I flood-proof door was 2.3 feet above the concret floor. Given the Palmers' data from their leveling survey, the flood crested at an elevation of 1230.4 feet . That puts it well up on the flood plain around the Mystery I ticket building. The normal river level at the Mystery I entrance is about 1224 feet elevation so the river crested about 6.4 feet above normal flow. Inside the cave the high water mark was about 1218 feet elevation in the Formation Room and about 1220 feet in the Bomb Shelter. According to the Palmers' cross sections the normal water level in the Disappearing River at Needle's Eye is about 1180 feet. The water level inside the cave near the Mystery I entrance was, therefore, about 40 feet above normal flow. There were probably strong gradients in the water levels as the waters rose up through the crevices nearest the river and then sank back into the same crevices further into the cave. Commercial Mystery I was thoroughly flooded.

In Flim Flam Creek in Mystery II, the water level rose about 24 feet above normal flow levels but the crevice above Flim Flam extends up about 45 feet to the floor of the Door-to-Door route. The flood did not reach the commercial levels in Mystery II.

"How fast did it rise" is a fascinating question but the answer is complicated and only partially known. The surface flood first: Figure 47 includes the water level (stage) and precipitation record for March 30-31, 1993 from the weather station and the South Branch of the Root at Mystery I. The South Branch began to rise about noon on March 29 in response to a steady rain falling on the snow. That rain had begun about 6 AM on the 29th and continued until the afternoon of the 30th. By midnight on the 29th the river has risen about 2 feet. Between 10 PM and midnight on March 30 rate at which the river rose averaged 1.7 inches per hour. At 01:30 AM on March 31, the pressure transducer overpressured and we lost our record.

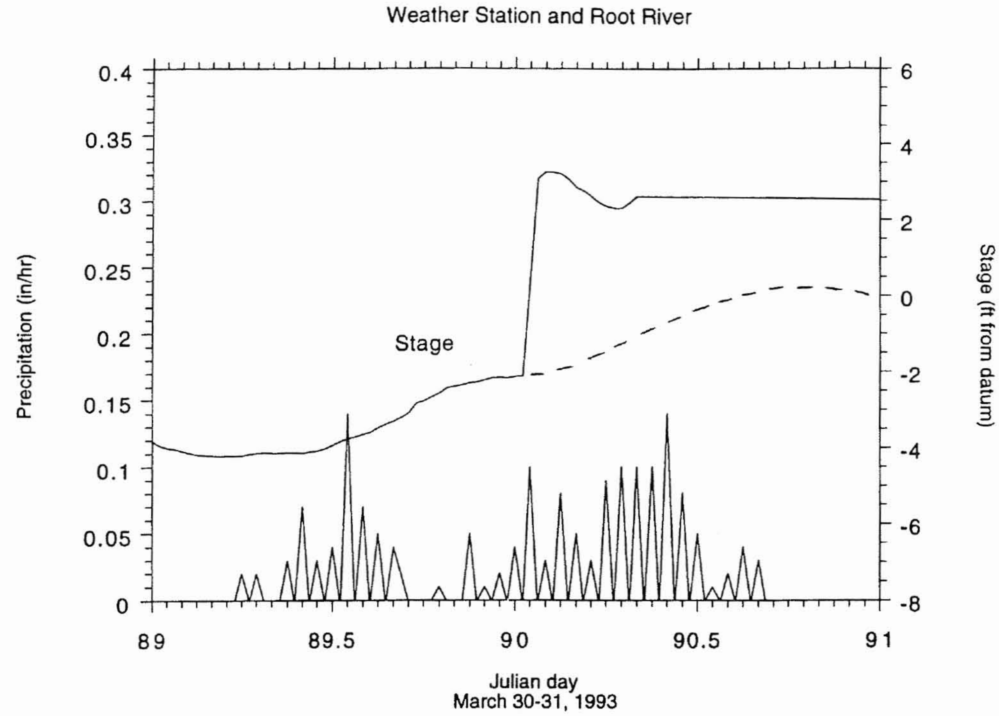
Figure 47 includes the water level and water temperature record for March 30-31, 1993 from Flim Flam Creek. The water level in Flim Flam began to rise about noon on March 30, about the same time the river level began to go up. By 9 PM on March 30 the water level in Flim Flam was rising at about 1.2 feet per hour. At about 1 AM on March 31 when the water level had risen about 8 feet, the pressure transducer in Flim Flam overpressured and we lost our record.

The flood dropped fast. Figure 48 shows a 15 day time span including the same flood. Figure 48 includes the stage and precipitation record from the weather station and the Root River at Mystery I. On April 1, the water level in the river dropped about 6 feet in a little over two hours. It then quickly rose 3 feet in response to another rain event and dropped 3.5 feet a few hours later. During the evening of April 2 the river level again jumped up about 3 feet in a couple of hours and then dropped back equally rapidly.

Figure 48 includes the stage and water temperature record from Flim Flam Creek for the 15 day time span. The water level in Flim Flam did not drop low enough for the pressure transducer to begin recording until the early morning of April 2. By that time the water level was dropping a foot every couple of hours.

10) Are there any data supporting the idea that weather goes through dry (late 80's early 90's) and wet ('92, '93, and '94?) cycles? If so how much does the groundwater go up and down with the changes in the amount of rain water? How do these cycles affect the ecology of the caves in S.E. Minnesota?

Yes. The weather in any region goes through cycles of a number of different time scales. The study of those cycles and the attempt to understand their causes and to predict their future occurrences is one of the most active research areas in climatology today. Historic records of rainfall in Minnesota go back to the early 1800s in some cases. In Fillmore County there are good records for almost 50 years. Figure 49 is plot of the rainfall data from Lanesboro from 1955



