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Groundwater Contamination and Sinkhole Collapse

Induced By Leaky Impoundments
In Soluble Rock Terrain

By Thomas J. Aley
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U.S. GEOLOGICAL SURVEY AND WATER RESOURCES
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GROUNDWATER CONTAMINATION AND SINKHOLE COLLAPSE
INDUCED BY LEAKY IMPOUNDMENTS
IN SOLUBLE ROCK TERRAIN

By Thomas J. Aley
James H. Williams
James W. Massello

ABSTRACT

The effects of leaky impoundments on groundwater contamination and collapse of the land surface in soluble rock regions have previously received scant attention in the literature. One effect of leaky impoundments can be to induce catastrophic sinkhole collapse which may endanger life and property. A second effect which can result from leaky impoundments is groundwater contamination due to the artificial introduction of poor quality water underground.

Our concern is with those regions where secondary porosity of bedrock (due mainly to solution) is significant. These areas are typically characterized by sinkholes, caves, springs, disappearing and losing streams, and other karst features.

We have reviewed technical literature on sinkhole collapse and groundwater contamination from a number of areas. Some of the most pertinent information comes from the soluble rock terrain of the Far West Rand in South Africa. In this area deep mining has greatly altered natural groundwater conditions and has been responsible for numerous sinkhole collapses with attendant loss of life and damage to property.

In the case history analysis portion of this report we have documented 20 cases of land collapse in Missouri. These collapses have been related to sewage lagoons, leaky impoundments, and other construction which has changed groundwater regimens. Eight of the collapses were apparently unrelated to man's activities (although agricultural practices could have been related in three of the eight cases).

Although frequent reference is made to conditions in Missouri, we believe our findings and conclusions are applicable to many other regions where soluble bedrock is widespread. We conclude that leaky impoundments in soluble rock terrain can cause groundwater contamination and induce sinkhole collapse. We believe these hazards are significant in Missouri and pose a serious environmental threat.

ACKNOWLEDGMENTS

Much of the information in this report is a result of investigations by the United States Forest Service on the Hurricane Creek Barometer Watershed, Mark Twain National Forest, Missouri. A number of the case histories, which offer verification of the groundwater contamination and collapse problems, were documented by the Missouri Geological Survey and Water Resources.

We greatly appreciate the help of many individuals who supplied source material for the case history analysis. In particular, we thank John T. Renfrow and Leon Pace of West Plains, Missouri and Carl E. Chaney of Birch Tree, Missouri. In addition, the assistance of several staff geologists of the Missouri Geological Survey and Water Resources, and in particular Jerry D. Vineyard is sincerely appreciated.

INTRODUCTION

Perhaps in no other natural environment are geohydrologic factors so delicately balanced as in soluble rock terrain. To change the surface is to change the subsurface as is evidenced in the Salem and Springfield plateaus of the Ozark Province where collapse of the land surface and groundwater contamination follow in lock-step with the activities of man.

The Ozarks is a landform where soluble bedrock has been a major controlling factor. Approximately 70 percent of the bedrock is limestone or dolomite with significant areas subject to catastrophic sinkhole collapse (fig. 1). Typical karst landforms such as sinkholes, although predominant on the Springfield plateau, are not widespread in the Salem plateau. Nonetheless, other karst features such as large springs, abrupt variations in shallow groundwater levels, little surface runoff, and bedrock-controlled drainageways typify the region. In the central portion of the Ozarks, major watersheds of several hundred square miles are drained internally and have little surface flow.

A significant portion of Missouri's economy is centered in the Ozarks, thus, these soluble rock lands are subject to major environmental impacts when changes in land use occur. Missouri is presently experiencing major urban, industrial, and rural changes. For example, the City of Springfield in the midst of a karst plain, has grown to a population of 125,000. St. Louis suburbs are spreading southwestward over the ridge and valley soluble rock terrain of the eastern Ozarks. Several cities in the Ozarks

have populations in excess of 5,000; there are many communities with populations in excess of 500. All must dispose of wastes and most must contend with the added cost and complexity of waste disposal in soluble rock terrain.

The world's largest lead resource is being mined in the central Ozarks. Cattle feedlots and similar operations are becoming more common features throughout the Ozarks.

While waste disposal problems are being created (and at least partially and gradually solved) water impoundments pose a more spectacular problem. Dams to provide recreational lakes are eagerly sought and frequently built in the Ozarks. Numerous dams are proposed for flood protection in some of the valleys draining through communities. Unfortunately, dams built in the soluble rock lands often fail to impound water. Beside the obvious financial loss of an unsuccessful lake, far-reaching effects of lake failure also occur but are frequently unrecognized.

A leaky impoundment in the soluble rock lands can induce sinkhole collapse of the land surface and can cause groundwater contamination by introducing poor quality water underground. In this paper we will discuss the hydrologic and geologic factors responsible for impoundment failures, and will use case histories to illustrate the nature and magnitude of the problem. It is our hope that this paper will help the reader make a better assessment of the hazards involved in impoundment construction in soluble rock terrain.

LAND COLLAPSE AND SUBSIDENCE

Collapse is the abrupt failure of the land surface due to the movement of material into underlying

cavities. Subsidence is a gradual lowering of land surface. Subsidence in soluble rock areas is due either to

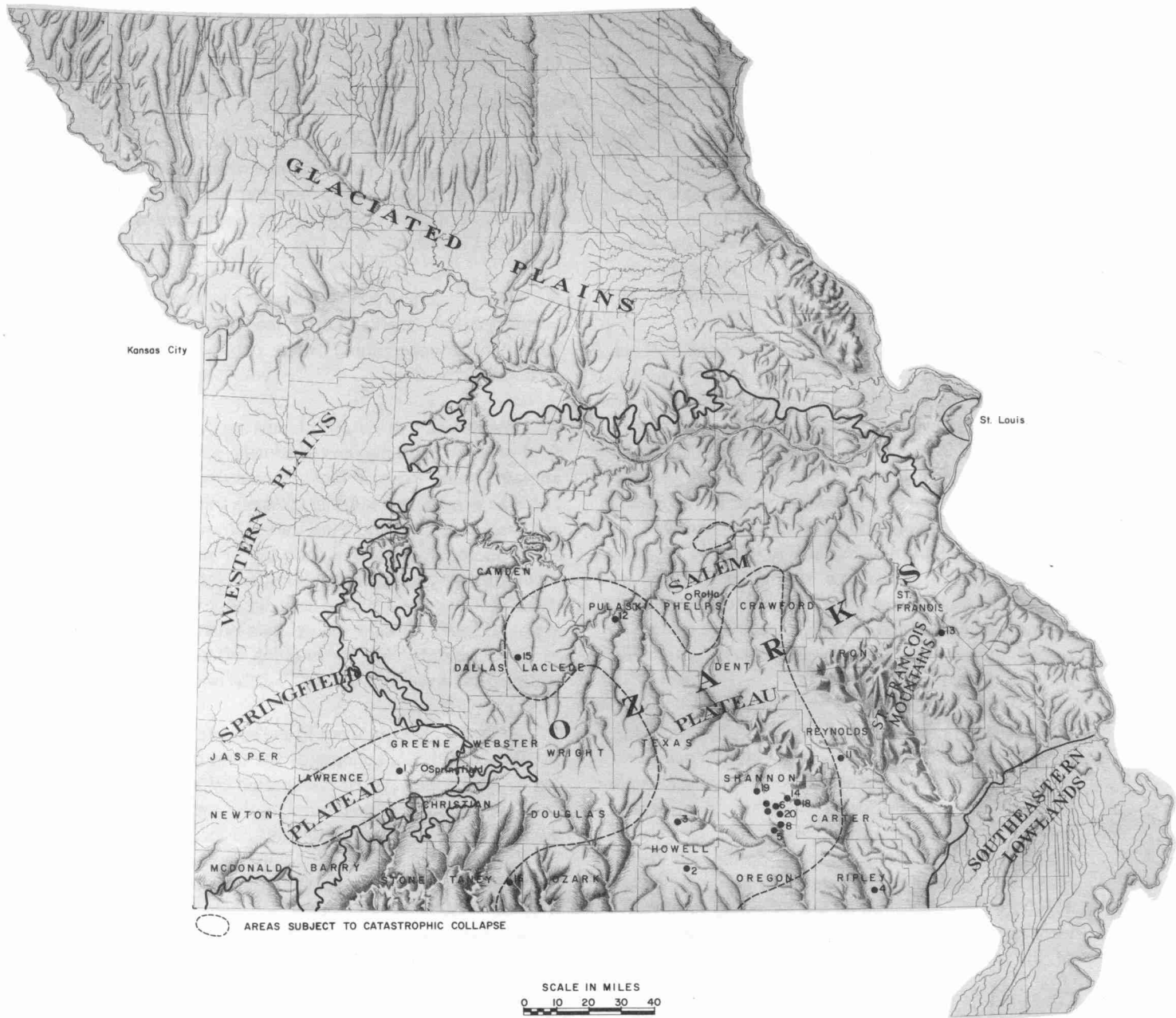


Figure 1

Areas in Missouri that are particularly subject to catastrophic sinkhole collapse. Sites of collapses and groundwater contamination investigated for case history analyses are also shown.

the gradual movement of earth into underlying voids, or else to consolidation of overburden materials. The important distinction between collapse and subsidence is that collapse is abrupt while subsidence is gradual. Subsidence and sinkhole collapse are typical occurrences in soluble rock terrains, and in many cases are not man-induced. Man can, however, drastically accelerate these processes. Man-induced collapse and subsidence can be caused by the addition of weight, but it is primarily caused by changes in subsurface water regimens.

