DISCRIMINATION BETWEEN FLOW-THROUGH AND PULSE-THROUGH COMPONENTS OF AN ALPINE CARBONATE AQUIFER, SALT RIVER RANGE, WYOMING

M. Blanchard, J. Drever, and P. Huntoon

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Mark R. Blanchard
James I. Drever
and
Peter W. Huntoon
Department of Geology and Geophysics
University of Wyoming
Laramie, Wyoming

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ABSTRACT

Water chemistry and temperature fluctuations in the discharge of Periodic Spring indicate the existence of a karstic conduit system in the Madison Limestone that is not apparent from field observations in the Salt River Range. Contamination in the recharge area of Periodic Spring would pose both immediate and long term problems for the Afton, Wyoming water supply.

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INTRODUCTION

PURPOSE

Hydraulic loading of a carbonate spring's recharge area produces two effects. First, the energy pulse of the recharge event will pass through the system. Second, the recharge water itself eventually will pass through the system to discharge at the spring.

Flow-through is defined as the coincident passage of recharge water with the energy pulse caused by the recharge event. This is essentially what is often referred to as "plug" or "piston" flow (Huntoon, Pers. Comm., 1989).

Pulse-through is defined as the disjuncted passage of the energy pulse from the passage of the actual water. Spring discharge caused by the energy of the recharge event is old water derived from storage rather than the recharge water itself (Huntoon, Pers. Comm., 1989).

Figure 1 shows these concepts schematically. These terms have been used by Huntoon (Pers. Comm., 1989), but have never been fully developed through application to a

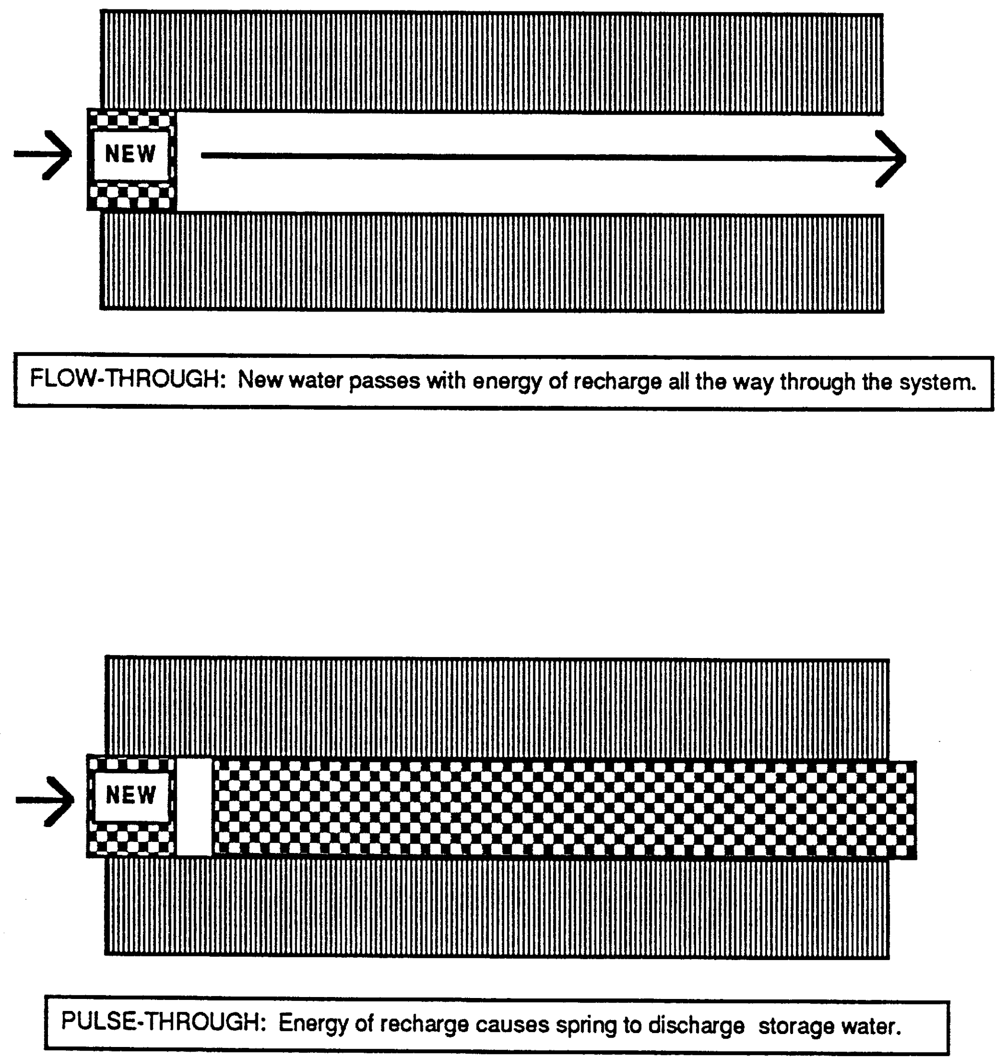


Fig.1. Schematic representation of pulse-through and flow-through. Flow-through water moves through system coincident with the energy caused by hydraulic loading in the recharge area. Pulse-through water lags the energy movement. These two concepts represent endmembers of the type of flow that may actually occur in a carbonate aquifer.

specific system. Note that they are endmembers of the process of water movement through a carbonate system. Real systems will likely fall in between.

Periodic Spring is located in the Salt River Range on the south side of Swift Creek 4 miles (6.4 km) east-northeast of Afton, Wyoming (Fig.2). It discharges from a cave in the upper Madison Limestone 200 feet (61 m) above and 500 feet (150 m) back from Swift Creek. Periodic Spring is ideal for developing the pulse-through/flow-through concepts because (1) it is fed by a carbonate aquifer, (2) it varies from low flows of 5 cubic feet per second (cfs) to high flows of up to 100 cfs (0.14 to 2.8 m^3/s) (Huntoon and Coogan, 1987), and (3) it discharges from a cave, yet the extent of karstic development in the range is unknown. It thus holds potential for either pulse-through or flow-through. Furthermore, an improved understanding of Periodic Spring is important to the city of Afton, Wyoming, because the untreated spring water is the town's water supply.