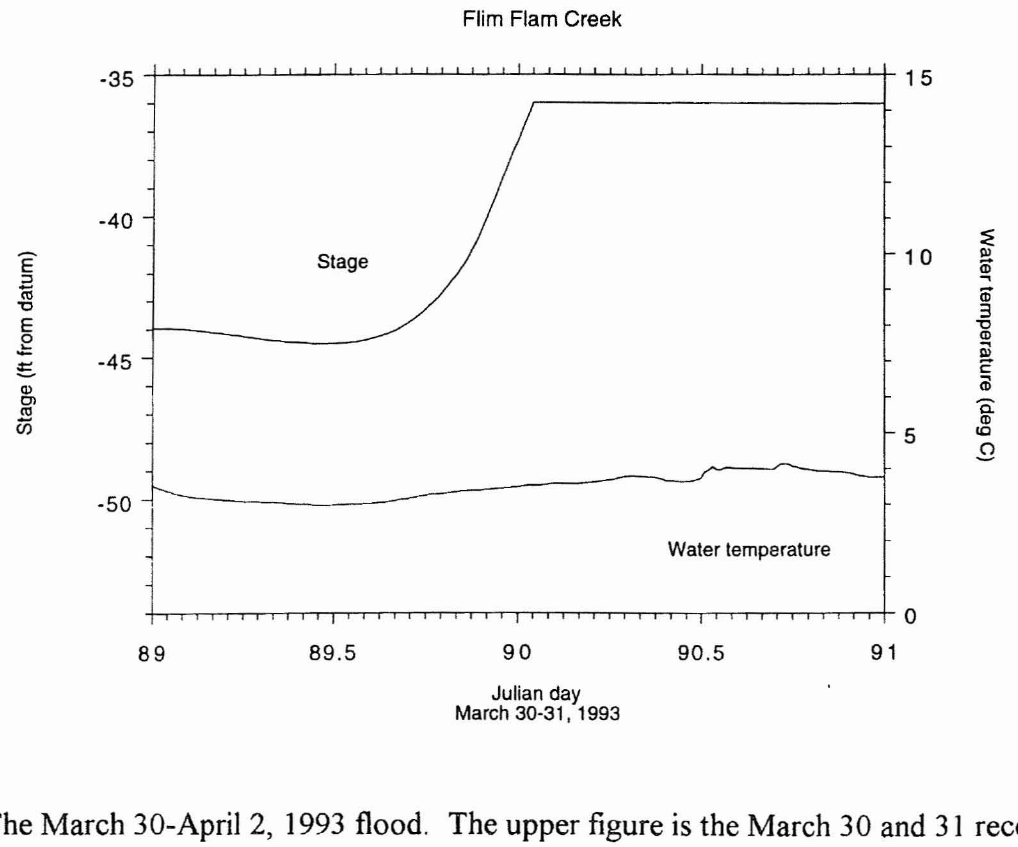


Figure 47. The March 30-April 2, 1993 flood. The upper figure is the March 30 and 31 record of stage (water level) from the South Branch of the Root River and precipitation record from the weather station, both near the Mystery I entrance. The smallest units indicated on the horizontal axis are hours. The lower figure is the stage and water temperature record from Flim Flam Creek in Mystery II. The horizontal scale is the same in both figures.

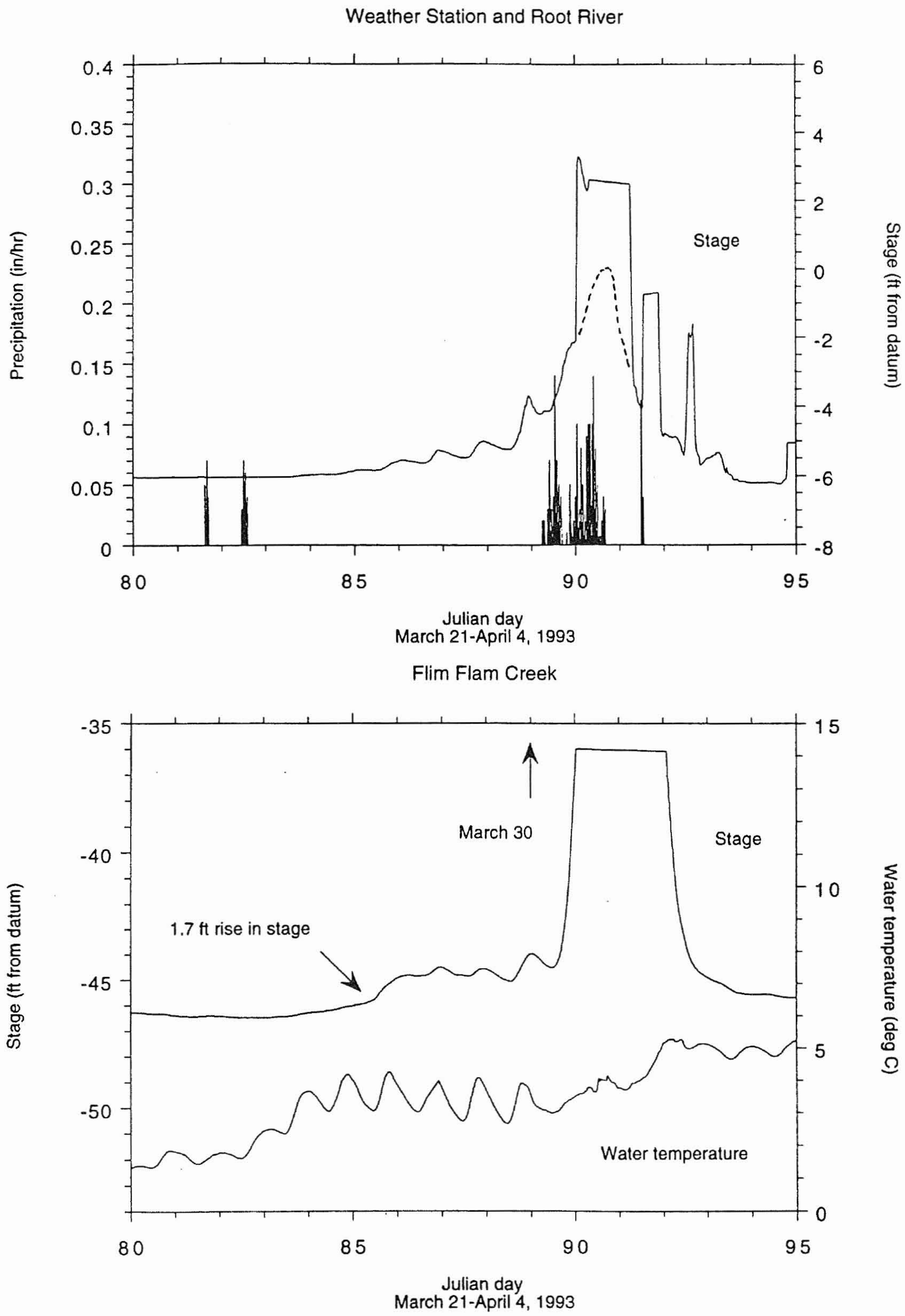


Figure 48. The March 30-April 2, 1993 flood. The upper figure is the March 21 through April 4 record of stage (water level) from the South Branch of the Root River and precipitation record from the weather station, both near the Mystery I entrance. The smallest units indicated on the horizontal axis are days. The lower figure is the stage and water temperature record from Flim Flam Creek in Mystery II. The horizontal scale is the same in both figures.

through June 1993. The average annual rainfall in Lanesboro is about 30 inches. In a plot of cumulative departure from normal, periods of average rain fall form horizontal portions of the graph. Periods of dryer than normal form descending segments of the graph and wetter than normal periods are ascending segments.