Foose (1968) reports that collapse tends to occur over pinnacled soluble bedrock, whereas subsidence occurs where pinnacles are either widely spaced or absent. He lists seven conditions leading to sinkhole collapse which are as follows:

- "(1) Unconsolidated debris is relatively thick. Few sinkholes are known where the debris is less than 10 meters thick. The size of the resulting sinkhole is related to the thickness of the debris column.
- (2) Unconsolidated debris is non-uniform and heterogeneous in character. Where the debris is uniform in character there is more likely to be gradual consolidation, compaction and subsidence.
- (3) The groundwater table was originally higher than the bedrock surface and in the debris. Subsequent lowering initiates desiccation and compaction. However, sinkholes have formed where the original groundwater table was in the bedrock as a consequence of flushing out underlying bedrock openings during lowering.
- (4) Irregular and pinnacle-type weathering characterize the bedrock. This feature has been observed in every area where catastrophic sinkholes have occurred.
- (5) Cavernous openings in the bedrock are extensively interconnected, thereby providing for easy movement of ground water and for downward migration of debris.
- (6) Major structural elements occur in the underlying bedrock. These control the location of zones of deep vertical weathering. Steeply dipping joints, faults, shear zones, and formational contacts are preferred lineaments.
- (7) Ground water moves with greatest ease. Groundwater movement is usually controlled by rock structures; sometimes by compositional changes in lithology.

Along such lines, ground water flushing of unconsolidated particles may occur."

Many of the soluble rock areas of Missouri have most, or all, of the conditions listed by Foose (1968). Deep residuum of a non-uniform character overlies much of the bedrock in the Ozarks.

In some of the areas in Shannon, Carter and Oregon Counties, where we have done much of the field work for this paper, residuum depths sometimes reach 500 feet. A well drilled by the U.S. Forest Service at Lewis Lake in Shannon County (Sec. 6, T. 27 N., R. 3 W.) bottomed in residuum at 510 feet.

Irregular and pinnacled weathering of the bedrock is characteristic of many of the soluble rock formations in the state. This type of weathering is very pronounced in some of the Mississippian formations in the vicinity of Springfield in Greene County. Fellows (1965) has described bedrock cutters and pinnacles in this area.

Cavernous openings in the bedrock are common in Missouri, and they are very well interconnected. Major structural elements occur in the bedrock and are important in directing water to some of the major springs in the state. Groundwater tracing with fluorescent dyes and *Lycopodium* spores in conjunction with the Hurricane Creek Barometer Watershed project on eight separate occasions has demonstrated subsurface flow from the Eleven Point River basin to Big Spring. Straightline travel distances for these groundwater traces range from 15½ to 39½ miles; travel times are typically one to three weeks. It is interesting that all tracer injections have been in areas topographically tributary to the Eleven Point River; Big Spring is tributary to the Current River. Groundwater flow is thus occurring beneath a major topographic river basin divide.

Vineyard and Williams (1967) listed 11 features which typify stream valleys in soluble rock terrain where sinkhole collapse may occur. These diagnostic features are:

- "1. Valleys dry or nearly so most of the year.
2. Poorly graded alluvium due to lack of sorting by sustained flow.

GROUNDWATER CONTAMINATION AND SINKHOLE COLLAPSE

3. Wide, flat floodplains bounded by steep valley slopes.
4. Absence of terraces.
5. Abrupt variations in valley profiles, which may suggest subterranean stream piracy.
6. Lack of water-supported vegetation.
7. Abrupt changes in valley alignment, which may indicate intersection of an underlying, structure controlled cave system.
8. Low water tables.
9. Absence of bedrock outcrops and/or presence of pinnacled bedrock.
10. Limited amounts of fine sediment in floodplain deposits.
11. Sinkholes and/or sinking streams."

COLLAPSE INDUCED BY LOWERING GROUNDWATER LEVELS

Lowering of groundwater levels has induced collapse and subsidence in many soluble rock regions of the world. Some of the most spectacular collapses have occurred in South Africa (Jennings, 1966). In this area, sinkholes nearly 400 feet in diameter and 150 feet deep have formed in thick, unconsolidated residuum overlying weathered, pinnacled dolomite. In one case, a sink formed without warning and claimed the lives of 29 people. In another, a family of five was killed when their home dropped into a suddenly formed 100-foot deep sinkhole. In the South African cases, collapse was accelerated by drastic lowering of water levels due to local mining.

Jennings (1966) listed four triggering mechanisms necessary to induce the collapse of a residuum void's roof:

- “(a) excess water entering the arch material and so causing a loss of strength. This is by far the most common trigger;
- (b) earth tremors causing vertical and lateral accelerations, thus resulting in externally applied body forces to the materials of the arch;
- (c) ground movements resulting from subsidences associated with mining. These movements might be irregular, resulting in differential movement which can upset the geometry of the arch;
- (d) surface loading of vibratory nature, particularly where the energy of vibration is great and sustained.”

Less drastic effects occurred near Hershey, Pennsylvania (Foose, 1969) where once again lowering of groundwater levels by mining caused sinkhole collapse and the drying up of springs, wells, and previously perennial surface streams. In this area

nearly 100 new sinkholes formed in the alluvial and residual material overlying pinnacled limestone.

The examples from South Africa and Pennsylvania involved drastic lowering of groundwater levels due to mining. Collapse and subsidence can also occur when groundwater levels are only moderately lowered. Sinkhole collapses at Bartow, Florida and nearby U.S. Highway 98 were related to lowering water tables as the result of seasonal moisture changes and pumping (Coker, et al., 1969).

Powell and LaMoreaux (1969) described land subsidence in a limestone terrain at Columbiana, Alabama. They found that most of the subsidence was confined to the area above the bedrock. The subsidence was attributed to municipal water pumping which removed silt, sand, and calcareous and colloidal material and reduced the bearing strength of the overlying material. As a result of this subsidence, several buildings were damaged and a municipal water tank developed a serious lean. The bedrock was apparently not pinnacled; using Foose's (1968) criteria, this would be a significant factor in causing subsidence rather than collapse.

A very interesting case of man-induced collapse by lowering of groundwater levels occurred in the St. Francis River Valley in St. Francois County, Missouri, 1948 (Bretz, 1956, p. 323):

“The drilling rig was set up on an alluvial terrace in the St. Francis River Valley, about 30 feet above stream level. From a depth of 33 to 70 feet the drill penetrated solid rock. At 70 feet the drill entered a cavity which was filled with mud and water. Passing this, the drill continued in rock to 330 feet where it

GROUNDWATER CONTAMINATION AND SINKHOLE COLLAPSE

dropped 3 feet into another cavity. Immediately, the water and mud at the 70-foot level ran down the drillhole with a roar that was audible 50 feet away from the drilling rig. Within an hour or so, small sinks began developing in the surface of the alluvial flat close to the rig. In two days nearly 20 such sinks had been formed within a radial distance of 500 feet. By this time, casing had been set past the 330-foot level and the roaring had stopped. Except for minor deepening of three or four of the sinks, the collapsing also ceased."

The largest sink formed was 90 feet long and 20 feet wide. Bretz noted that the sinks had a linear form, and deduced that the outlets were vertical or nearly vertical, solutionally widened joints in the bedrock which were connected to the crevice at 70 feet. The drillhole permitted buoyancy loss of supporting material by the rapid flow of mud and water down the hole thus causing a readjustment of the surface.

COLLAPSE INDUCED BY RAISING GROUNDWATER LEVELS

To this point we have considered collapse and subsidence induced by lowering of groundwater levels. In the case of leaky impoundments, groundwater levels are raised, not lowered. It is our contention that if foundation and hydrologic conditions in an area are such that sinkhole collapse is induced by lowering water levels, sinkhole collapse may also be induced by raising water levels.