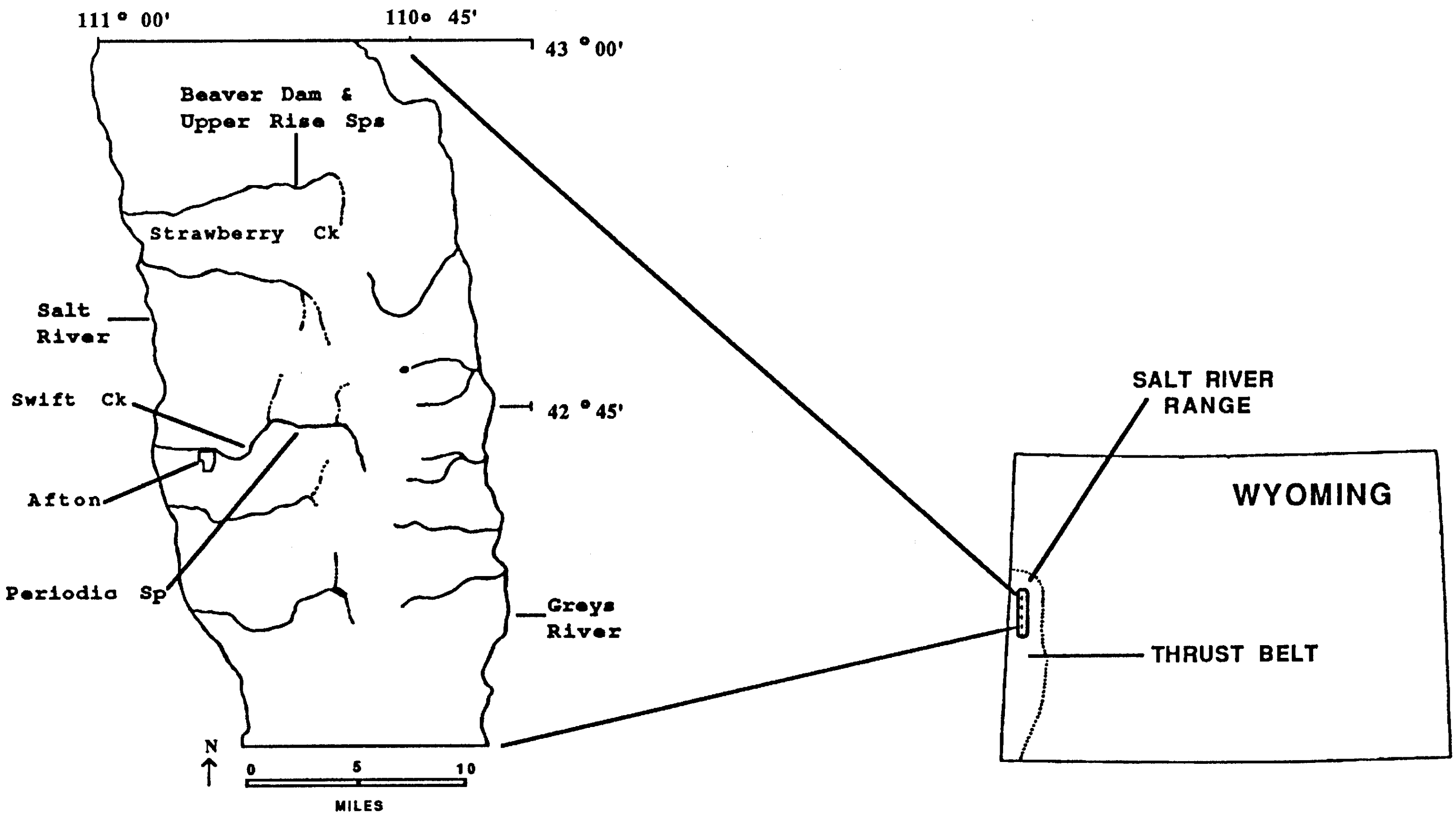


Fig. 2. Location map showing Salt River Range area near the Idaho/Wyoming border.

The objectives of this study are to

1. develop a technique to discriminate between pulse-through and flow-through discharge by the analysis of seasonal variations in major ion chemistry and temperature;
2. determine from spring water chemistry and temperature data whether or not Periodic Spring is fed by a karstic flow system;
3. define the recharge area of Periodic Spring; and
4. assess the potential impact of contamination in the recharge area of Periodic Spring through an understanding of the flow system in terms of the flow-through and pulse-through concepts.

SETTING

The study area is located in the Bridger-Teton National Forest in the Salt River Range (Fig. 2). The range is oriented north-south and is bound by the Greys River Valley to the east and Star Valley to the west. These valleys range in elevation from 6200 to 7000 feet (1890-2130 m), while the crest of the range reaches 10,000 to 11,000 feet (3050-3350 m).

The range is bound by the Absaroka Thrust to the east and the Star Valley Normal Fault to the west

(Fig. 3). Steeply dipping units and tight folds characterize the structural geology. Geologic maps of the area have been produced by Rubey (1973) and Oriel and Platt (1980). Figure 4 is a portion of a cross section developed by Huntoon and Coogan (1987) Periodic Spring is located in the nearly vertical, east-dipping limb of Periodic Anticline, which is the west limb of Mill Hollow Syncline.

PREVIOUS WORK

Although numerous hydrologic studies have been conducted in neighboring Star Valley, little hydrologic work has been conducted in the Salt River Range. Rubey (1972) made numerous measurements while mapping in the range, and with the aid of Shreve, developed a model to explain the oscillating flow of Periodic Spring. This siphon model was first published by Huntoon and Coogan (1987) after they discovered it in the University of Wyoming American Heritage Center collection.

Using Rubey and Shreve's model as a basis, Huntoon and Coogan (1987) developed a preliminary description of Periodic Spring and the Madison aquifer, which feeds the spring. They identified the east side of the topographic divide of the range as the probable recharge area for

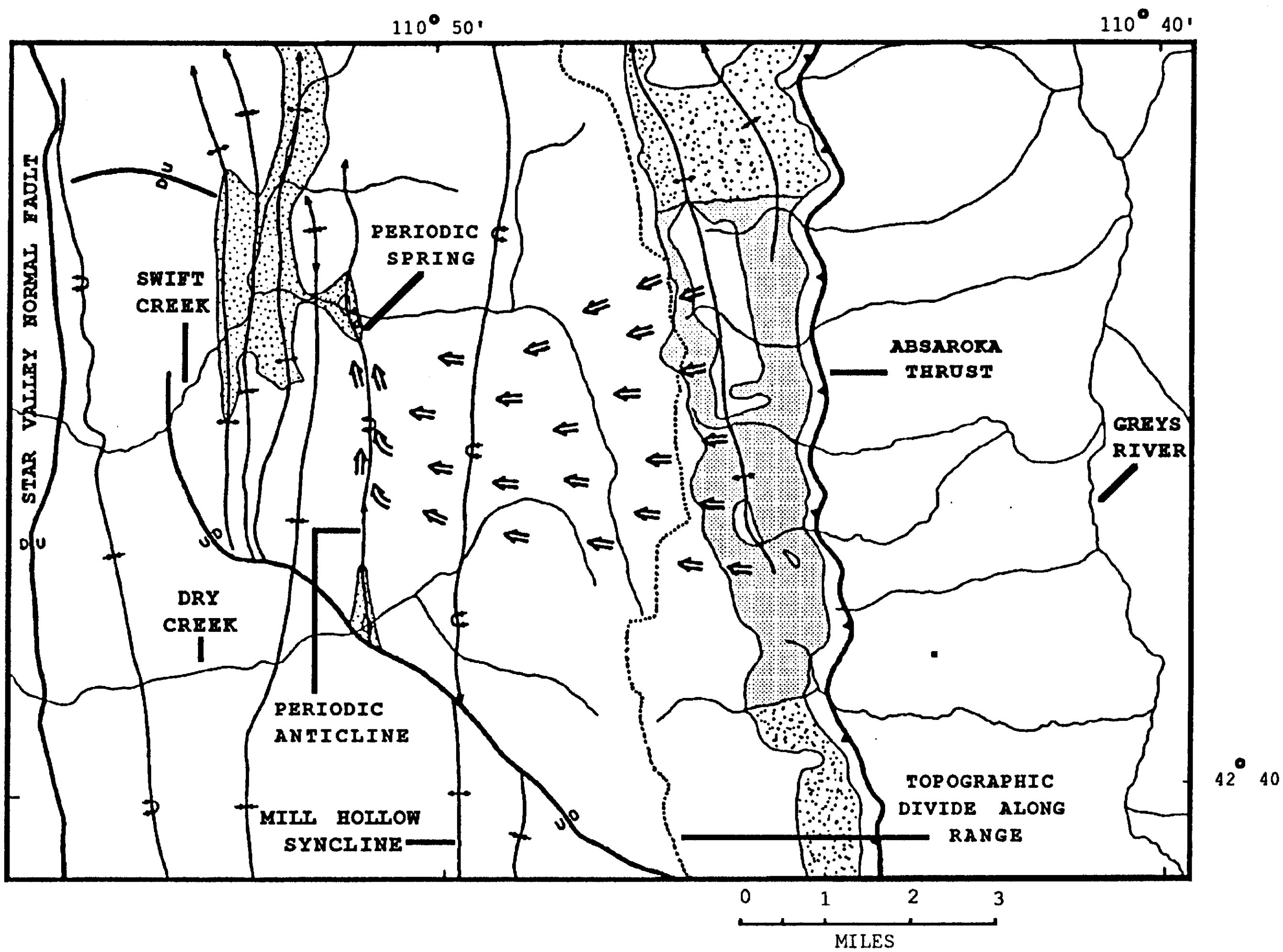


Fig. 3. Map showing Salt River Range in the vicinity of Periodic Spring. Stipling indicates Madison Limestone outcrop - fine stipling is the recharge area for Periodic Spring. See Fig. 4 for cross section. Modified from Huntoon and Coogan (1987).

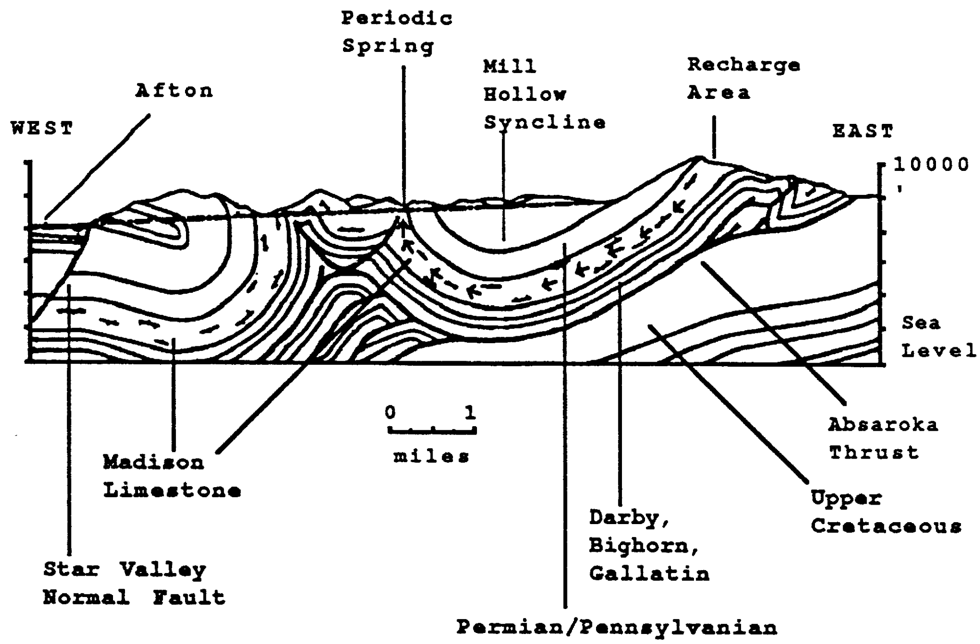


Fig. 4. Portion of a cross section through the overthrust belt developed by Huntoon and Coogan (1987). Arrows denote the flow of water from the eastern topographic high of the range westward through Mill Hollow Syncline to Periodic Spring.