At Lanesboro rainfall records breaks out as follows:

1955 to Nov 1962	roughly normal rainfall
Nov. 1962 to Jan 1965	very dry -- 25" less than average
Jan 1965 to July 1972	long dry period -- 10" less than average
July 1972 to Nov 1973	wet period -- 13" more than average
Nov 1973 to May 1976	average rainfall
May 1976 to Jan 1977	very dry -- 14" less than average
Jan 1977 to Aug 1979	average rainfall
Aug 1979 to Mar 1985	prolonged wet period -- 50" more than average
Mar 1985 to May 1988	average rainfall
May 1988 to Mar 1990	dry period -- 15" less than average
Mar 1990 to July 1993	very wet -- 34" more than average

These cycles of wet and dry periods have profound effects on both the water levels and the water quality. During the start of a wet cycle, the water levels go up and the concentrations of anthropogenic contaminants also go up. The groundwater levels may rise tens of feet regionally and more than that locally. The increase in concentration along with an increase in water volume is counter-intuitive. Apparently, the increased infiltration washes increased amounts of pollutants out of the soil into the groundwater. In terms of cave ecology, both the rise in water levels and rise in pollutant levels can do damage. One dramatic example may be the bat bones beyond Bone Yard Crawl in Mystery III. A simple explanation for the concentration of bones is that bats fly through the crawl from The Fingers area during low water and are trapped and starve when the water level rises and sumps the crawl.

11) How old is the water in the cave's lakes, streams, and drips? People wonder how long the water has been going through the ground to get to the point they are looking at.

The water in the cave streams left the surface a few minutes to hours before it is seen in the cave. The dye tracing, temperature and chemical fluctuations, and rapid changes in flow levels of the streams, leave no room for doubt. These steams are directly connected to the South Branch.

The question of how long the water coming out of drips and in the lakes and pools has been underground is more complicated. The flow rates of some of the cave drips respond in minutes to hours to recharge events on the surface. Some respond on time scales of months and some show very little change in flow on time scales up to years. Even the drips that respond very quickly to surface recharge often do not show the chemical or temperature signatures of direct surface recharge. The flow may increase in minutes after the rain on the surface, but the water flowing out the drip may not be the rain that just fell on the surface. It may be water that has

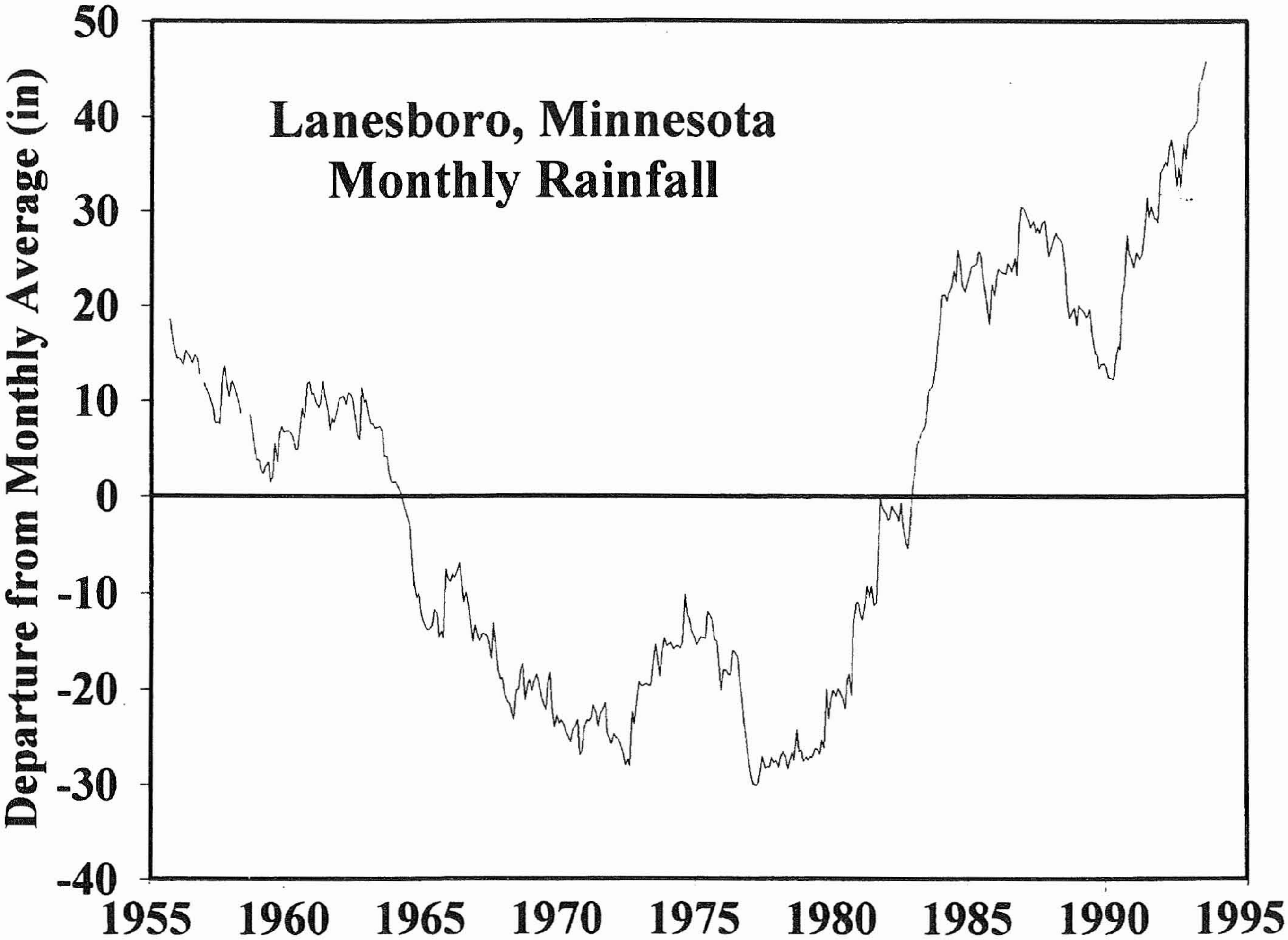


Figure 49. Rainfall record from 1955 to 1993 from Lanesboro, Minnesota. The long term average rainfall for each month is subtracted from the actual rainfall for the months. A running sum of the resulting departures from normal rainfall produces the graph. The years 1955 to 1964 were wet, 1964 to 1983 were dry, and it has been wet since 1983.

spent weeks, months, or perhaps even years in the zone between the land surface and the cave. The simple, quick, and mostly correct answer is probably "a few days to a few months". This answer will suffice in most cases but be prepared to get arguments from some informed visitors.