The construction of impoundments, lakes, and sewage lagoons in soluble rock areas has caused collapse. Trumbull (1970) reported that the construction of a series of large reservoirs on the Angara River in the Soviet Union caused extensive collapse with sinkholes up to 30 feet deep and 18 feet in diameter. At Cave City, California, a dam built about 1920 resulted in the formation of 15 sink-

holes near and above the high water level of the impoundment (Aley, 1962). All these sinks were developed in unconsolidated material overlying limestone. Construction of a leaky impoundment in a karst region of Czechoslovakia (Silar, 1969) resulted in the formation of numerous sinks. The impoundment was in a polje, which is hydrologically similar to the broad, underdrained valleys of the Ozarks. Construction of the Lone Pine Reservoir in Arizona (Kiersch, 1958) caused substantial collapse in the impoundment area.

Subsidence and collapse have been reported from artificial recharge of groundwater through wells in limestone regions (Sternau, 1967). In one case, a sink 20 feet deep and 45 feet in diameter developed at the point of recharge.

GROUNDWATER CONTAMINATION BY LEAKY IMPOUNDMENTS

Leaky impoundments can function as groundwater spreading basins. Water quality is of great concern in groundwater spreading operations; it must also concern us as leaky impoundments are proposed for or constructed on soluble rock terrain.

There are three types of groundwater contamination which can result from leaky impoundments:

a. Bacterial and viral contamination.

- b. Chemical contamination; in the Ozarks contamination by nutrients is particularly important.
- c. Physical contamination; this includes waters bearing sediment or organic materials.

The concentration of bacterial and viral contaminants is often much greater in flood water than in

water under normal flow conditions. Human and animal wastes can be flushed into streams during storm periods. This material contributes greatly to bacterial and viral water contamination. If this contaminated water remains on the surface, sunlight and oxygenation will ultimately destroy most of the bacterial and viral contaminants. Similarly, these contaminants would be destroyed if they were filtered through an adequate amount of soil (Drewry and Eliassen, 1968) (Romero, 1970). If, however, they enter solution channels via highly permeable valley materials, a substantial amount of the bacteria and viruses will not be destroyed. The potential groundwater pollution hazard of a sinkhole collapse in the bottom of a waste disposal lagoon or the loss of effluent discharged from a waste treatment works to a losing stream and thus ultimately into solution-enlarged channels in soluble rock is obvious.

Underground streams in soluble rock regions are notorious for transporting viruses and bacteria; they provide little effective filtering and protect the viruses and bacteria from sunlight. Mosley (1959) reports a number of cases of infectious hepatitis and gastroenteritis resulting from drinking contaminated spring and well waters in limestone or fissured rock areas. As an indication of the hazard, the Public Health Service (U.S. Department of Health, Education, and Welfare, 1970) found:

"Eighty-three (69 percent) of the 120 water supply systems that exceeded the coliform organism density limit, which indicated disease potential, were from poorly protected and/or inadequately treated spring and well sources." (page iii)

"... the combination of small communities and untreated springs in Region 1 (Vermont) caused 29 percent of all of the supplies there to exceed the coliform density limit. In the entire Community Water Supply Study 53 percent of all the systems exceeding the coliform density limit were in Region 1." (page 50)

The geologic setting of the springs was not reported, but there is little soluble rock in Vermont. In general, groundwater contamination hazards in soluble rock regions are greater than in non-soluble rock areas.

The senior author has recently begun groundwater tracing work utilizing stained *Lycopodium*

spores as the tracing agent. This work is being conducted in the soluble rock terrain of southern Missouri in an attempt to qualitatively assess the effectiveness of natural filtration in karst groundwater systems.

Lycopodium spores were selected for this work because they are 10 or 15 times larger than most bacteria. The mean diameter of *Lycopodium* spores is approximately 33 microns; this is substantially larger than the causative bacteria of typhoid fever, *Salmonella typhosa*, which is 0.6 to 0.7 microns in diameter and 2.0 to 3.0 microns long (Breed, Murray, Smith et al., 1957). The size of *S. typhosa* is similar to most pathogenic bacteria.

Two groundwater traces with stained *Lycopodium* spores have been attempted from losing streams. In both cases the alluvial materials into which the spores were injected were typical of those encountered in losing streams in the soluble rock lands of Missouri.

The *Lycopodium* spore injection point in the first trace was near Blowing Spring in the channel of Hurricane Creek (Sec. 3, T. 25 N., R. 3 W., Oregon County, Missouri). Five pounds of colored spores were injected near Blowing Spring, and over 4,000 of these spores were later caught in the collecting equipment at Big Spring near Van Buren. The straight line distance from point of injection to point of recovery is 17 miles, the mean gradient is 12 feet per mile, and the first spores appeared at Big Spring approximately 12 days after injection.

The second groundwater tracing with stained *Lycopodium* spores was from the channel of the Middle Fork of the Eleven Point River two miles northeast of Fanchon (near the section line between Sec. 25 and 26, T. 25 N., R. 7 W., Howell County, Missouri). Six pounds of stained *Lycopodium* spores were injected in a losing portion of the stream; approximately 560 spores were subsequently recovered in sampling equipment placed at Big Spring. The straight line distance from point of injection to point of recovery is 39.5 miles, the mean gradient is about 10 feet per mile, and the first spores appeared at Big Spring approximately 13 days after injection.

The groundwater tracing with *Lycopodium*

spores demonstrates that the groundwater system connecting losing streams to major springs in some cases does not provide effective water filtration. How frequently effective filtration does occur we do not know, yet the data obtained to date indicates that bacterial and viral contamination of groundwater can be a frequent occurrence in soluble rock lands.

Leaky impoundments in soluble rock regions will introduce bacteria and viruses into the groundwater. Where the watershed area receives little use, these contaminants may not cause significant problems. If the watershed includes communities without adequate sewage treatment, substantial contamination can result. Similarly, if the watershed now has, or ultimately will have feedlots, turkey lots, or large poultry houses, groundwater supplies could be seriously contaminated by bacterial and viral material.

Chemical contamination of groundwater is also inherent in the introduction of flood water or waste effluent underground. In the Ozarks, nutrients such as phosphates and nitrates are generally in low concentrations in natural situations. Substantial change in the flora and appearance of springs and rivers occurs with increases in these nutrients.

Wells are the primary source of water in much of the Ozarks (and in many other soluble rock areas as well). Substantial care must be taken to insure protection of these water supplies. Some of the springs and spring-fed rivers in the Ozarks are of national importance; the Eleven Point River is included in the Wild and Scenic Rivers Systems, and portions of the Current River and Jacks Fork including Big Spring, Alley Spring and Round Spring, are administered by the National Park Service. These waters must not be degraded.

Domestic wells in soluble rock regions can be contaminated or polluted by nutrients. In a study in the James River-Wilson Creek area near Springfield, Missouri (FWPCA, 1969) several wells showed nitrate concentrations greater than the levels recommended for drinking water (U.S. Public Health Service, 1962).

Feedlots and similar activities in the watershed of a leaky impoundment could lead to serious nutrient contamination of groundwater. Stewart et al. (1967) discussed nitrate pollution from feedlots, and indicated that nitrates can have serious effects on groundwater quality. Scalf (1968) in a study of nitrate pollution in artificially recharged groundwater found that nitrates move freely through aquifers.

Degradation of groundwater can be caused by introducing water low in dissolved oxygen or high in biochemical oxygen demand (BOD). The introduction of this water can cause a reduction or total depletion of dissolved oxygen in groundwater or spring systems. Organic material accumulating in the bottom of Noblett Lake, Howell County, Missouri, is believed responsible for the occasional anaerobic condition of Redbud Spring, located a short distance downstream of the dam. Similar groundwater effects could occur from other leaky impoundments.

It must be realized that any activity which introduces poor quality water into the groundwater system will degrade groundwater quality. Although this paper is concerned with the role of leaky impoundments in introducing poor quality water underground, there are other of man's activities which present similar and highly significant hazards. Sewage lagoons which leak or those which collapse into cave-spring systems are a readily apparent example. Discharging of sewage or other wastes into losing streams which recharge groundwater systems has caused serious groundwater contamination in Missouri.

CASE HISTORY ANALYSIS

It is our contention that leaky impoundments in soluble rock terrain can induce sinkhole collapse and cause groundwater contamination. To support this contention, we have examined a number of sites in Missouri where these problems have occurred (fig. 1).