Periodic Spring, and speculated that the age of the discharge water is on the order of decades to centuries. They also speculated that the cave from which the spring discharges may indicate karstic development in the Madison Limestone.

The two springs that are contrasted with Periodic Spring in this study are located in the upper reach of Strawberry Creek (Fig. 2). Over the past two years Erickson (Unpub. data) has been working in this area as part of his Master's Thesis project. He has found that, unlike Periodic Spring, none of the springs along Strawberry Creek discharges directly from the Madison, rather the water must flow through valley floor colluvium before reaching the surface. He defined the recharge area for these springs and estimated that water requires more than one year to pass through the system.

METHODOLOGY

<u>STRATEGY</u>. The basis of the sampling program was to frequently sample between spring and fall in order to capture a record of seasonal changes in water chemistry and temperature. Water samples were collected in the field and then brought back to the laboratory to be analyzed before the next sampling trip.

FIELD-METHODS. All water samples were filtered in the field with a 0.45 micron membrane filter and collected in acid-washed polyethylene bottles. The water collected was separated during the filtering process into two bottles - one for cation analyses and one for anion analyses. Water in the cation bottle was adjusted to pH 3 with Ultrex™ nitric acid to prevent precipitation of calcite. The anion bottle was untreated. All bottles were stored in an ice chest to minimize temperature changes.

Temperature was measured as close as possible to spring orifices. pH was measured in the field for roughly a quarter of the samples and in the laboratory for all samples. Agreement between field and lab pH values justified using lab pH values in calculations.

Aliquots for tritium, deuterium, and oxygen-18 analyses were placed in glass bottles and sealed with wax to prevent exchange with the atmosphere.

Spring discharge was calculated by multiplying the cross-sectional area by the flow velocity.

LABORATORY METHODS. Alkalinity, reported as bicarbonate, was measured by titration. Cl^-, NO_3^-, PO_4^{3-}, and SO_4^{2-}, were analyzed by ion chromatography. Ca^{2+} and Mg^{2+} were determined by flame atomic absorption (AA) spectrophotometry. In 1989 K^+ and Na^+ were determined by chromatography, but in 1990 they were determined by flame AA. Silica was determined by a blue silicomolybdate colorimetric method.

The above analyses were performed in the University of Wyoming rock-water chemistry laboratory. Tritium, deuterium, and oxygen-18 were determined by Geochron Laboratories, Cambridge, Massachusetts.

CHAPTER II

HYDROLOGIC SETTING

SPRINGS STUDIED

The locations of Periodic Spring, Beaver Dam Spring, and Strawberry Creek Upper Rise Spring (referred to hereafter as Upper Rise Spring) are shown in Fig. 5. The focus of this study is Periodic Spring. The other two springs studied were selected because of their contrast to Periodic Spring in terms of discharge and location.

Figure 6 shows two photographs of Periodic Spring taken 20 minutes apart. Note that the spring is "off," or has zero discharge, in the first photo, but is discharging approximately 90 cfs (2.5 m^3/s) in the second photo. During the fall, winter, and early spring discharge during the on cycle fluctuates between zero flow and 5-10 cfs (0.14-2.8 m^3/s). This flow pattern was previously described by Rubey (1972). A schematic drawing of the siphon model developed by Rubey and Shreve (Huntoon and Coogan, 1987) is shown in figure 7. In this model the lower part of the spring's reservoir is always filled. Once the reservoir fills to the level of the

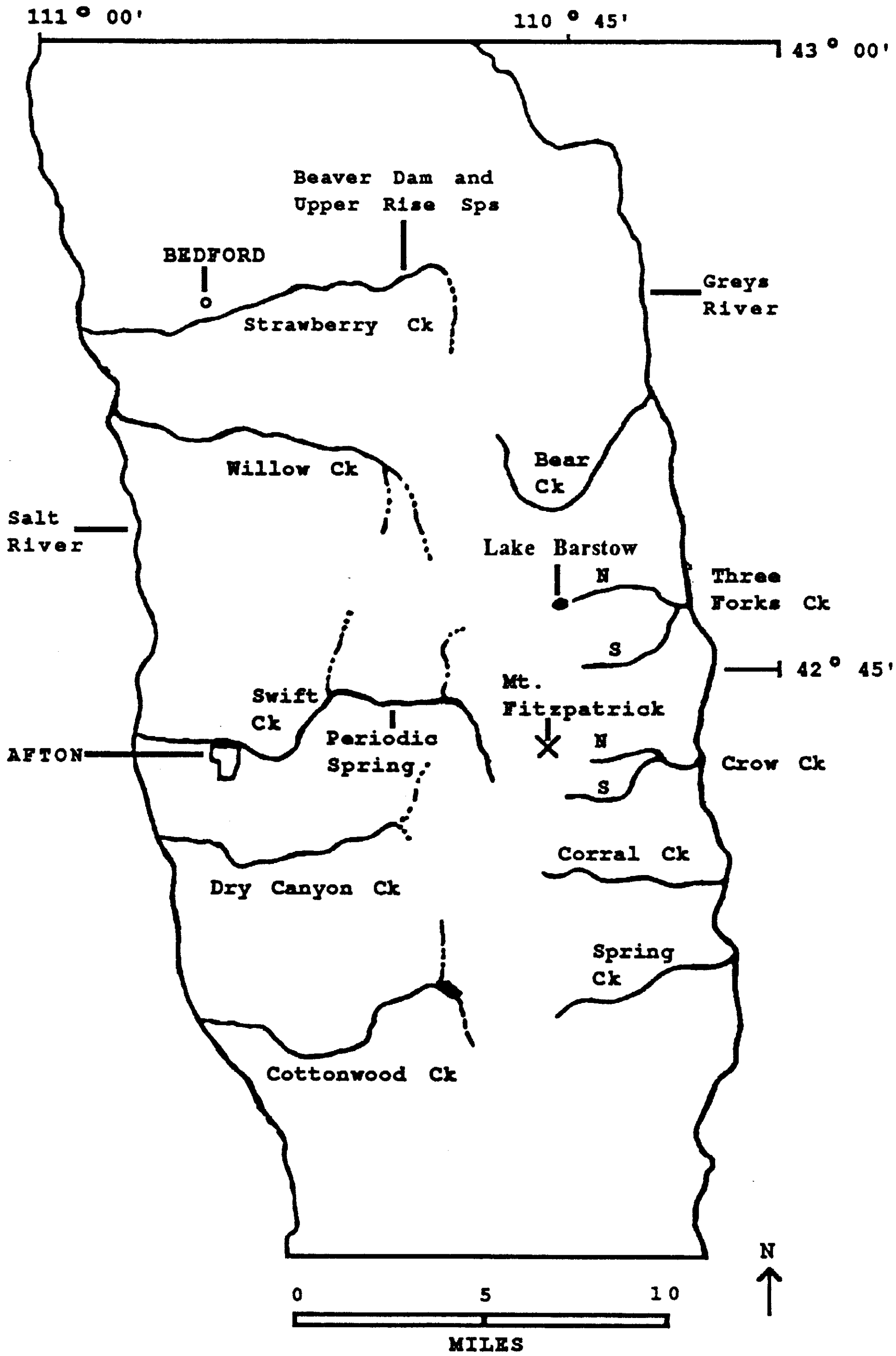


Fig. 5: Map showing Salt River Range area. Periodic Spring feeds the Afton, Wyoming water supply. Beaver Dam and Upper Rise Springs feed the reservoir used by Bedford, Wyoming.