12) Where does the water in the ceiling drips come from?

All of the ceiling drips in the main levels of Mystery Cave appear to be fed by precipitation water that has infiltrated through the soil, loess, and bedrock directly over the cave.

13) Where does the water in the pools come from? Turquoise Lake? Blue Lake? Why is the water blue?

Both Blue Lake and Turquoise Lake are fed by water infiltrating through the surface more or less directly over them. Neither pool is fed by the surface river. The permanent flow of water into Turquoise Lake indicates that it is fed by a considerably larger area than is Blue Lake. The water in Turquoise Lake has significantly higher levels of nitrate and chloride than does the water in Blue Lake. Chloride and nitrate are indicators of human impact on the infiltrating water. The larger recharge area of Turquoise evidently contains more human impact than does the recharge area for Blue Lake.

The water feeding Turquoise Lake can be seen running into the back of the lake across the flowstone. That water is pumped out of the lake on a semi-coninuous basis to maintain the water level.

Blue Lake fills episodically after the largest recharge events in the year. When it is full it over flows to form Blue Lake Springs in the passage east of the Lake. Once the recharge ceases and the level drops below the conduits to Blue Lake Springs, the water level in Blue Lake slowly drops over six to nine months. Part of the water in Blue Lake is evaporating but most of it appears to be slowly seeping out through the sediment at the bottom of the lake.

The blue color of Blue Lake, Turquoise Lake (and Dragon's Jaw Lake) is caused by Rayleigh scattering by calcite molecules ($CaCO_3^0$) and by complexes of up to a few thousand molecules in the water. Molecules and particles much smaller than the wavelength of light selectively scatter the blue wavelengths relative to the red wavelengths. When a light beam shines into the water, the calcite molecules selectively scatter the blue light toward the observer. (This is the same process that causes the sky to appear blue, except in the sky nitrogen and oxygen molecules and very small aresols produce the scattering. When you look directly at the light source, say a rising or setting sun, it appears reddish due to the removal by scattering of part of the blue light.)

14) Where does the water in the cave streams come from?

The major fraction of the water in the cave streams comes from the South Branch of the Root River a few minutes to hours before it is seen in the cave. The dye tracing, temperature and chemical fluctuations, and rapid changes in flow levels of the streams leave no doubt about how directly these steams are connected to the South Branch.

All of the drips seen in the cave and all of the water that flows down joints between the cave passages also flows through the cave streams. Water infiltrating through the soil and bedrock over the cave also contribute to the total cave stream flow.

15) Where does the water flowing through the cave go? How long does it take? Where does the water go after it leaves the cave?

All of the dye tracing to date indicates that the water that flows through Mystery Cave travels through various tributaries of the Disappearing River and resurges at Seven Springs about one-half mile east northeast of Garden-of-the-Gods.

The residence time of the water in the cave varies. The ceiling drips may only be in the cave a few seconds to minutes. It doesn't take long for the water to flow out of a ceiling joint, flow down the wall or fall through the cave, and then sink into the floor below the cave. The longest residence times of water in the cave are in the range of several months to a year. The water in Blue Lake, for example, fills two or three times per year and then slowly drains and evaporates. In the late fall, the water in Blue Lake can have been there since early spring.

Once the water reaches the Disappearing River it takes 10 hours or less for it to reach Seven Springs. The longest times are for water near the Mystery I entrance during dry periods. The shortest transit times are for water near Garden-of-the-Gods in Mystery II during high flow. Such water may only take a couple of hours to reach Seven Springs. A good overall average for the entire cave is 6 to 8 hours.

16) Is it safe to be in the cave since it is below river level?

Commercial Mystery I flooded twice in 1993. It would have been dangerous to be in Mystery I during these floods. It is doubtful, however, that the water level in those floods rose rapidly enough to endanger a visitor had anyone been in the cave at the time of the floods. There is no indication that major flooding has reached the Commercial Mystery II tour trails since the cave was discovered, although minor surface flooding is an ongoing anoyance near the Mystery II entrance. It is doubtful that there is any real threat to visitors on either commercial tour during any weather reasonable enough for the visitor to want to go on a tour.

The lower stream levels in Mystery Cave are subject to much more frequent flooding. It is dangerous to go into the lower stream levels anytime rain is a possibility or has recently occurred. The very rapid and very large water level rises that occur many times a year in the lower stream levels could easily trap and drown an unwary caver. The safest time to visit the lower stream levels is in winter when the temperature outside is well below freezing.

17) Is it safe to be in the cave if it is raining outside?

Not in the lower stream levels. The water levels in the lower stream level can rise many feet in a short time in response to major recharge events. Such a rise could easily trap and drown an unwarry caver. The response to any individual rain storm depends on the intensity and duration of the storm and on the antecedent moisture conditions. The largest flood events typically include spring snow melt and high intensity storms in the spring and fall. Equally intense storms in late summer can produce little if any rise in the cave streams. The safest periods to visit the lower level streams are in the middle of winter when the outside temperature is well below freezing and any precipitation that falls will be snow.

It is safe to be in the upper, commercial levels during all but the heaviest rains. It can be very informative to be in the upper level passages along either commercial tour when it starts raining on the outside. The noise level in the cave increases noticeably due to all of the ceiling drips that start running. It is very dramatic and a graphic illustration of how rapidly surface water can reach the cave. However, if you are ever in Mystery I when a torrential rain occurs and water starts flowing out of the lower level crevices into the main passage level, exit the cave immediately.

18) How fast do the lake levels and ceiling drips respond to rain on the surface?

The response time varies tremendously. There are some lakes and drips in the cave that are very constant and do not responds quickly to rain on the surface. Conversely, there are many ceiling drips that respond in minutes to rain on the surface. Many of the ceiling drips near the Mystery I entrance respond rapidly to surface rain. Blue Lake is an intermediate case. It responds to the largest recharge events only and even then may have several days delay between the recharge event and the time Blue Lake begins to rise.

In many cases, even though the lake or ceiling drip responds rapidly to the rain on the surface, the water coming out the ceiling drip or filling the lake is not the water that is falling on the surface. The chemistry of these waters and their temperatures are the strongest evidence of this displaced water. In contrast, many ceiling drips near the entrances and the lower level streams show clear chemical and temperature signals indicative of rapid infiltration of surface water after rains.

19) Is there a specific point/area of entry and exit for the water in Lakes Blue and Turquoise? From where to where? What is the flow rate (average) in these lakes?