We have placed the emphasis in this case history analysis on documenting instances of collapse because the concept that leaky impoundments can induce collapse has received little attention in the technical literature. We will also offer some examples of groundwater contamination in the soluble rock areas of Missouri, but we basically feel that the current technical literature provides ample documentation of the inherent hazards of introducing poor quality water underground. It is not our intent to imply that collapse is a greater hazard than groundwater

quality degradation in Missouri. In some cases collapse may be the more important concern; in other cases the protection of groundwater quality may be of paramount importance.

We have divided the case histories of sinkhole collapse into four sections: (a) collapse related to sewage lagoons, (b) collapse related to impoundments, (c) collapse related to changing water regimens, and (d) collapse which appears to be unrelated to man's activities. The case history analysis is based upon our field work, some historical evidence, and information from the files of the Mark Twain National Forest and the Missouri Geological Survey and Water Resources. A bibliography of source material for our analysis is included at the end of this section.

SINKHOLE COLLAPSE RELATED TO SEWAGE LAGOONS

Sewage lagoons are frequently used in the Ozarks to provide treatment of waste waters. There have been several instances in Missouri where

lagoons have triggered sinkhole collapse and caused groundwater contamination at points distant from the lagoon site.

REPUBLIC SEWAGE LAGOON

Perhaps the best known sewage lagoon collapse in Missouri is at Republic (Sec. 20, T. 28 N., R. 23 W., Greene County). A catastrophic sinkhole collapse

about 6 feet in diameter and 6 feet deep occurred on October 29, 1968. An estimated four million gallons of sewage entered the groundwater system through

this sinkhole in a 24-hour period. Two days later, on October 31, another collapse occurred in the lagoon.

The Republic Lagoon rests on about 15 feet of stony clay which in turn overlies pinnacled, Mississippian limestone. The clay is a well structured, low density, moderately permeable residuum of the limestone.

The collapses within the Republic Lagoon had several effects. Several springs tributary to Shuyler Creek were polluted with the sewage, as was Shuyler Creek itself. Although most of the sewage reappeared within a mile of the lagoon, some more distant contamination also occurred. Dye and effluent from the lagoon reappeared in two domestic wells about 1½ miles east of the lagoon. Other wells may have been contaminated, but information is lacking.

WEST PLAINS SEWAGE LAGOON

Collapse within sewage lagoons has also occurred at West Plains, Howell County, Missouri (fig. 2). The

lagoon system for the city is in Sec. 27, T. 24 N., R. 8 W., and consists of two cells with an impound-

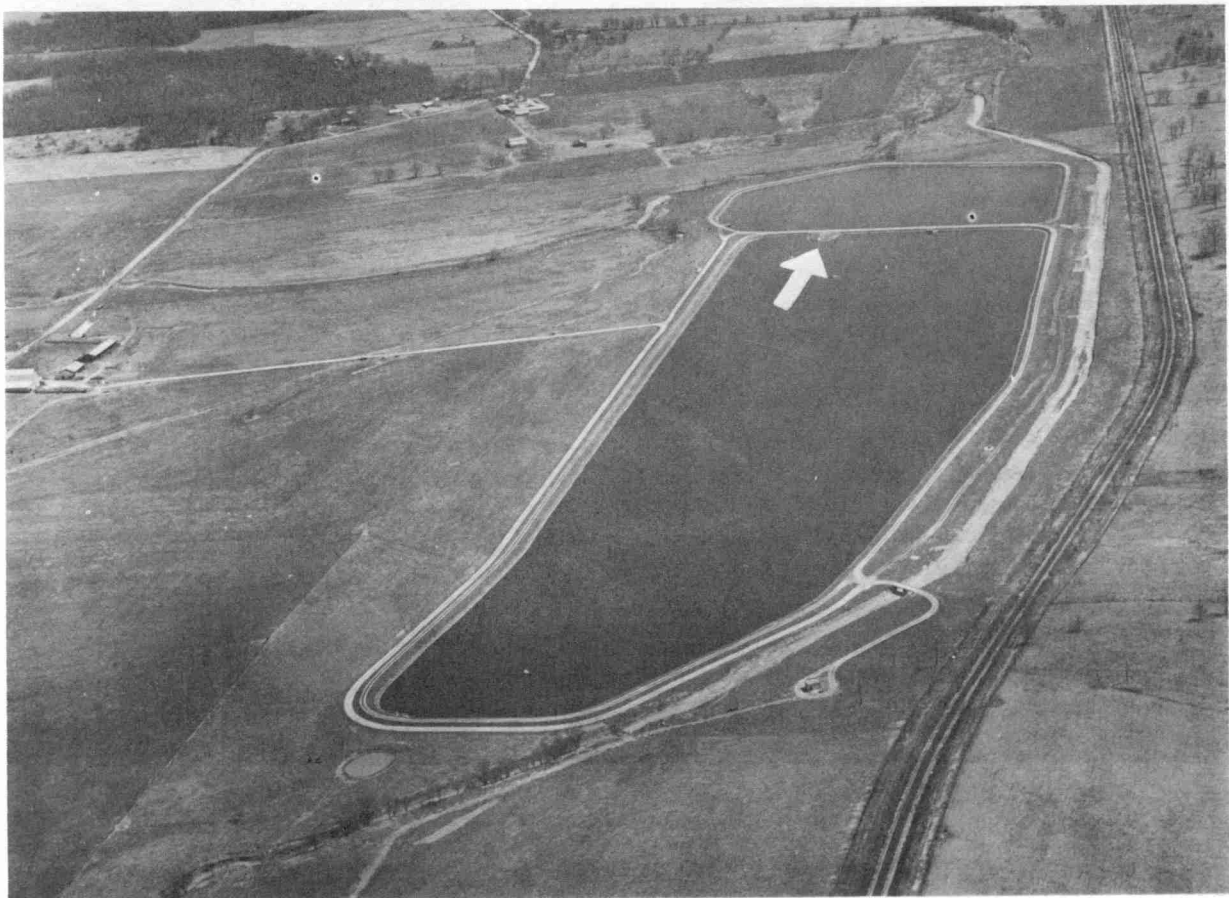


Figure 2

Aerial view of the West Plains sewage lagoon as it appeared in 1971. The area which collapsed in 1966 is shown by the arrow. Photo by Jerry D. Vineyard.



Figure 3

The large cell of the West Plains sewage lagoon. A catastrophic sink occurred in 1966 beneath the peninsula shown in the foreground. Subsequent to the collapse the sink was filled with clay and bentonite and the lagoon was returned to use. Photo by James W. Massello.

ment area of 49 acres and a normal water depth of about 3 feet. The lagoons are in the broad valley of Howell Creek, an intermittent stream. The valley floor has been noticeably sculptured by sinks, and substantial losses of surface flow to ground water occur from the stream channel.

The lagoon system was constructed in 1964 and reached full operation in 1966. The smaller cell, which occupies about seven acres, collapsed in two points in 1964. The larger of these collapses was about 17 feet in diameter and probably 10 to 20 feet deep; the sinks were plugged with cement, clay, and bentonite and reportedly no longer leak.

A collapse occurred in the larger cell of the lagoon system in 1966 (fig. 3). This cell contained

about 136 acre-feet of effluent at the time of collapse; all the water drained out within 52 hours. Mr. Pace, City of West Plains, reports that the collapse and leakage created a vortex of such size that he was unwilling to get close to it with a boat. This is hardly surprising; the average leakage rate for the 52 hours was 29 cubic feet per second.

The 1966 collapse at the West Plains lagoon was about 34 feet in diameter, and probably 10 to 20 feet deep. This hole was filled with clay and bentonite to the level of the dike wall and the lagoon was returned to use. Mr. Renfrow, formerly Assistant City Engineer of West Plains, reported that he walked about 4 miles of the Howell Creek channel below the lagoon collapse, but found no evidence of lagoon water. There were no reports of well contamination

Table 1

Comparison of typical sewage lagoons and impoundments proposed for the soluble rock land of Missouri.

| | LAGOONS | IMPOUNDMENTS |
|--|---|---|
| <i>Maximum area inundated</i> | <i>A few thousand sq. ft. to 50 acres</i> | <i>10 to 400 acres</i> |
| <i>Maximum depth of standing water</i> | <i>3 to 5 feet</i> | <i>15 to 80 feet</i> |
| <i>Leakage through bottom of impoundment permissible?</i> | <i>No</i> | <i>Depends on purpose; sometimes claimed as a benefit (Farmer, 1970).</i> |
| <i>Annual water level fluctuation (including groundwater levels)</i> | <i>Less than 3 feet</i> | <i>Ranges between a few feet to more than 100 feet.</i> |

in connection with either the 1964 or 1966 collapse. The water probably appeared at one of the large springs in the region. Bretz (1956, p. 322-333) in discussing Stalactite Cave 3 miles downstream of the lagoon on a tributary of Howell Creek, postulated subsurface flow from this area to Mammoth Spring, Arkansas.