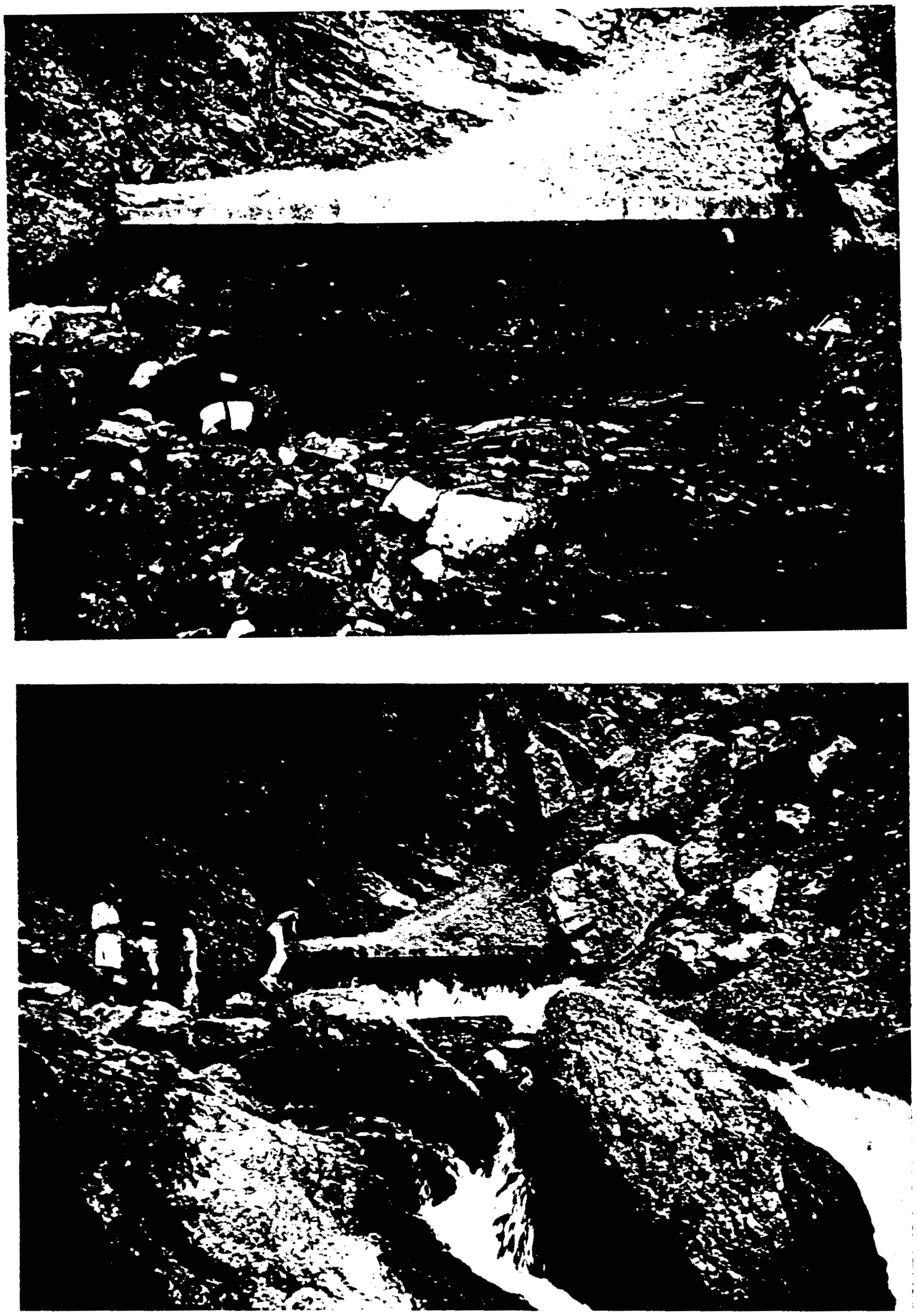


Fig. 6. Photographs of Periodic Spring showing "off" (upper) and "on" (lower) stages. The pipe that feeds the Afton, Wyoming water supply is visible in the upper photograph.

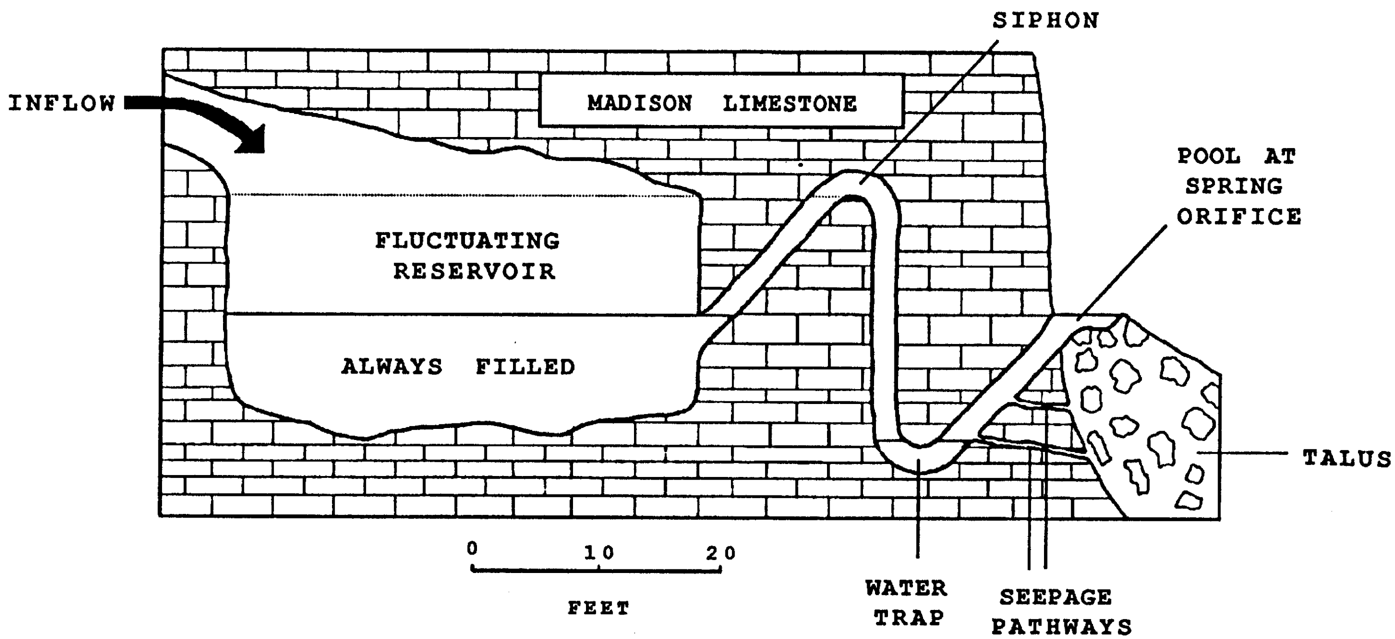


Fig. 7: Siphon model of Periodic Spring reservoir. When the reservoir water level reaches the siphon level flow commences. Flow continues until the reservoir level drops to base level. Modified from Huntoon and Coogan (1987).

siphon the spring flows, emptying the reservoir to the low stage again. The discharge cave is about 12 feet (3.7 m) deep and 5 feet (1.5 m) across. Beyond 12 feet it is filled with talus.

From late May to late August Periodic Spring flows continuously, indicating rapid filling of the reservoir. Based on his 1933 measurements, Rubey (1972) estimated the volume of the fluctuating reservoir to be 14,000 cubic feet (400 m^3). During low flow times when the spring cycles on and off, it flows for approximately 20 minutes and then is dry for roughly the same amount of time. Given 20 minutes to fill the 14,000 cubic foot volume the flow rate into the reservoir would have to be 12 cfs (0.34 m^3/s).

Storage within the Madison allows Periodic Spring to flow year-round. The lowest average flow rate has been measured at about 5 cfs (0.14 m^3/s) (Community Consultants, 1980). Assuming flow fifty percent of the time, this represents 216,000 cubic feet per day (6120 m^3/day). The total discharge between October and April, roughly 180 days, is on the order of 3.9 million cubic feet (110,000 m^3). This represents a low estimate of storage because the spring does not dry up before the next year's snowmelt reloads the system.

Beaver Dam Spring and Upper Rise Spring are located in the upper reach of Strawberry Creek 6 miles (9.7 km) east of Bedford, Wyoming (Fig. 5). Beaver Dam Spring discharges up to 1 cfs (0.028 m^3/s) along the bank of a beaver pond north of Strawberry Creek. Upper Rise Spring discharges 1 - 2 cfs (0.028 - 0.056 m^3/s) along the northern bank of Strawberry Creek. Except during peak snowmelt runoff time, Strawberry Creek is dry above Upper Rise Spring.

Beaver Dam and Upper Rise springs are typical of the many small springs along the reach of Strawberry Creek overlying the Madison Limestone in that water must flow from the Madison through overlying valley colluvium before reaching the surface(Erickson, Unpub. data). Unlike springs located higher up the valley, they do not dry up.