The water that fills Blue Lake enters from the back of the lake in a few episodes a year after the largest recharge events such as a strong rain in the fall or the spring snow melt. These filling episodes last a few days to a few weeks. If Blue Lake fills completely, it overflows through an ephemeral spring in the commercial path east of the lake. Once the lake drops below these overflow springs, the water slowly seeps out of the lake. Some of the seeps must be near the bottom of the lake because the water level will drop almost to nothing if another filling episode does not occur too soon. The flow into and out of Blue Lake is very slow except during the filling episodes.

The water that fills Turquoise Lake flows continuously into the back of the Lake across the flowstone. The water level in Turquoise Lake is artificially maintained by the dam across the front and a sump pump that periodically lowers the water level in the lake. We have never attempted to measure the rate of water flowing into Turquoise Lake for fear of damaging the delicate formations around the back of the lake.

20) How much of the water in the cave percolates through the rock pores and how much simply "flows" through fissures/cracks?

The rocks in which Mystery Cave is formed have negligible primary porosity. When fresh exposures of these rocks are examined in one of the local quarries, there is very little evidence that any significant water percolates "through" the rock. **Essentially all of the groundwater flow into Mystery Cave is from joints, cracks, fissures, bedding planes and solution channels.**

21) How is it possible for the water to seemingly disappear and then reappear in springs many miles from where it sank?

The karst conduits, of which Mystery Cave is a spectacular example, provide underground channels through which waters can flow. The water sinks into the conduits, flows through them, and then returns to the surface in springs. Typical flow velocities in these conduits are measured in miles per day rather than the feet per year velocities typical of conventional, porous media aquifers.

The longest documented straight-line underground flow path that has been traced from a sink to a spring in Minnesota is the 10 mile path between the York Blind Valley sinks and Odessa Spring. York Blind Valley, the largest blind valley in Minnesota, is about six miles south and one mile east of Mystery Cave. Odessa Spring is on the Upper Iowa River about 0.5 miles north of the Iowa border, about 2 miles west-southwest of Niagra Cave. In November 1993, a dye trace run as part of the DNR's Fillmore County Atlas project documented a flow connection between the blind valley and Odessa Spring. The flow time was about a week.

Speleothems

22) How are the cave formations deposited?

Most of the common cave formations are calcium carbonate. Calcium carbonate occurs in Mystery Cave in two crystal forms, as calcite and as aragonite. Both crystal forms of calcium carbonate form by reactions that can be summarized as:

$$\mathbf{Ca^{+2} + 2\,HCO_3^- \longrightarrow CaCO_3 + CO_2 + H_2O}$$

This reaction proceeds as written when: 1) CO_2 degasses from the cave water, 2) when the water evaporates, and/or 3) when both processes occur simultaneously. All three situations occur in

Mystery Cave. Deposition of soda straw stalactites is mostly driven by CO_2 degassing. The formation of the aragonite needles on the lower wall of 5th Avenue in Mystery II is primarily driven by water evaporation (although CO_2 degassing of necessity occurs during evaporation). The formation of the crystals in Sugar Lake is probably occur due to a combination of CO_2 degassing and evaporation.

23) Is there an easy, definitive answer to explain why "lime" deposits form in domestic and agricultural situations? Do we see the same type of deposition in the cave or surrounding streams? How do the (lime) deposits, say on people's cookware , differ from the deposition of the speleothems? Why don't we see "lime ridges" in the cave after a flood?

The "lime" deposits that form during the use of well water from carbonate aquifers is calcium carbonate. The lime deposits form by reactions that can be summarized as:

$$\mathbf{Ca^{+2} + 2\,HCO_3^- \longrightarrow CaCO_3 + CO_2 + H_2O}$$

This is same reaction that describes the formation of speleothems. The major difference between speleothem deposition and lime deposits on cookware is that the water in cookware is heated. The heating does two things to deposit the lime.

First, as the water is heated, the CO_2 degasses. (Warm pop fizzes more than cold pop. Carbon dioxide is more soluble in cold water than in warm or hot water and therefore degasses as water is heated. Notice the bubbles that form on the sides of the pan before the water begins to boil.) Boiling the water degasses it almost completely. The lime deposits on agricultural watering tanks forms fastest in the summer when the water is warmed by the air.

Second, as the water heats up and eventually boils it is evaporated. The evaporation of the water also causes calcium carbonate to precipitate. The good news is that weak acids such as vinegar will reverse this process. Soaking cookware or watering equipment in vinegar will dissolve the lime deposits.

For outside watering tanks there is a third process that deposits lime. Algae growing in the water removes CO_2 as part of the photosynthesis process. In many watering tanks in the summer time this can be the dominant process. Note that evaporation and heating are also going on under the same conditions. Similar conditions prevail around many karst springs. Large mounds of tufa form at and downstream from the springs. Tufa is calcium carbonate.

There are indeed a number of "lime ridges" or "rings" visible in Mystery Cave. There are a number of "lime ridges" visible on the walls above Turquoise Lake. The Palmers indicate that parts of these rings are made of an unusual speleothem called folia. These ridges record the levels of earlier versions of Turquoise Lake and are analogous to the lime ridges that form on watering tanks.

24) Are there any cave formations that formed by evaporation instead of by degassing CO_2?

Yes. The aragonite and calcite crusts on the lower parts of the walls of 5th Ave. in the eastern section of Mystery II are one good example. Evaporation is potentially significant anywhere (or anytime) the relative humidity is less than 100% .

Karst

25) What is a sinkhole? How does it form?

To karst specialists, a sinkhole is one of the characteristic features of a karst landscape. Karst sinkholes are closed depressions that form over soluble geologic formations. Sinkholes form as precipitation infiltrates into the soluble rocks, dissolve them to produce subsurface voids, and then surface material erodes or collapses into the voids. Sinkholes come in a wide variety of shapes and sizes up to several miles across. The sinkholes in Fillmore county are typically a few tens of feet across and are funnel to bowl shaped. Sinkholes can appear suddenly as the surface collapses into a subterranean void or slowly as surface material settles into the subsurface voids. Work for the new County Atlas has mapped over 6,000 sinkholes in Fillmore County. We estimate the total number of sinkholes in Fillmore County is at least 9,000 to 10,000.

26) Are karst processes in the Mystery Cave area more or less intense than in the past?

We are not sure, but the evidence is accumulating that karst activity is increasing. The original landscape of southeastern Minnesota was a mixture of hardwood forest and oak savanna with open patches of prairie. When Fillmore County was settled by Europeans in the 1840s and 1850s, agriculture quickly became the dominant land use. The original farming practices led to large, rapid erosion losses of soil. This rapid erosion silted in many of the valleys and appears to have clogged many of the sinkholes and underground conduits with sediments.