We believe we have offered adequate examples to indicate that sinkhole collapse can and does occur within sewage lagoons. One effect of this collapse is pollution of groundwater supplies. Wells, springs, and surface streams ultimately received the polluted water. It should be noted that these effects may be distant

from the site of the collapse. Similar hazards will be inherent in the construction of leaky impoundments.

Sinkhole collapse induced by sewage lagoons indicates that at least in some locales there is significant instability in the alluvial and residual materials. In table 1 we have compared sewage lagoons with typical impoundments proposed for the soluble rock lands of Missouri. The four features we have compared are integrally related to the hazard of induced collapse. It is our conclusion that there will be a much greater incidence of sinkhole collapse with leaky impoundments than with sewage lagoons.

SINKHOLE COLLAPSE RELATED TO IMPOUNDMENTS

There are a number of instances in Missouri where sinks have developed after the construction of impoundments. In several cases these sinks have drained the lakes -- sometimes the impoundment would never again hold water. A sink developed beneath the wall of a Johnson City, Tennessee reservoir and caused its failure (Purdue, 1913). Sink

development beneath dams is one of the hazards inherent in soluble rock regions. If an impoundment failure occurs, greater volumes of poor quality surface water may be channeled underground for longer periods than from a collapse in a sewage lagoon floor.

DEAN W. DAVIS RESERVOIR

The Dean W. Davis Reservoir (now called the Dean W. Davis Wildlife Area) was a recreational impoundment built near Pomona, in Sec. 26, T. 26 N., R. 9 W., Howell County, Missouri (see fig. 4). The dam is in a broad, intermittent, highly permeable stream valley underlain by Roubidoux residuum.

For a short period after construction, the

impoundment held a substantial volume of water. Unfortunately, a sinkhole suddenly formed in the floor of the impoundment and drained all the water from the reservoir. Substantial efforts were made to stop the leakage, but they have failed. Personnel of the Missouri Geological Survey report seeing flows of 10 cubic feet per second disappearing underground within the impoundment area.



Figure 4

Aerial view of a portion of the planned impoundment area of the Dean W. Davis Reservoir near Pomona. The arrow indicates the dam. A catastrophic sink formed within 75 yards of the dam and totally drained the impoundment overnight. Extensive attempts to seal the impoundment were unsuccessful. Photo by Jerry D. Vineyard.

EDERER LAKE

Ederer Lake, located in Sec. 1, T. 22 N., R. 2 E., Ripley County, Missouri, developed a small sink in

1967, 3 to 4 feet in diameter and 6 feet deep which drained the impoundment. There is no bedrock

exposed in the small valley where the impoundment was constructed. The bottom of the sinkhole is on bedrock ledges of the Jefferson City formation;

solution channels are apparent in the bedrock. Transport of alluvial material through the solution channels was responsible for the formation of the sink.

DAVIS IMPOUNDMENT

A collapse similar to the Ederer Lake sink occurred in the mid-1960's in the seven-acre impoundment area of Davis Lake* in Sec. 18, T. 25 N., R. 3 W., Oregon County, Missouri. The dam was built in a shallow upland drainage underlain by Roubidoux residuum; there is no bedrock exposed in the vicinity, and the local landscape is molded by sinkholes. During major storm periods the impoundment nearly fills, but it holds water for only a few days. The

impoundment does provide a permanent pond of about one-fourth acre which extends to the edge of a small sink. Fluorescein dye injected in this sink by the U.S. Forest Service in 1970 reappeared within a week 3½ miles away at Graveyard Spring on the Eleven Point River. The area intermittently flooded by Davis Lake has received heavy cattle use in the past with the resulting effect of introducing poor quality water into the groundwater system.

NORTON DAM

A most spectacular group of collapses induced by construction of an impoundment is found at Norton Dam, 2 miles south of Winona in Sec. 30, T. 27 N., R. 3 W., Shannon County, Missouri (fig. 5). The dam was built on an intermittent stream tributary to Pike Creek. The impoundment site is underlain by deep Roubidoux residuum; there are no bedrock exposures near the impoundment site.

The dam rises about 15 feet above original stream level; excavation for borrow material within the impoundment area removed about 10 feet of residual material from the stream valley. The dam was built in 1967 or 1968.

Within the impoundment area there is evidence of one, and perhaps two, old sinks which collapsed prior to the construction of the dam. Subsequent to the construction, there have been four collapses within or near the impoundment area. The smallest

was formed about 1968, and is presently 6 feet in diameter and 3 feet deep. During the winter of 1968-1969 three additional collapses occurred in the valley. One of these is 10 feet in diameter and 6 feet deep; another is 25 feet in diameter and 15 feet deep. The largest sink of all occurred in February 1969. It is about 75 feet long, 35 feet wide, and 25 to 30 feet deep. According to Mrs. Norton, who lives about one-quarter mile from the dam, there was a noise similar to a sonic boom when the sink formed. She said the house shook, and it prompted her to call neighbors to find out if they had felt anything. The new sink was discovered the next day. Mrs. Norton is very concerned about the sinkholes, and reports that if they get any closer to the house she is going to move.

The Norton Dam has been unsuccessful in producing a permanent lake. During storm periods the impoundment will temporarily fill, but the water level falls rapidly to about the original stream

*This is not the Dean W. Davis Reservoir discussed earlier.



Figure 5

Aerial view of Norton Dam and a portion of the impoundment area. The largest of the four catastrophic sinkholes induced by this impoundment is shown above, in the left-center of the photo. The other three sinkholes lie upstream of the area pictured. Photo by Jerry D. Vineyard.

level. At the time of our visit in early April 1970 the only water in the impoundment was where material had been excavated.

We are convinced that the Norton impoundment led to the formation of the sinks. The dam has had four effects on water regimens in the valley. The first effect has been to spread flood water over the entire valley floor. The second effect, since the impoundment site leaks, is to induce recharge of groundwater from the impoundment area. This recharge tends to be localized in the more permeable areas, which in turn tends to move fine materials into underlying solution channels and voids. The third effect of the dam has been to make the residuum in

the impoundment area more plastic during and immediately after the impoundment has retarded water. Making the residuum more plastic decreases its structural strength and increases its tendency to deform. If there are voids, caves, or solution channels in or beneath the residuum, then the probability of subsidence or collapse into these cavities is increased. A fourth effect of the dam (and the temporary lake it creates) is to increase the loading on the valley fills. This could also tend to induce collapse.

The Norton Dam has provided us with an excellent opportunity to observe the relationship between changes in the valley floor water regimen and sinkhole collapse. The Norton Dam is not, however, unique in its relationship to sinkhole collapse.

TRAMWAY-LOGGING DAM

A dam was built in Shannon County, Missouri in Sec. 17, T. 26 N., R. 4 W., in a narrow intermittent stream valley underlain by Roubidoux residuum. There are no bedrock exposures in the area. The dam was built in the 1870's or 1880's to provide water for a logging settlement. The impoundment area is two or three acres; a small sinkhole formed in the floor of the impoundment shortly after construction and the impoundment has never permanently held water. Subsequent to the construction of the dam and a railroad tramway down the nearby hollow, five sinkhole collapses occurred. These will be discussed later (under the heading Tributary to Hurricane Creek) in

conjunction with sinks related to changing valley water regimens. Both the leaky impoundment and the tramway are implicated in these collapses, and it is impossible to separate their effects.

Our investigations have shown that the construction of leaky impoundments in soluble rock terrain can induce sinkhole collapse. This collapse tends to be located within the impoundment area, but may also occur remote from both the dam and the impoundment. Collapses can endanger life, the lake, the dam, and adjacent lands and structures.

SINKHOLE COLLAPSE RELATED TO CHANGING WATER REGIMENS

We have already considered the role of sewage lagoons and impoundments in triggering catastrophic sinkhole collapse. We will now consider the relationship between some of man's other activities and sinkhole collapse.

Altering the water regimens of valley fills increases the chance of sinkhole collapse within these fills. The probability of collapse increases with the magnitude of alteration of the water regimen. For example, collapses are more likely to be related to the construction of a large leaky impoundment than to a small sewage lagoon. The lake alters the water regimen more than the lagoon.

In the late 1800's there were a number of logging railways (trams) in Carter, Oregon, and Shannon Counties, Missouri. A number of the trams were constructed in the intermittent stream valleys. Typically,

fill dirt was excavated from the valley floor to build a roadbed elevated 4 or 5 feet above the general level of the valley. The excavations tended to increase infiltration into the valley fills. The elevated trams served as dikes and produced shallow groundwater spreading basins. Viewed in this light, the construction of the tramways affected valley water regimens in a manner similar to leaky impoundments.