Two field observations demonstrate that the Madison contributes significantly to Strawberry Creek. First, when the upper reaches of Strawberry Creek are dry, below the Madison reach the creek flows 10 to 20 cfs (0.28 - 0.56 m^3/s). Similarly, when the upper reaches are flowing, the flow increases by a factor of 2 to 4 across this reach. Second, during the creek's peak flow during summer 1990, streamwater above the Madison reach was 52° C, while below the Madison reach the water was 42° C.

HYDROSTRATIGRAPHY

Figure 8 is a stratigraphic column developed from data compiled by Erickson (Unpub. data). Note that the units of the lower sections are thinly bedded whereas those of the upper section are thickly bedded limestones. The top of the Madison is a brecciated paleokarst. In addition to the limestones, the Madison contains dolomites, dolomitic limestones, and some shales (Sando 1977). The Madison aquifer is confined above by the Amsden Formation. Erickson (Unpub. data) lumped the underlying Bighorn, Darby, and Gallatin formations in with the Madison aquifer because the Gros Ventre shale is the best confining layer underlying the Madison.

Erickson (Unpub. data) identified bedding and fractures as important flow paths. A small hollow in the Madison Limestone is located 80 feet (24 m) up on the south side of Swift Creek directly across from the North Fork of Swift Creek. It is approximately 15 feet (4.6 m) deep, 10 feet (3 m) across, and up to 10 feet (3 m) high. Seepage from both bedding and fractures was observed, substantiating Erickson's observations in the northern

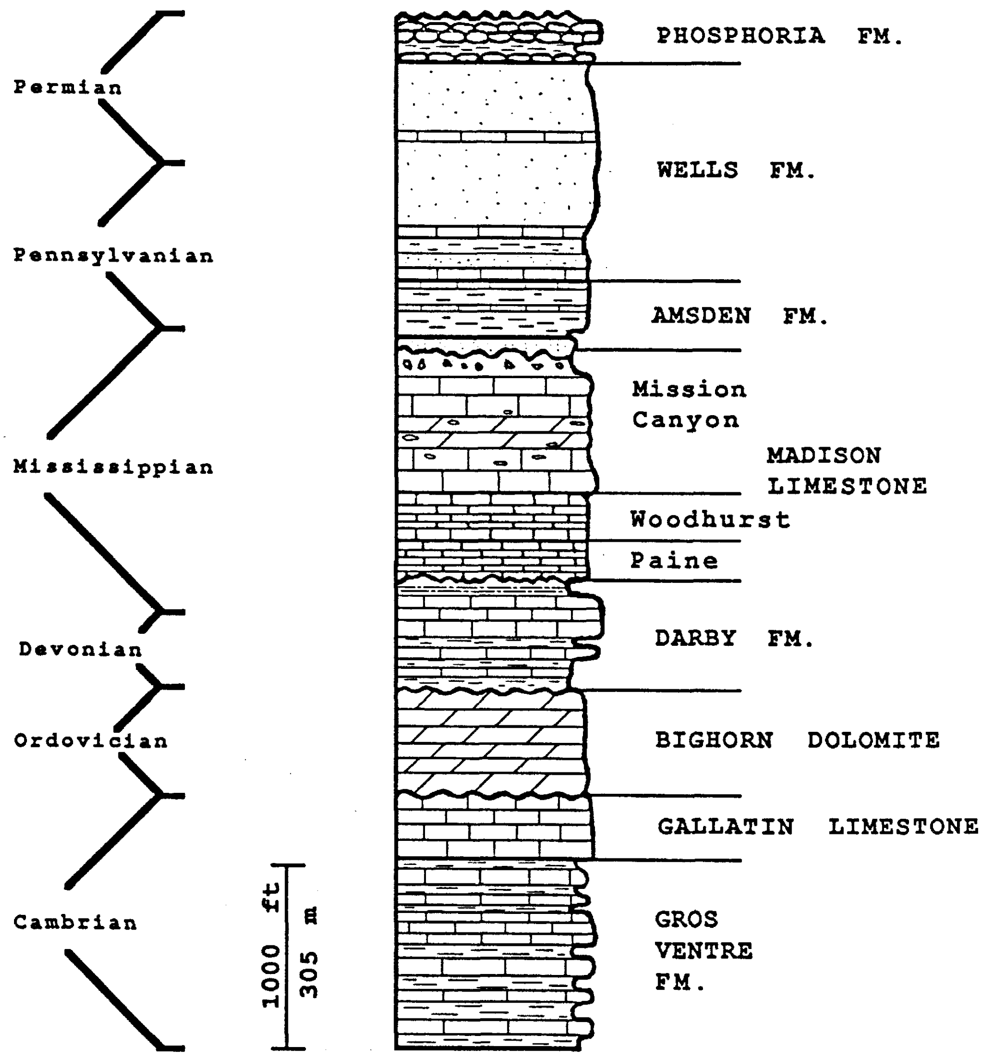


Fig. 8. Stratigraphic column of Paleozoic rocks in the Salt River Range, Wyoming. The Madison is composed of limestone, dolomitic limestone, and dolomite. Erickson (Unpub. data) includes the Gallatin, Bighorn, and Darby in the Madison Aquifer. After Erickson (Unpub. data).

part of the range. The fact that Periodic Spring discharges from a cave raises the question as to whether or not flow may also occur in a cave system in the Madison.

During the middle to late Mississippian the Madison Limestone was karstified (Sando, 1974; Sando et al., 1975). The brecciated zone that developed from this karst may be observed at the top of the Madison in the Salt River Range. The reddish material is the lower member of the Amsden Formation, the Darwin Sandstone, which filled in the paleokarst. Throughout the range springs are not preferentially located in this zone of the Madison, indicating that this paleokarst is not important hydrologically.

There is no surface evidence for a well-developed modern karst in the Salt River Range. Small dolines were observed, but, other than Periodic Spring cave, no caves were found. The lack of extensive karst development is caused by the fact that (1) the cirques that catch and retain snow in the recharge area have existed only since the last glaciation, and (2) much of the Madison Limestone is confined. The lack of surface evidence for karst places the Madison under the classification of a Merokarst (Milanovic, 1981).

RECHARGE

Spring snowmelt during May and June is the main yearly recharge to the Madison aquifer. Climate data from Martner (1986) and the Wyoming Water Resources Data System indicate that evapotranspiration balances precipitation during the summer and fall. The loading of hydraulic head in the recharge area causes spring discharge to increase in the summer. The peak in the discharge of Periodic Spring in middle June to early July observed in both 1989 and 1990 is reflected by Wyoming Water Resources Data System stream gauging data from a downstream station on Swift Creek. At the same time, snowmelt recharge must also account for the replenishment of stored water in the aquifer.

Huntoon and Coogan (1987) identified the cirques along the backbone of the range as the recharge area for Periodic Spring because of their high elevation and snow retention capacity, stratigraphic continuity between the cirques and Periodic Spring, and the parallel orientation of bedding with the hydraulic gradient. Figure 9 is a photograph of one of these cirques which is located in the recharge area of Periodic Spring on the north side of Mt. Fitzpatrick. Note the clear drops in level of the

Fig. 9. Photograph of the cirque located in the recharge area of Periodic Spring on the north side of Mt. Fitzpatrick, Salt River Range, Wyoming. Tarns drain internally to recharge Madison Limestone.

several small lakes in this particular cirque. Except during the initial rush of snowmelt, these tarns drain internally. Corral Creek Lake, which is 2.5 miles (4 km) south of Mt. Fitspatrick, is another good example. The lake was full on September 19, 1989, but was nearly empty on July 1, 1990. The snow along the edges of the cirque had not all melted by July 1st, 1990. Thus the slow drainage of at least some of these lakes provides sustained recharge to the system.

The recharge area for Periodic Spring is shown in figure 3. The south boundary to this area was placed at Corral Creek because the creek crosses the Madison, thus providing a potentiometric low. Furthermore, Dry Creek, which parallels Swift Creek 4 miles (6.4 km) to the south and is across the range from Corral Creek, also intersects the Madison. The northern boundary is more difficult to pinpoint. It is probably in the area of poor cirque development between the cirque just north of Mt. Fitzpatrick and Barstow Lake. Besides the fact that the lack of cirques would inhibit infiltration, water flowing from the north would have to flow under Swift Creek and then upward in order to reach Periodic Spring. Observations at Swift Creek do not support this. Along the northern side of Swift between Periodic Spring and the North Fork, small springs and seeps occur at bank level, indicating that the Madison Limestone is saturated on the north side of Swift Creek and that the creek is a potentiometric low.