Major soil conservation efforts began as an outgrowth of the great depression and dust bowl of the 1930s. Sixty years latter in the 1990s, the three-generation-long conservation effort is beginning to bear fruit. Soil erosion, while still too large in many areas, has been dramatically reduced. Many of the stream valleys are beginning to wash themselves clean of the previous century's accumulation of sediments. We suspect, but can not prove, that a similar process is beginning to occur in the sinkholes and underground conduits. The rate of catastrophic sinkhole formation, for example, may be increasing.

27) Were any conclusions made about the large stream sink that suddenly formed at the bridge in front of the Mystery Cave driveway in the summer of 1992?

No. The water was too high all of last year to dye trace from that area. That stream sink is high on the list of place we would like to conduct a dye trace from, however. Complicated speculations involving anecdotal memories of when Saxifrage Springs, which are downstream from Seven Springs, were and were not flowing, indicate that this stream sink may be a major source of water for the Saxifrage Spring system. Those speculations plus one successful dye trace can led to some firm conclusions. We are waiting for another dry summer.

28) Many people have asked me about the sinkholes. Is it O.K. to fill them up with trash?

No it is not O.K. to fill sinholes with trash. Such practices are illegal and self defeating. Such practices produce direct groundwater pollution problems. One of the outstanding successes of groundwater management in southeast Minnesota's karst area has been the change in public attitude toward waste dumping into sinkholes. Twenty years ago such dumping was a routine, open practice. Today, the elected County Commissioners, Representatives, and Senators have, at the public's request, passed ordinances, rules and regulations, and laws forbidding such proactices. Many of the sinkholes filled with waste materials in the past are being cleaned out and rehabilitated.

How should sinkholes be protected? Different situations require different management approaches. The basic principles are the same however. Do not place anything in a sinkhole you are not willing to drink. Control the quality and quantity of water running into sinkholes. Successful practices include: 1) elimination of all waste dumping into sinkholes, 2) diverting surface runoff away from the sinkholes via dikes, etc., 3) installing grassed waterways to limit the amount of sediments and agricultural chemicals flowing into the sinkholes, 4) reducing the application of agricultural chemicals near sinkholes, 5) placing sinkholes in conservation reserve land, and in some cases, 6) filling and sealing the sinkholes.

Can we plow and fertilize crops next to them? Sometimes. The critical issue is do sediment and agricultural chemicals run off into the sinkhole? If the land slopes away from the sinkhole, it may be possible to safely farm to within a few feet of the sinkhole rim. If the slope of the land funnels the runoff into the sinkhole, as is often the case, then greater setbacks are necessary to protect the water quality. The farmers do not buy agricultural chemicals to dump them in sinkholes. They buy them to improve their crop production. Any agricultural chemicals that get into sinkholes are a waste of money to the operator in addition to being a threat to their water supply. It is to the farmers' advantage to limit the loss of agricultural chemicals into sinkholes from both economic and environmental/groundwater quality perspectives.

How fast do they take up water and soil? Many sinkholes will swallow water and anything carried in that water as rapidly as the water can run into the hole. In these cases, the water and any pollutants carried by the water may descend to the water table in seconds to minutes.

29) It would be interesting to know the water actions that formed the picnic area at Mystery I and if the sinkhole west of there holds any relation to the cave.

The picnic area at Mystery I is an interesting area. There is more going on there than meets the casual eye. The whole area is on the inside of an intrenched meander loop of the South Branch of the Root River. Seismic soundings (Palmer and Palmer, 1993a, p.36) indicate that the bedrock valley is about 20 to 23 feet deeper than the present land surface. The surface that the Mystery I ticket building sits on is the current flood plain of the South Branch. This is part of the rivers' natural method of handling high water flows. All of the sediments have probably been deposited since the last ice age melted back about 11, 000 years ago. Buried in those sediments are bedrock highs. Some of those bedrock highs extend almost to the land surface. Walnut Cave, which is located west of the ticket building on the flood plain, is one site where the bedrock extends almost to the surface. The field west of the picnic area slopes upward to the west to the edge of the woods. That surface probably formed as the river meander intrenched itself and eroded eastward into Mystery Cave. Both the slope and the current flood plain were created by the South Branch.

The sinkhole west of the picnic area in the edge of the woods has been dye traced. The dye from that trace was the only dye we have yet recovered from Saxifrage Springs. Water does not flow into the sinkhole except after large recharge events and the sinkhole cannot be a significant source of the flow from Saxifrage Springs. It not at all clear what route the dye traveled from the sinkhole to the Saxifrage Springs. The dye could have traveled south, under the South Branch and then flowed east to Saxifrage. It can have traveled south of the Disappearing River system in Mystery Cave. Alternatively, the dye could have initially travel north and east and then turned southeast and traveled **under** the Disappearing River system to emerge at Saxifrage Springs. This second possibility is a much more complicated route but is consistent with our current ideas on the source of the flow from Saxifrage Springs.

Miscellaneous

30) What is the humidity in the cave?

The relative humidity in Mystery Cave is close to 100% much of the time, in most places -- but interesting things happen in the places and at the times when the relative humidity is not 100%. The relative humidity can locally be above 100% when the temperature outside is warmer than that in the cave. These are the conditions that prevail during the visitor season at Mystery and are therefore the ones guides may encounter during tours.

Two different processes can operate, sometimes at the same time, to raise the relative humidity in the Cave above 100%. Near entrances warm moist air can flow into the cave. If that air starts enters the cave with an absolute humidity (dew point) greater than that in the cave, as the air is cooled by contact with the walls of the cave, relative humidities of > 100% will be formed. When that occurs, part of the water will condense to form fog in the air or water droplets on the cave walls. Such warm, moist air is less dense than normal cave air and so the fog or condensation drops will be most evident on the ceiling of the cave. The ceiling of the Mystery I entrance room is often covered with condensation drops on warm summer days. They are particularly evident on the flat metal plates between the rock bolts.

The second process involves warm water flowing from the river into the cave streams. When the temperature in the cave streams rise significantly above the cave temperature, the streams begin to add water vapor to the cave air. On hot summer days, dense fogs are often observed in the lower stream levels as water evaporated from the stream condenses in the cooler cave atmosphere. This same phenomenon is often seen above surface rivers and lakes in the fall when the atmospheric temperature falls below the water temperature. The warm moist air and fog from the underground rivers in Mystery rise upward until they cool and condense their excess water.

Relative humidities of less than 100% occur in the opposite situations when cold dry air enters the cave in the winter or when the water in the lower level streams falls below cave temperature. The cold dry air is denser than cave air and tends to flow along the floors of the cave passages. The frostwork along the lower walls of 5th Avenue in Mystery II, particularly from the entrance east toward Gardern of the Gods, was produced by evaporation of cave waters. The effect of the cold stream waters is not as pronounced because the cold, dry, dense air that forms directly above the streams does not rise and therefore tends to isolate the rest of the cave from the cold water.