We have visited three areas in Shannon and Oregon Counties where we believe tramways have induced sinkhole collapse. The areas are located as follows: (1) Sheep Ranch Hollow — Sec. 33, T. 26 N., R. 4 W., Oregon County; (2) tributary to Hurricane Creek — Sec. 17, T. 26 N., R. 4 W., Shannon County; and (3) Hurricane Creek — at the border of Secs. 16 and 17, T. 26 N., R. 4 W., Shannon County. We are confident that other similar areas could be found in the region, and that the features described are not unique.

SHEEP RANCH HOLLOW

The catastrophic sinkhole collapses which have occurred in Sheep Ranch Hollow (fig. 6) provide an

excellent example of tram-induced collapse. Sheep Ranch Hollow is underlain by Roubidoux residuum;

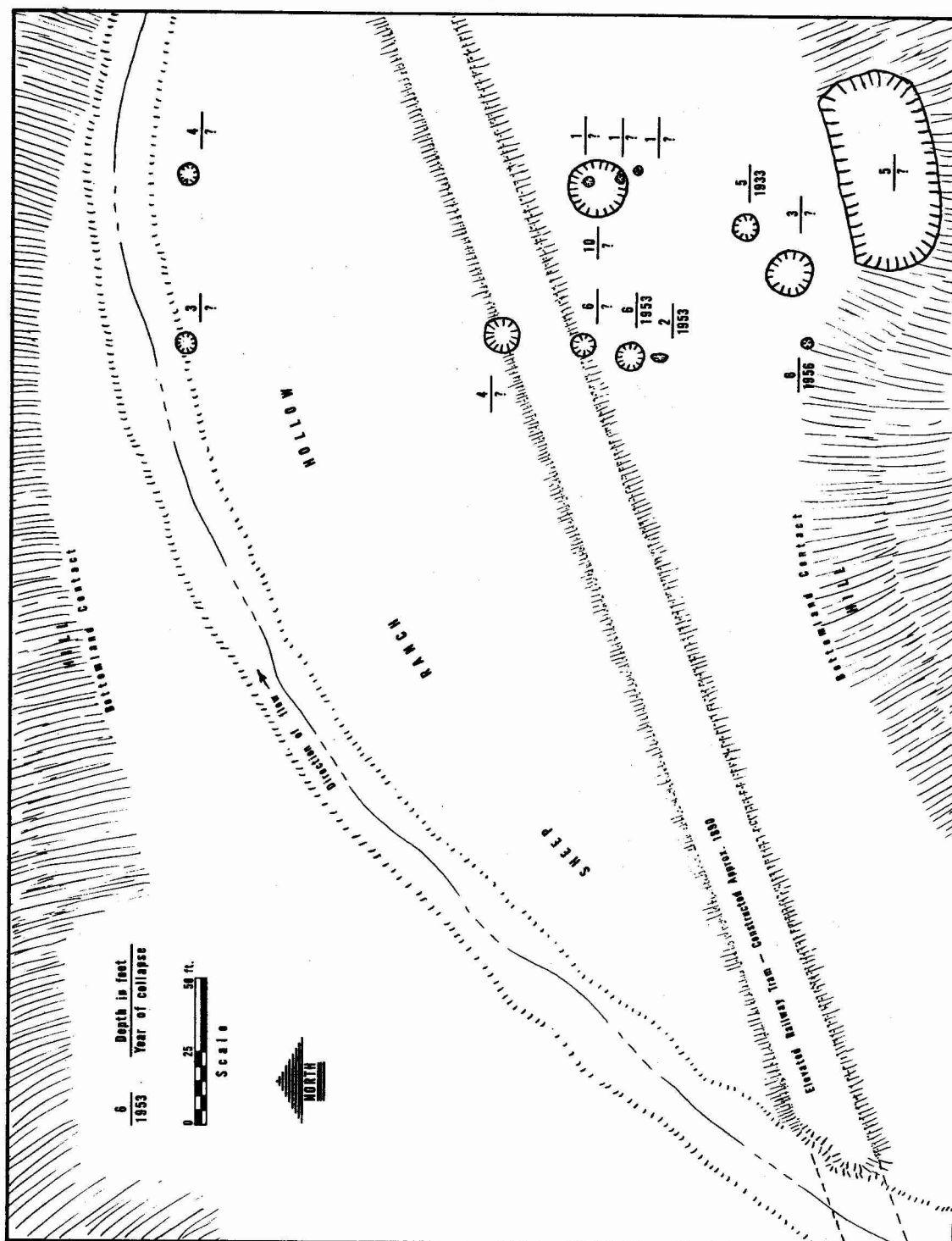


Figure 6

Sinkhole collapses in Sheep Ranch Hollow induced by construction of a logging tramway in about 1890. Sinkhole sizes were measured in January 1971. (Illustration courtesy of Mark Twain National Forest)

there are no rock outcrops in the immediate vicinity. The intermittent stream valley of Sheep Ranch Hollow averages about 200 feet wide and is relatively level.

The sinks are found in two clusters within a ten-acre area. The illustration (fig. 6) shows only the downstream cluster consisting of 13 sinks of recent origin. The upstream cluster includes five recent sinks. Not all of the sinks formed immediately after construction of the tramway. One formed in 1933, two

formed in 1953, and another formed in 1956. The sink which formed in 1933 was initially 1 foot in diameter at the surface and 12 to 15 feet deep. The sink increased in diameter with depth. The sinks which formed in 1953 were initially 18 to 20 inches in diameter at the surface and about 18 feet deep. They also increased in diameter with depth. The 1956 sink was about 1 foot in diameter and 6 feet deep. This sink was located on a woods road and was filled with a bulldozer soon after discovery. The sinks formed in 1933 and 1953 are now bowl-shaped.

TRIBUTARY TO HURRICANE CREEK

The second area of tram-induced sinks is on a tributary to Hurricane Creek in Shannon County. This group of sinks is complicated by the existence of a leaky impoundment of two or three acres built at about the same time as the tramway (1870's or 1880's); we discussed this impoundment earlier in this paper under the name Tramway-Logging Dam.

There are five sinkhole collapses which appear to have been induced by the dam and/or the tramway. One of these formed in the 1920's and two of the others appear to have formed in the 1960's. The sizes of the sinks are similar to those in Sheep Ranch Hollow.

HURRICANE CREEK

The third example of tram-induced sinkhole collapse is in the intermittent stream valley of Hurricane Creek near the border of Secs. 16 and 17, T. 26 N., R. 4 W., in Shannon County. The area is underlain by Roubidoux residuum; there are no bed-rock outcrops in the vicinity.

A railroad tramway was constructed down the valley in the 1870's or 1880's. The year after the construction of the tramway a large sinkhole collapse occurred. Initially the sinkhole was fairly deep (probably more than 15 feet). It is presently 4 to 6 feet deep and 100 feet in diameter.

For a number of years after the formation of the sinkhole it was capable of swallowing the entire flow of this major branch of Hurricane Creek draining

a surface watershed of 7.0 square miles. Our informant, Mr. Williams of Birch Tree, lived for many years on a farm downstream of the sink; he reports that there were no flooding problems at his farm for a number of years after the formation of the sink. Through time, debris and sediments have reduced the rate of water movement into this sink; an estimated flow of one cubic foot per second was entering the groundwater system through this sink during a small storm flow in the spring of 1970.

The sinks related to railroad tramways are generally small (although the Hurricane Creek sink is a notable exception). Many of the collapses occurred shortly after the construction of the trams, but some collapses are still occurring in the areas 90 years after the construction.

FARMINGTON, MISSOURI

At Farmington, St. Francois County, Missouri there have been at least 16 sinkhole collapses within the last 10 years. These collapses have apparently been triggered by changes in groundwater regimens. The sinks have formed near and under houses, schools, streets, and rest homes. One sinkhole 75 feet deep collapsed under a house in January 1967 following a heavy rain. Three hundred truckloads of rubble were required to fill the sinkhole. The homeowners lost their basement and contents (including a washing machine) into the muddy waters of the sinkhole.

The Missouri Geological Survey conducted investigations in the Farmington area and made the following recommendations:

"Homeowners can take some steps to safeguard their property. Land should be well drained. Water should not be allowed to accumulate around houses where it might saturate and weaken the soil. Provisions should be made, where possible, for quick and efficient storm-water drainage.