The recharge area for the Madison springs along Strawberry Creek has been identified by Erickson (Unpub. data). Again, snow collects in cirques and upon melting infiltrates the Madison.

FLOW DIRECTION

Water in the cirques in the recharge area infiltrates the Madison and moves through the Mill Hollow Syncline to Periodic Spring (Fig. 4). Huntoon and Coogan (1987) identified the enhanced permeability along the axis of Periodic Anticline as a probable flow path once water has moved through the syncline. This enables the spring to tap an extensive recharge area.

The greater portion of recharge flows in the direction of Periodic Spring because water can flow along bedding, whereas it must flow perpendicular to bedding to reach Crow Creek, the discharge area opposite Periodic Spring on the east side of the range. This is supported by the field observation that the discharge from the

Madison reach of Crow Creek reaches only 2 to 4 cfs (0.056 - 0.113 m^3/s) during the summertime peak flow.

Hydraulic gradient from, not proximity to, the recharge area controls flow. This is important in realizing that the proximity of springs east of the cirques to the recharge area does not make them preferential to Periodic Spring as discharge points. The critical test is a comparison of the hydraulic gradients from the cirque on the south side of Mt. Fitzpatrick to either Periodic Spring or the springs of the Madison reach of Crow Creek (Figs. 3 & 5). This large cirque captures a large amount of snow and lies on the line between Periodic Spring and Crow Creek.

The elevation of the cirque ranges 9400 to 9800 feet (2870-2990 m). Periodic Spring is 4 miles (6.4 km) away at 7200 feet (2190 m) elevation. The Madison reach of Crow Creek is 1.8 miles (2.9 km) away at 8500 feet (2590 m) elevation. This gives a gradient range of 550 to 650 feet/mile (110-125 m/km) for Periodic Spring and 500 to 720 feet/mile (97-140 m/km) for Crow Creek. These gradients are essentially the same given the approximations in the calculations.

CHAPTER III

PULSE-THROUGH VERSUS FLOW-THROUGH

PARAMETERS USED TO DISTINGUISH FLOW-THROUGH AND PULSE-THROUGH EVENTS

In a well developed karst system dye-tracing tests can be performed to determine the time it takes for water to pass from the recharge area to the discharge point. This is not the case in the Salt River Range because there are no sinkholes in which to place dye. Natural tracers are the only recourse. Major ions, temperature, tritium, deuterium, and oxygen-18 were the parameters chosen for this study.

The chemistry and temperature of flow-through water differs from water derived from storage because rapid flow prevents the recharge water from reacting much with the aquifer wall rock. This variation appears in the discharge coincidentally with the discharge peak.

In contrast, in a pulse-through system, the peak discharge caused by the energy of a recharge event is water derived from storage. Thus the temperature and chemistry of the water of the peak discharge will not differ from that of the discharge prior to the peak.

In general, pulse-through water is closer to saturation with respect to the mineral phases in the aquifer than flow-through water because it is in contact with the aquifer for a longer time. Following the same reasoning, the temperature of pulse-through water will be closer to the temperature of the aquifer than that of flow-through water. Note however, that variations in chemistry and temperature are possible in a pulse-through system, but that they will occur subsequent to the peak discharge.

Therefore two factors are important. First, are there variations over time in the chemistry and temperature of the spring discharge? Second, do these variations coincide with the peak discharge?

RESULTS

Periodic Spring was sampled 7 times between mid-May and late September 1989 and 17 times between late April and late September 1990. Several dates involved duplicate and triplicate sampling to evaluate analytical accuracy. Data are reported in Appendix A.

Figure 10 shows composition diagrams (Mazor, 1990a) of Periodic Spring water from summer 1989 and summer 1990. The concentration of total dissolved ions was slightly lower in the 1989 waters because 1989 was a higher water flow year than 1990. The linear positive correlation observed is interpreted as a mixing line between snowmelt and more concentrated storage water because the low concentration samples are midsummer samples taken during increased discharge caused by snowmelt loading of the recharge area. Furthermore, evolution of the water is not a likely explanation because (1) the trend is a seasonal pattern observed in both 1989 and 1990, and (2) all the waters are traveling through the same material.

The mixing pattern is clearest in the plots of calcium, magnesium, and alkalinity, indicating the water chemistry is controlled by the carbonate system - a logical explanation considering the Madison is a carbonate aquifer. Sulfate shows a similar, but more scattered, pattern.

Figure 11 shows fingerprint diagrams (Mazor, 1990a) of spring, midsummer, and fall samples of Periodic Spring from both years. The fact that summertime water has a similar pattern to spring and fall water, but with lower

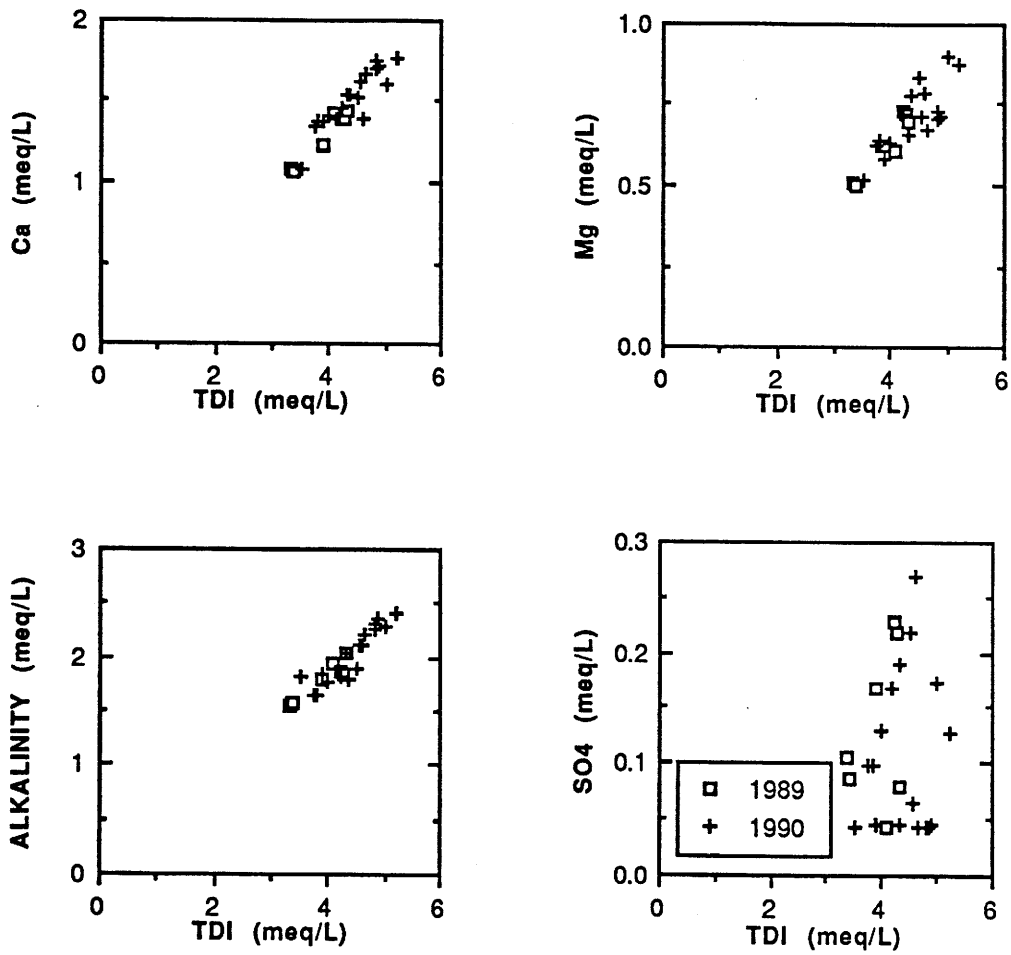
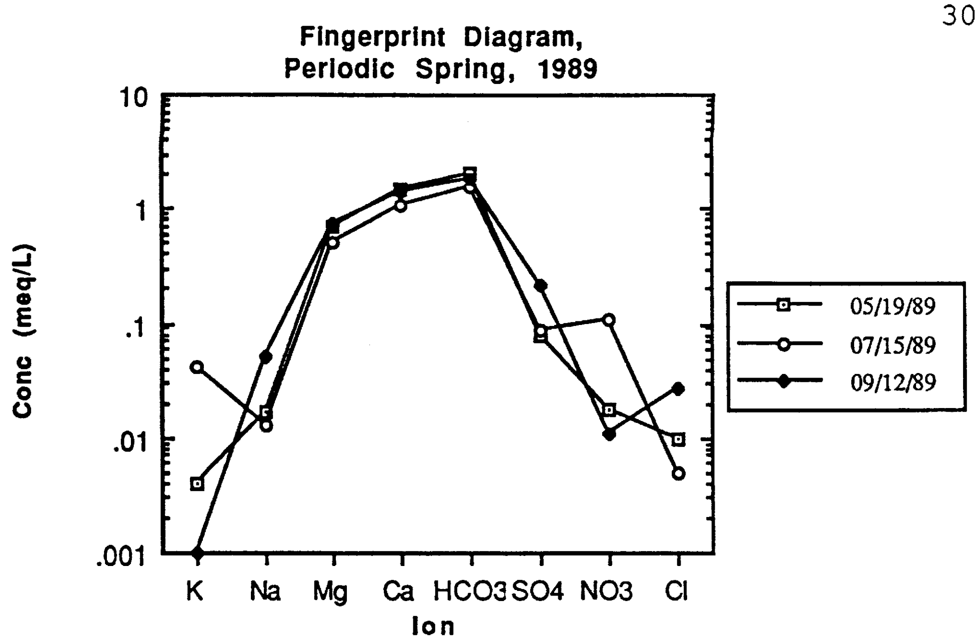