31) How long does it take rainwater to reach the aquifers?

This is the first question to ask about aquifers. **Aquifers** are defined as natural geologic materials that yield useful amounts of water. Aquifers are separated and partially isolated by relatively impermeable geologic materials collectively referred to as **aquitards** or **confining units**. Aquifers are recharged by the fraction of precipitation that infiltrates through the soil rather than evaporating or running off the surface through rivers and lakes. The portion of rainwater that infiltrates through the soil varies enormously. In the Mystery Cave area Broussard and others (1975) show an average rainfall of about 31 inches per year. About 24 inches of that water is lost to evapotranspiration. The remaining 7 inches per year runs off or infiltrates through the soil. The water that infiltrates travels through the near-surface aquifers and then resurges in springs and flows down the rivers.

Rainwater can reach the **watertable** in an upper aquifer on a time scale of minutes. Rainwater may also take hundreds to thousands of years to reach the top aquifer. Remember that most rainfall evaporates or runs off and never reaches the aquifer. In the area around Mystery Cave, the time to the top of the first watertable is in the fast part of this time range. That portion of the rainwater over Mystery Cave that infiltrates can reach the cave on time-scales as short as minutes and probably rarely takes longer than months. Even over an area as small as Mystery Cave there is not a single time scale. There is rather a whole range of time scales.

Once the water reaches the top of the watertable, a number of different things can happen. Much of the water in and around Mystery Cave flows to Seven Springs. It only take a few hours to a few days for the water to flow to Seven Springs once it reaches the underground rivers. In other areas the water that reaches the water table may recharge deeper aquifers where the residence times can be tens of thousands of years.

32) What per cent of runoff adds to our water problem?

In the vicinity of Mystery Cave the runoff (both surface and groundwater) corresponds to about 7 inches per year. That water ultimately supplies all of the ground water and surface water in the region. All of that water travels over (as surface runoff) or through (as groundwater recharge) the surface of the land and picks up what ever human activities have placed on and in that land surface. Runoff is both 100% of our "problem" and 100% of our "resource". When there is more or less water on the surface or in the subsurface than we want, or when that water has picked up contaminants from human or natural sources, a "problem" exists. When the quality and quantity of the surface or groundwater corresponds to our needs then it is a desirable resource.

33) Does the Mississippi affect our stream or groundwater in any way, if so how?

The Mississippi River is the regional base level toward which all surface and groundwater around Mystery Cave is flowing. However, the Mississippi is far downstream from Mystery Cave in both distance and elevation. The Mississippi River does not directly affect the water quality or quantity in the cave area.

34) We never see sanitary landfills in the area. Why? Where are they?

Fillmore County's only landfill, the Ironwood Sanitary Landfill, was established in the early 1970s on the north bank of the South Branch of the Root River south of Spring Valley. The Ironwood Landfill is about 3.5 miles west of the Mystery Cave I entrance and is upstream of the cave. The site was originally constructed as a series of five tailings ponds for an iron ore washing and shipping facility. In late 1979, 1,400 barrels of illegally buried industrial waste were discovered in Ironwood. Those barrels were removed in winter and spring of 1980. When excavated, 500 of the barrels were empty.

The groundwater beneath the Ironwood Landfill was found to be heavily contaminated with the industrial solvents that had been in the barrels. A groundwater pumpout operation was begun to control the spread of the contaminants in the subsurface and to eventually clean up the groundwater. That pumpout operation is ongoing at the present time and will continue for the foreseeable future. The solvent levels in the contaminated water pumped out of the landfill correspond to a couple of barrels of solvent per year at the current pumpout rates. The contaminated water is pumped into a pond on the site. The solvents are allowed to evaporate from the pond and then the pond is dumped into the South Branch. As part of this study, we tested a sample from the South Branch at Mystery I for the solvents in the contaminated pumpout water from Ironwood. None of the solvents were detectable at the Mystery I entrance or in the lower stream levels.

Ironwood Sanitary Landfill was closed in the early 1980s. This left Fillmore County without a landfill. For several years, the waste stream from Fillmore County was hauled to a landfill in Howard County, Iowa. Fillmore County then constructed a composting and recycling center in Preston. For the last several years, all of Fillmore County's waste stream has been recycled and composted.

Other counties in southeastern Minnesota have landfills constructed in the 1970s. Most if not all of those landfills show evidence of groundwater contamination to some degree. Olmsted

County's original landfill near Oronoco is a Super Fund Site. Olmsted County constructed a garbage burning/resource recovery operation in Rochester, closed the Oronoco landfill, and constructed a new, modern landfill for the ash from the garbage burning operation and for that part of the waste stream that is not burned or recycled. The new landfill has elaborate, state-of-the-art liners and leachate collection systems designed to prevent groundwater contamination and was carefully located in a non-karst part of Olmsted County.

35) Do landfills or farm ponds drain into the aquifers? If they do, can they contaminate the water?

Yes. Any facility that is not very carefully engineered to prevent groundwater or surface water contamination will probably contaminate the groundwater, the surface water or both. It is only in the last few years that landfills and ponds in the area have been constructed with liners. The MPCA has identified 22 community waste water treatment lagoons and three industrial lagoons in southeastern Minnesota. Three of those community lagoons have catastrophically failed to date (Alexander and others, 1993). There are thousands of manure storage lagoons, ponds and runoff control structures that have been built in the area, but no inventory of them exists. A number of these structures have failed, but no centralized records of these failures are kept.

36) What are the correct names of the local aquifers?

Geologic nomenclature is very boring to most people -- but the question was asked. The aquifers are named for the rock units that comprise them. In addition, there are several group names that are also in use. The definitive source for the nomenclature Minnesota rocks and aquifers in the Minnesota Geological Survey. The most recent publication on the subject is Mossler (1987).

All of the bedrock aquifers above the Decorah Shale aquitard have historically been lumped together as the **upper carbonate aquifer** in Minnesota. That term is falling into disuse as more and more evidence accumulates that these rocks comprise at least two and perhaps three reasonably separate aquifers. Nonetheless, you will encounter the term in the literature and hear people using it.

There is growing evidence that the Maquoketa Formation, particularly to the southwest of Mystery Cave, acts as an aquitard. The Dubuque Formation is not usually considered an aquifer although there is obviously water flowing through and from it at several places in Mystery and in other caves of southeastern Minnesota. The Dubuque Formation just can't get no respect from most hydrogeologists. The new Fillmore County Atlas is mapping the Dubuque together with the Maquoketa. Cavers know and love the Dubuque, however, for the big "Dubuque walking passages" that often develop in the formation.