As mentioned previously, property owners can

test their own land at little expense by auger drilling small-diameter holes in bedrock to determine whether their homes are in safe areas over bedrock, or over clay-filled cavities in the bedrock. Tractor or truck-mounted backhoes can easily determine depth to bedrock. Persons whose house foundations rest on bedrock, of course, have no cause for alarm. If such exploration is undertaken, it would assist the study of the area by the Missouri Geological Survey if we were present during the drilling or were furnished data of the results.

City officials might well consider the adoption of ordinances requiring simple foundation investigations prior to issuing construction permits within the city, and to recommend such steps to local builders, especially in areas likely to be annexed in the future expansion of Farmington."

The above recommendations seek to maintain the water regimen of the area in as near normal condition as possible (provide adequate drainage; groundwater recharge tends to trigger collapse). Foundation investigations seem most advisable in this area, especially since groundwater regimens have been changed by man.

SINKHOLE COLLAPSE APPARENTLY UNRELATED TO MAN'S ACTIVITIES

Sinkholes are common features in soluble rock terrain, and in no case are they all related to man's activities. Some of the quadrangle maps in the Ozarks show hundreds of sinkholes, but most of

these are relatively old features. We have documented several recent sinkhole collapses which we believe are unrelated to man's activities (although in several cases there may be some relationship between sinkhole collapses and farming activities).

SYCAMORE CREEK

A sinkhole collapse occurred in the summer of 1966 adjacent to the channel of Sycamore Creek in Sec. 15, T. 27 N., R. 3 W., Shannon County, Missouri. The valley bottom of Sycamore Creek, an intermittent

stream, is about 800 feet wide where the collapse occurred. The area is underlain by residuum, and no rock outcrops are apparent in the vicinity.

The sink was visited about two weeks after it formed, and at that time it was about 25 feet in diameter, 60 feet deep, and nearly cylindrical in shape. By 1968 (fig. 8) stream gravels had nearly filled the sink; in a few years most, if not all, of the topographic expression of the sink will have disappeared.

In discussing the Sycamore sink with local residents, we have heard of other similar collapses in this valley, but have been unable to get specific information on them. Considering the speed with which the Sycamore sink is being obliterated; this is understandable.



Figure 8

Sycamore Creek Sink two years after its formation. The sinkhole has been nearly filled with sand and gravel transported by Sycamore Creek. Photo by James W. Massello.

LACLEDE COUNTY SINK

A second example of a catastrophic sinkhole collapse, apparently unrelated to man's activities, occurred in late March or early April 1964 in Sec. 21, T. 34 N., R. 16 W., Laclede County, Missouri

(Vineyard and Williams, 1964). The sink occurred in the gently rolling upland surface of the Salem Plateau; the entire depth of the sink was in Roubidoux residuum.

When the sink was first visited on April 10, 1964 it was 42 feet in diameter and 60 to 65 feet deep. The sink was cylindrical and had 10 to 15 feet

of water in the bottom (fig. 9). Vineyard and Williams (1964) suggested that the sinkhole collapse may have been triggered by the Alaskan earthquake of March 27, 1964.

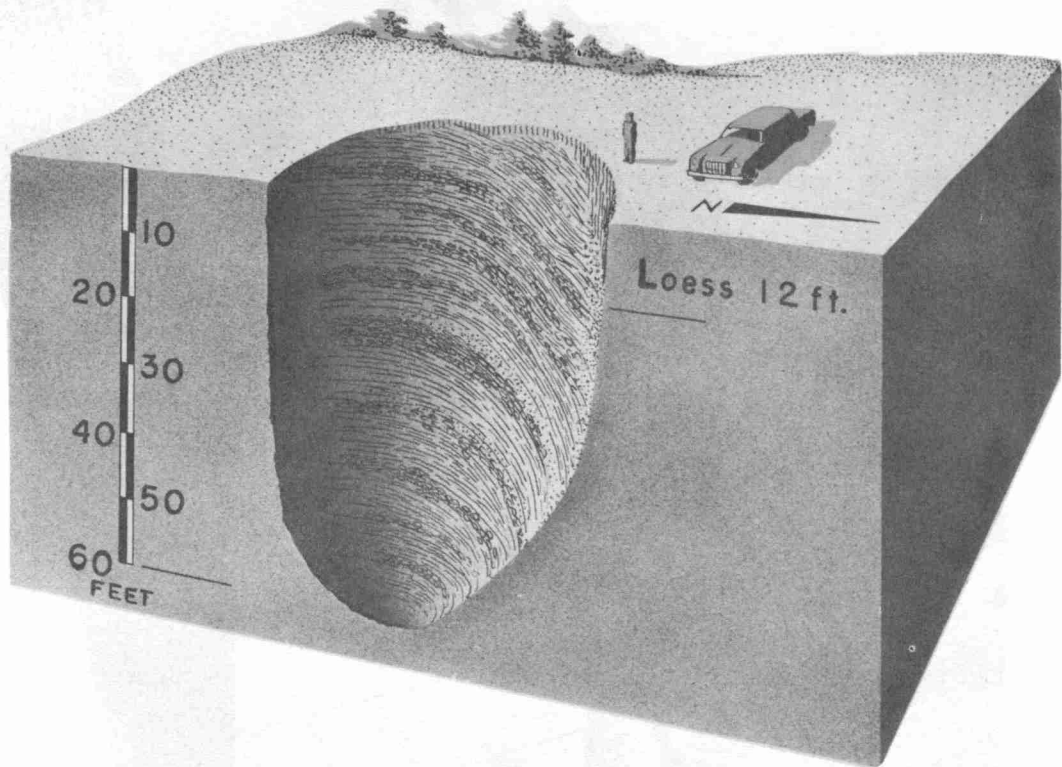


Figure 9

Block diagram of a collapse sink that formed near Lebanon, Mo. contemporaneously with the Alaskan earthquake in March 1964. Apparent bedding is in residuum of the Roubidoux Formation. Drawing by Douglas R. Stark.

RACETRACK RIDGE COLLAPSE

A third example of sinkhole collapse apparently unrelated to man's activities is the Racetrack Ridge collapse near Rueter, Taney County, Missouri, in Sec. 8, T. 22 N., R. 17 W. The sink formed in the 1960's and is about 80 feet long, 40 feet wide, and 60 feet deep. Its orientation is identical with the trend of the losing stream beneath which it has formed (fig. 10). The sink is in an area with shallow soils and numerous rock outcrops assigned to the Jefferson City-Cotter

formation; in this regard it differs from most of our other case histories, with the exception of those at Farmington. Although bedrock is exposed on the sides of the sink, there is no bedrock exposed at the ends of the sink. The senior author has explored several caves in the vicinity which also have residuum ceilings. The caves are typically narrow, vertical passages 2 to 20 feet wide and up to 60 feet high. The Racetrack Ridge sink is apparently an unroofed cave of this type.