Fig. 10. Composition diagrams of Periodic Spring samples from 1989 and 1990. Mixing trend is clearest in calcium, magnesium, and alkalinity plots. 1989 waters are slightly more dilute than 1990 waters because 1990 was a lower water flow year.



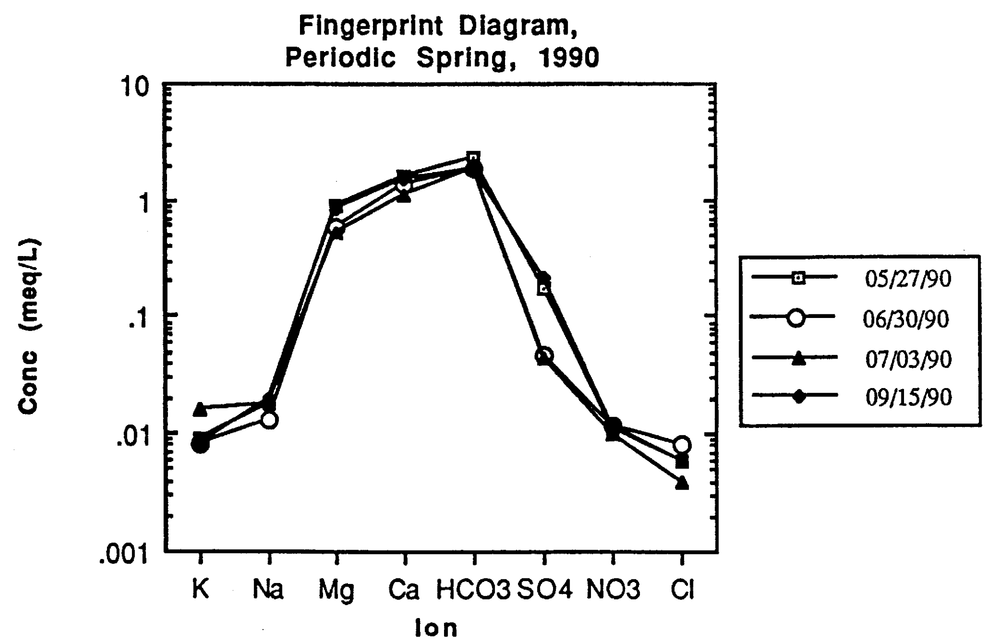


Fig. 11. Fingerprint diagrams for representative 1989 and 1990 Periodic Spring samples. Summer water has lower ion concentrations than spring and fall water. The fact that the pattern of summer water is the same as the spring and fall water patterns indicates that fresher water is diluting storage water.

ion concentrations, indicates that baseflow, or storage water, is diluted by a fresher water.

The seasonal variation is clearest in time series plots (Figs. 12 & 13) of the major ions. The temperature of spring water decreases coincidently with the decrease in ion concentrations. This decrease indicates that rapid flow must occur because the temperature of recharge water will equilibrate with the aquifer temperature within several weeks (Mazor 1990b). Note that the seasonal variation in chemistry and temperature is coincident in time with the peak discharge of Periodic Spring. This is extremely important because it indicates a flow-through event.

The saturation indices of calcite and dolomite, calculated by WATEQ4F (Plummer et al., 1976), show seasonal variation in the 1989 data, but not in the 1990 data (Fig. 14). The saturation index is the log of the ratio of the Ion Activity Product to the solubility product constant (Langmuir, 1971). The water is always undersaturated with respect to dolomite. In 1989 the midsummer dilution was sufficient to lower the saturation index of calcite to less than -0.8. The water was always close to saturation with respect to calcite in 1990.

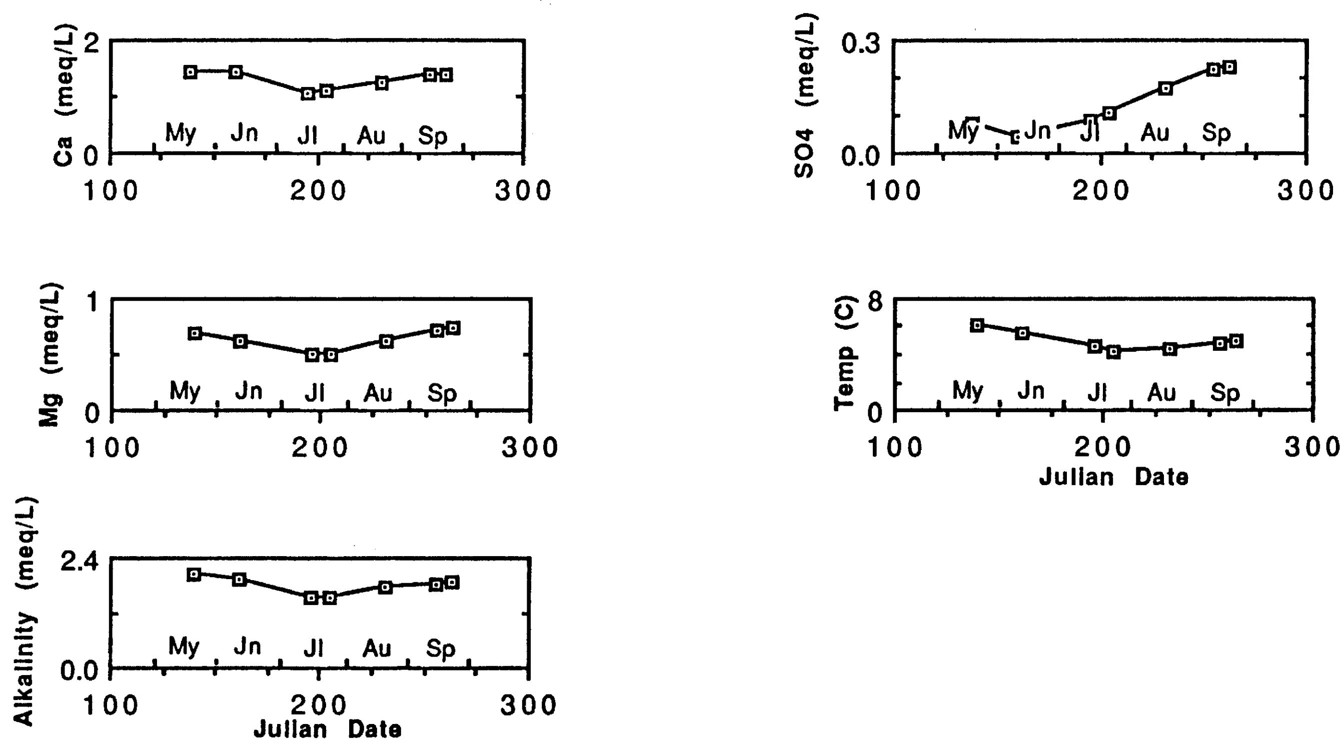


Fig. 12. Time series plots for 1989 Periodic Spring data. Note that temperature decrease coincides with ion concentration decrease.