The Galena Group is the main aquifer in which Mystery Cave is developed. Hydrogeologists conventionally call it the **Galena aquifer** and use a four letter code, OGAL, to represent it. The Galena Group consists (from the top down) of the Stewartville Formation, the Prosser Limestone, and the Cummingsville Formation. Before Mossler's (1987) work the Galena was taken (in Minnesota) to be a formation and the Stewartville, Prosser and Cummingsville beds were taken to be members of that formation. Mossler upgraded the Galena to a Group and the Stewartville, Prosser and Cummingsville to formations. In any Minnesota publication dated before 1987, the old nomenclature was used. In some of the publications dated after 1987 the new nomenclature is used.

One of geology's notorious "state line faults" occurs along the Minnesota/Iowa border. In Iowa a few miles south of Mystery, the Galena Group includes the Decorah and Dubuque formations. The Prosser and Cummingsville are lumped together as the Dunleith Formation and the Stewartville is called the Wise Lake Formation. (We told you this was boring.) The water in these rocks pays no attention to all of this nomenclature chauvinism and simply flows down hill. The Galena aquifer is an important water source in much of northeastern Iowa and consists of the equivalent rock formations to the Minnesota Galena aquifer.

37) What aquifers do the neighboring communities get their water from?

All of the neighboring communities have municipal wells that are cased and grouted into aquifers below the Decorah-Platteville-Glenwood aquitard. Spring Valley has two wells which produce water from the Prairie du Chien-Jordan aquifer and one which produces water from the St. Peter-Prairie du Chien-Jordan aquifer. Wykoff has two Jordan aquifer wells. Fountain has one Prairie du Chien-Jordan aquifer well and a new Jordan aquifer well. Preston has two Jordan aquifer wells. Greenleafton has a St. Peter aquifer well. Ostrander has a Prairie du Chien aquifer well. The new well at Mystery I is a St. Peter aquifer well.

All of the municipal wells are producing water that entered the aquifers before 1953. The Spring Valley and Ostrander municipal wells are producing water that has been in the ground for about 30,000 years.

38) Does mixing of water from different aquifers occur?

Yes. Mixing occurs both naturally and artificially. If an aquifer were completely surrounded by perfect aquitards, that aquifer would contain no water. All aquitards leak to some degree. In addition, erosion has truncated the aquitards.

Natural mixing occurs when the water flowing along the top of an aquitard reaches either the edge of the aquitard or a natural break in it. The Decorah Shale-Platteville Limestone-Glenwood Shale is conventionally mapped at the aquitard below the Galena aquifer. A regional study of the relationship between the Galena aquifer, the Decorah/Platteville/Glenwood aquitard and the underlying St. Peter/Prairie du Chien/Jordan aquifer by Delin (1991, p.1) concluded that "about 54 percent of recharge to the [St. Peter-Prairie du Chien-Jordan] aquifer in the area contributing water to Rochester is from a zone along the edge of the Decorah-Platteville-

Glenwood confining unit." This effect is the dominant source of recharge to regionally important aquifers.

Artificial mixing occurs in wells that are open hole in more than one aquifer. Such wells can no longer legally be drilled, but many older multi-aquifer wells exist. Some of these are still in use and many of them have been abandoned. These multi-aquifer wells represent major threats to the water quality in the lower aquifers.

39) Are there wells tapping into the same water supply as what we see in the cave?

Yes. Large scale dye traces in the early 1980s of the entire South Branch of the Root River demonstrated that several local shallow wells are directly connected to the same flow system as Mystery Cave. These traces were prompted by the discovery of groundwater contamination by industrial waste at the Ironwood Landfill, which is a few miles west and upstream of Mystery Cave. As far as we know, several of these shallow wells are still in use even though wells can not legally be completed in this near-surface aquifer today. However, these wells were drilled before the modern codes for constructing water supply wells were established in 1974.

40) How far does the Galena aquifer extend laterally?

Hundreds of miles. There are Galena wells in the southern edge of the Twin Cities and the aquifer extends across most of south central Minnesota, through Iowa and further south and east. The groundwater flow in the aquifer is, however, divided into a series of separate groundwater basins of varying sizes. Mystery Cave is near the lower end of a groundwater basin that extends to the headwaters of the South Branch in Mower County.

41) What are some practical examples of how the water quality could be improved? What can be done to clean up the water in S.E. Minnesota?

All kinds of things can be done to clean up the water in S.E. Minnesota. The list of practical, tested techniques to improve groundwater quality is much too long and changing too rapidly as it grows to give even representative examples. A large number of dedicated individuals are helping with the effort. The people are at least as important as the techniques. We will list only a few relevant examples of success stories:

1) The Interpretative Staff at State Parks can build a strong groundwater education and conservation component into their cave tours. It is difficult to imagine a more effective environment to get the message across. Very high success rate!
2) Stop disposing of waste materials in sinkholes. The change that has occurred in the last 15 years in southeastern Minnesota's karst lands has been truly amazing. Disposal of anything in sinkholes was a common activity a few years ago. Now almost everyone accepts that such dumping is a dangerous, socially unacceptable activity. Education and common interest were the keys.
3) Recycle materials rather than dispose of them after only one use. The reduction of the waste

stream is very significant.

4) Reduce the over application of fertilizers and pesticides in agricultural production. Set realistic yield goals, count credits for carryover from previous crop practices and manure applications, and adjust the application downward. Iowa decreased the amount of nitrogen fertilizer applied to farm land by over one million pounds and still produced their largest crop on record.
5) Maintain and upgrade individual septic systems. EPA studies have repeatedly indicated that individual septic systems are the largest single source of groundwater pollution in the U.S. Properly designed, installed, and maintained septic systems do a much better job of treating the sewage than improperly designed, installed, or maintained systems.

42) What do you consider the most important message to convey to the public about groundwater?

That **we** (everyone who lives, works, or plays in any area) are responsible for protecting groundwater quality and quantity in that area. It is **our** past activities that have impacted the groundwater quality. It is **our** efforts that will improve or degrade the resource in the future.

Groundwater does not start or stop at property or political boundaries. Groundwater is a renewable resource that can be managed successfully only by the combined efforts of all people who affect the resource. "Out of sight" is not out of your water supply and "no person is an island". The changes that can be wrought by people working toward a common goal are unlimited -- as is the potential for damage by thoughtless, short-sighted actions.

The recipe for success is very simple:

1. Learn about how your groundwater system operates.
2. Do all that you as an individual can do to lessen the impact of your activities on your groundwater system.
3. Share your knowledge and coordinate with your neighbors to extend and expand the impact of your individual efforts.

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