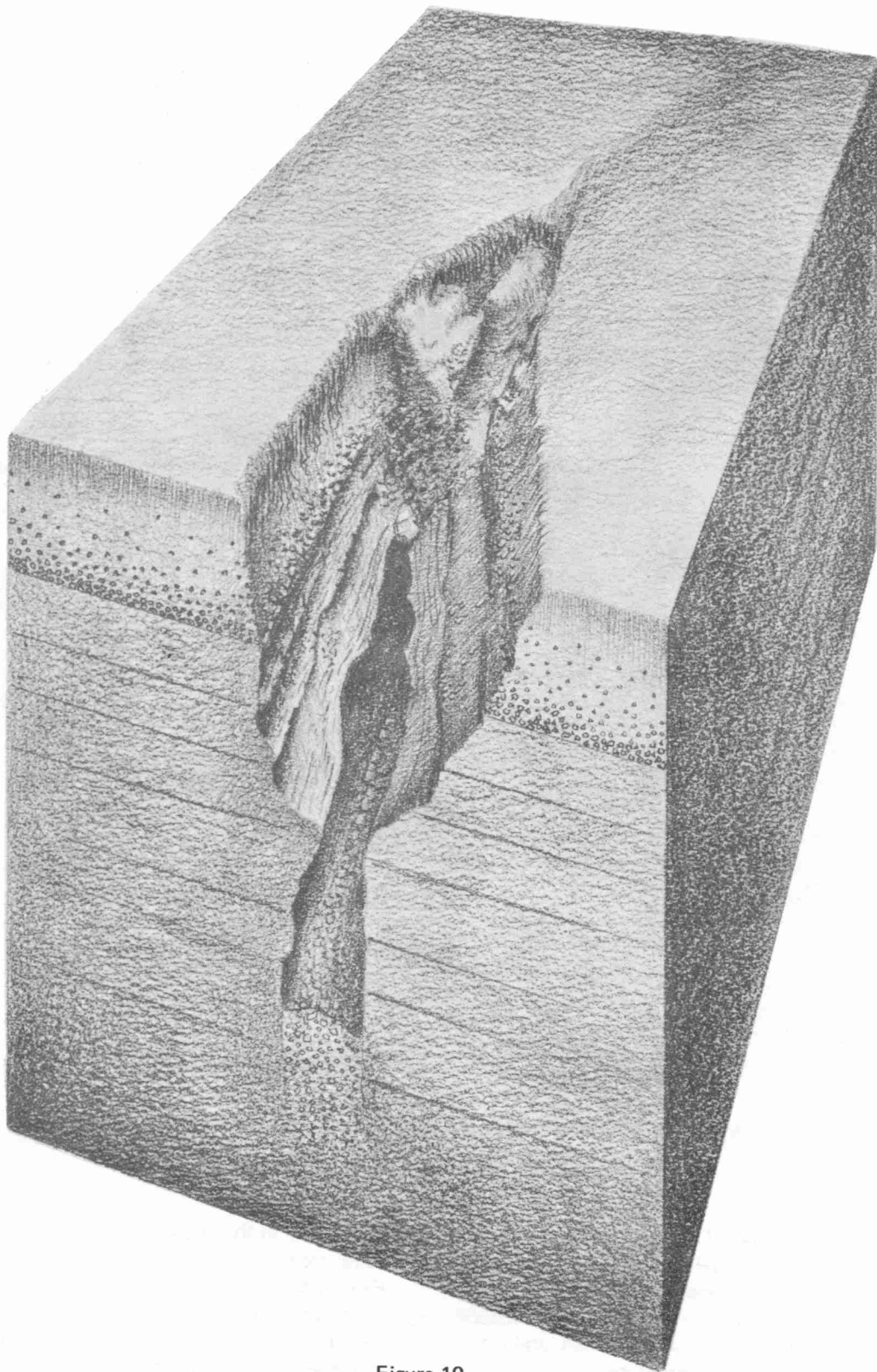


Figure 10

Racetrack Ridge collapse. This sinkhole was formed by the collapse of residuum into a solutional void in the bedrock. A portion of the original void still exists and can be entered from the bottom of the sink for about 20 feet. Drawing by Douglas R. Stark from photos by Thomas J. Aley.

SECTION 22 SINK

An unnamed sinkhole collapse occurred in the 1920's or 1930's in Sec. 22, T. 26 N., R. 4 W., Shannon County, Missouri. The sinkhole formed in a cultivated field in the valley floor

of Hurricane Creek; the area is underlain by Roubidoux residuum. When visited in 1970, the sink was about 25 feet in diameter and 10 feet deep.

SECTIONS 24 AND 25 SINKS

During the 1960's at least four small unnamed sinks have formed in Secs. 24 and 25, T. 27 N., R. 3 W., Shannon County, Missouri. All have occurred in plowed fields in the valley of Pike Creek, which in this area is entrenched into the Gasconade formation and floored by residual

and alluvial material. At least three or four sinkhole collapses occurred during or immediately after flood periods. The sinks were typically several feet in diameter and a few feet deep; all have been filled by the owner since they interfered with cultivation.

SECTION 12 SINK

Bridge (1930) reported a sinkhole collapse which occurred in 1922 in Sec. 12, T. 27 N., R. 5 W., Shannon County, Missouri. The sink occurred on the spur of a hill in an area underlain

by Roubidoux residuum. When Bridge visited the sink in 1924 he reported that it was 200 feet in diameter and about 30 feet deep; there was no bedrock exposed in the sink.

FALLING SPRING SINKS

A sinkhole collapse occurred in the spring of 1951 near Falling Spring in the valley of Hurricane Creek in Sec. 33, T. 26 N., R. 3 W., Oregon County, Missouri. The valley at this point is about $\frac{1}{4}$ mile wide and is entrenched within the upper portion of the Gasconade formation. The area is underlain by deep residuum. A test well drilled in the valley about 1 mile downstream penetrated 50 feet of the residuum without reaching bedrock.

saucer-shaped. The land was being row cropped in 1951 prior to collapse.

About one-half mile south of the Falling Spring sink is another sink (Sec. 4, T. 25 N., R. 3 W.) which occurred in the late 1950's or early 1960's. This valley bottom sink was immediately adjacent to a road and cemetery, and was filled about 1969 by dirt excavated in digging graves. In 1967 the sink was about 3 feet in diameter and 4 feet deep and provided drainage for the road and cemetery. Drainage from the roadway may have been implicated in the collapse of this small sinkhole.

When the Falling Spring sink was visited in 1970 it was 30 feet in diameter, 15 feet deep, and was

SOURCE MATERIAL FOR CASE HISTORY ANALYSIS

Numbers refer to locations shown in figure 1.

SINKHOLE COLLAPSE RELATED TO SEWAGE LAGOONS

1. **Republic Sewage Lagoon** — Report by J.H. Williams of the Missouri Geological Survey and Water Resources, November 1, 1968.
2. **West Plains Sewage Lagoon** — Discussion with John T. Renfrow and Leon Pace, West Plains. Field investigation by Massello.

SINKHOLE COLLAPSE RELATED TO IMPOUNDMENTS

3. **Dean W. Davis Reservoir** — Local reports. Field observations by Williams and Aley.
4. **Ederer Lake** — Report by James H. Williams of the Missouri Geological Survey, dated September 23, 1967.
5. **Davis Impoundment** — Discussion with landowner Bus Davis. Field investigation by Aley.
6. **Norton Dam** — Discussion with Mrs. Norton. Field investigation by Aley.
7. **Tramway-Logging Dam** — In Sec. 17, T. 26 N., R. 4 W. — Historical information from Jim Williams and Everett Chaney of Birch Tree, Missouri. Field investigation by Aley and Chaney.

SINKHOLE COLLAPSE RELATED TO CHANGING WATER REGIMENS

8. **Sheep Ranch Hollow** — Historical information from Everett Chaney. Field investigation by Aley and Chaney.
9. **Tributary to Hurricane Creek** — Historical information from Jim Williams and Everett Chaney of Birch Tree, Missouri. Field investigation by Aley and Chaney.
10. **Hurricane Creek** — Historical information from Jim Williams and Everett Chaney of Birch Tree, Missouri. Field investigation by Aley and Chaney.
11. **Darr Valley Sink** — Field investigation by Williams.

12. **Buckhorn Collapse** — Field investigation by Jerry D. Vineyard and Williams.
13. **Farmington, Missouri** — Report dated January 17, 1968 by W.C. Hayes, Jerry D. Vineyard, and James H. Williams, all of Missouri Geological Survey.

SINKHOLE COLLAPSE APPARENTLY UNRELATED TO MAN'S ACTIVITIES

14. **Sycamore Creek Sink** — Field investigations by Aley.
15. **Laclede County Sink** — Vineyard and Williams (1964).
16. **Racetrack Ridge Collapse** — Field investigations by Aley and Massello.
17. **Section 22 Sink** — (Sec. 22, T. 26 N., R. 4 W.) — Local report and field investigation by Aley.
18. **Sections 24 and 25 Sinks** — (Sec. 24 and 25, T. 27 N., R. 3 W.) — Interview by Aley with Ray Tucker, owner of land.
19. **Section 12 Sink** — (Sec. 12, T. 27 N., R. 5 W.) — Bridge (1930).
20. **Falling Spring Sinks** — Discussion with Bus Davis and Lewis Mack, Winona, Missouri. Field investigation by Aley.

CONCLUSION

While our investigations have centered on problems of collapse and groundwater contamination in soluble rock terrain, it is not our intent to conclude that man must not intrude onto this landscape. Rather, it is our purpose to emphasize the importance of a thorough hydrogeologic evaluation of soluble rock watersheds prior to the development of a project which could adversely affect land surface stability and groundwater quality.

If water impoundments are being considered, either for recreation or other purposes, investigations must extend beyond the immediate site. Diagnostic characteristics of areas subject to catastrophic sinkhole collapse and groundwater contamination include:

- a. surface streams which lose water
- b. valley geometry showing soluble rock effects
- c. a lack of stream terrace development
- d. poorly graded alluvium
- e. an absence of persistent sound bedrock
- f. relatively low but graded water levels
- g. a general regional landscape modification such as fewer valleys and subdued topographic features.

Where the above features exist, thorough hydrogeologic investigations are essential. The case histories presented in this paper give abundant evidence of the effects of impoundments where the hydrogeology of soluble rock lands is not adequately considered.

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COVER: The largest of four catastrophic sinkholes caused by Norton Dam is shown on the left of the cover illustration. Three other sinkholes lie upstream. Drawing by Douglas R. Stark.