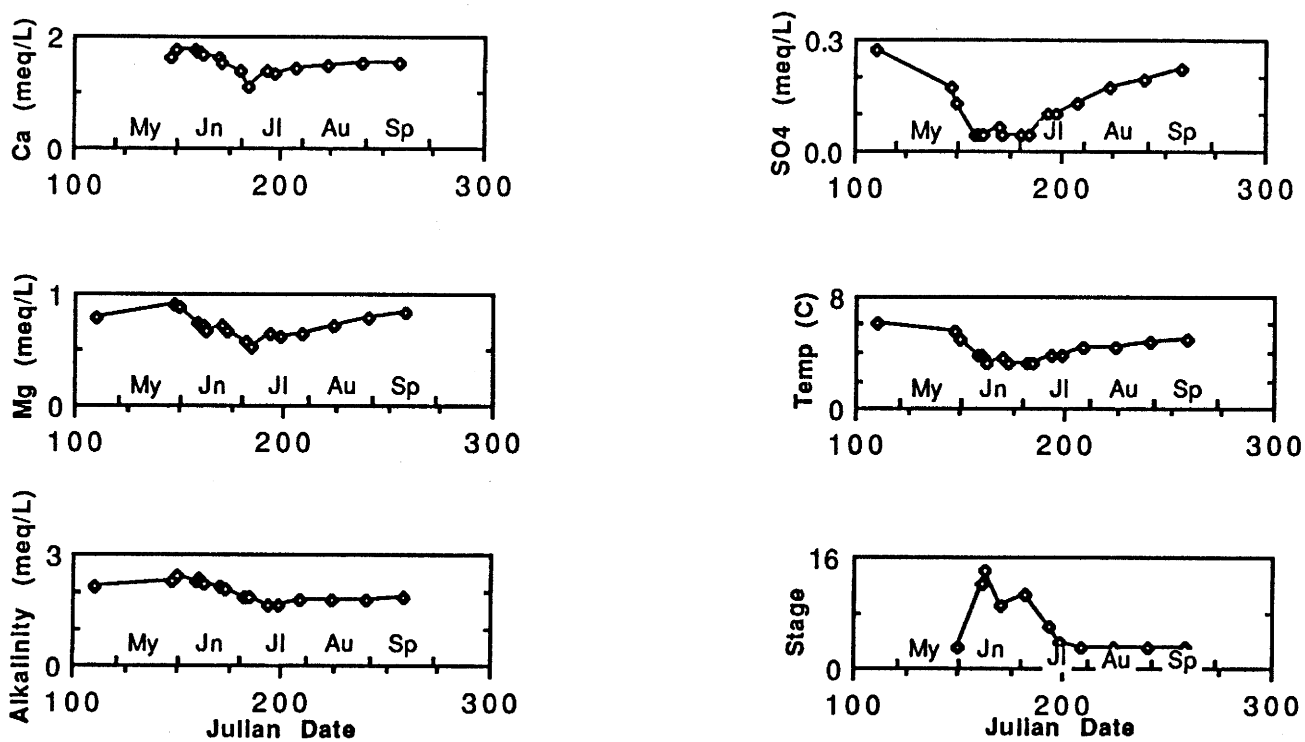


Fig. 13. Time series plots for 1990 Periodic Spring data. As with 1989 data the temperature pattern mimics the ion concentration pattern.

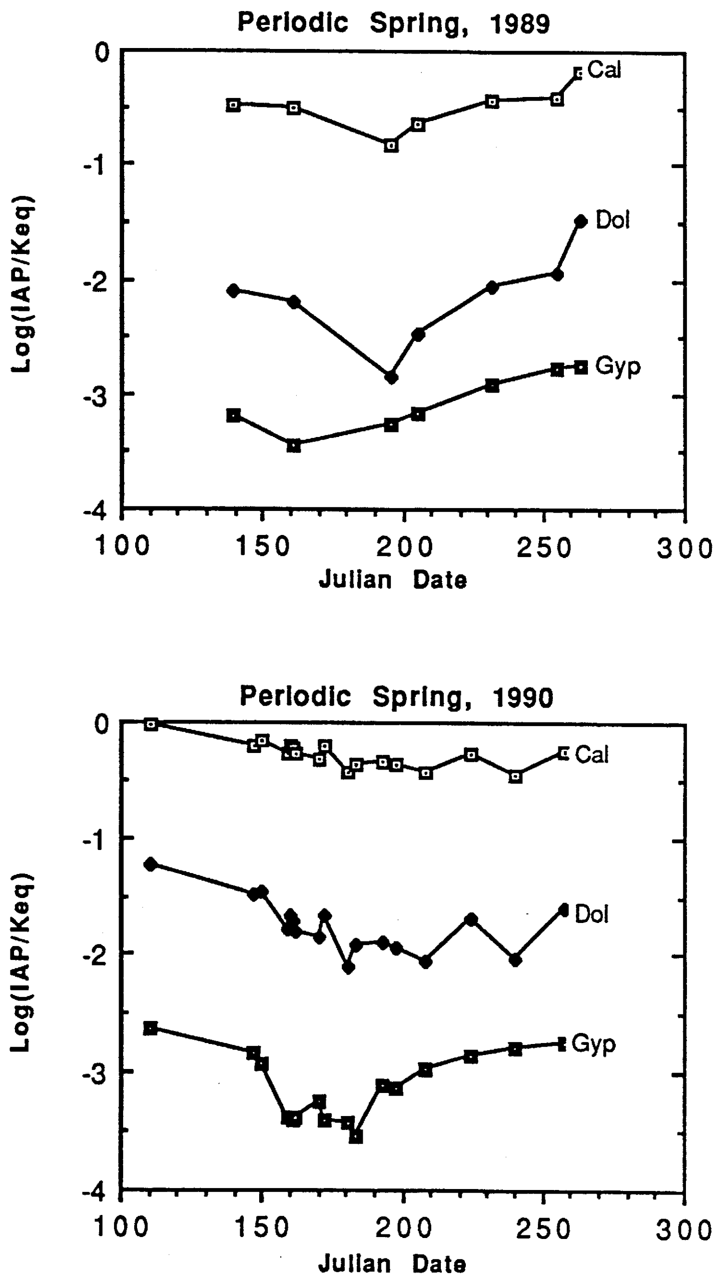


Fig. 14. Time series of saturation data calculated by WATEQ4F (Plummer et al., 1976) for 1989 and 1990 Periodic Spring data.

This result is not unusual because water flow was lower in 1990.

The discharge at Periodic Spring during the summer represents a mix of old storage water and fresh snowmelt. The percentages of each of these is here estimated from simple mixing calculations. The composition of the early spring and late fall samples is used as the storage water endmember. The composition of snowmelt is taken from data from regional NADP stations (NADP Data, 1990).

Table 1 summarizes the mixing calculations of the major cations for both years. The percentage of discharge representing snowmelt is 25 to 35%. Peak discharge of Periodic Spring is 50 to 100 cfs (1.4 - 2.8 m^3/s). Thus 12 to 35 cfs (0.34-0.99 m^3/s) of this water are derived from snowmelt while 38 to 65 cfs (1.1-1.8 m^3/s)are derived from storage.

However, this percentage is a minimum because the true mixing endmember is water that has reacted with the soil through which it must move to get to the aquifer rather than pure snowmelt. Huntoon and Coogan (1987) reported high flows as much as 100 cfs (2.8m^3/s) and low flows down to 5 cfs (0.14 m^3/s). Using these numbers and assuming that all flow above baseflow is snowmelt, up to 95% of peak discharge is snowmelt.

	Ca (meq/L)	Mg (meq/L)
1989		
Snowmelt	0.0192	0.0054
Mix (7/15,7/24)	1.0720	0.5033
Storage (5/19,6/10,9/12,9/20)	1.4283	0.6715
Percent Snowmelt	25	25
Percent Storage	75	75
1990		
Snowmelt	0.0192	0.0054
Mix (6/30,7/03)	1.2290	0.5490
Storage (5/27,5/30,8/28,9/15)	1.6055	0.8483
Percent Snowmelt	24	36
Percent Storage	76	64

Table 1. Calculation of the maximum percent of Periodic Spring discharge attributable to flow-through of snowmelt. Snowmelt is an average of regional NADP data. Mix is an average of the lowest concentration midsummer samples. Storage is an average of spring and fall samples. This calculation shows that snowmelt accounts for up to 25-35 percent of discharge in the midsummer.

The observed seasonal variation in chemistry and especially temperature of Periodic Spring discharge is coincident with the peak discharge. This means that flow-through conditions exist in the portion of the Madison aquifer that feeds Periodic Spring. Snowmelt occurs in May and early June, while the greatest change in water chemistry occurs in late June to middle July. Therefore at least part of the current year's recharge moves all the way through the system in a matter of weeks.

EVIDENCE FROM ISOTOPES

In 1989 three samples of Periodic Spring were analyzed for tritium, deuterium, and oxygen-18. All samples fall on or near the meteoric water line (Fig. 15). This indicates that recharge occurred during current climate conditions, and that partial evaporative concentration of the recharge water did not occur (Mazor, 1990a). While this is not particularly enlightening by itself, it does support the hypothesis that water moves through the system rapidly.

From June 1989 to September 1989 the concentration of tritium in Periodic Spring water doubled from 18.5 TU to a 38.9 TU. A sample in August 1989 had 21.4 TU. The

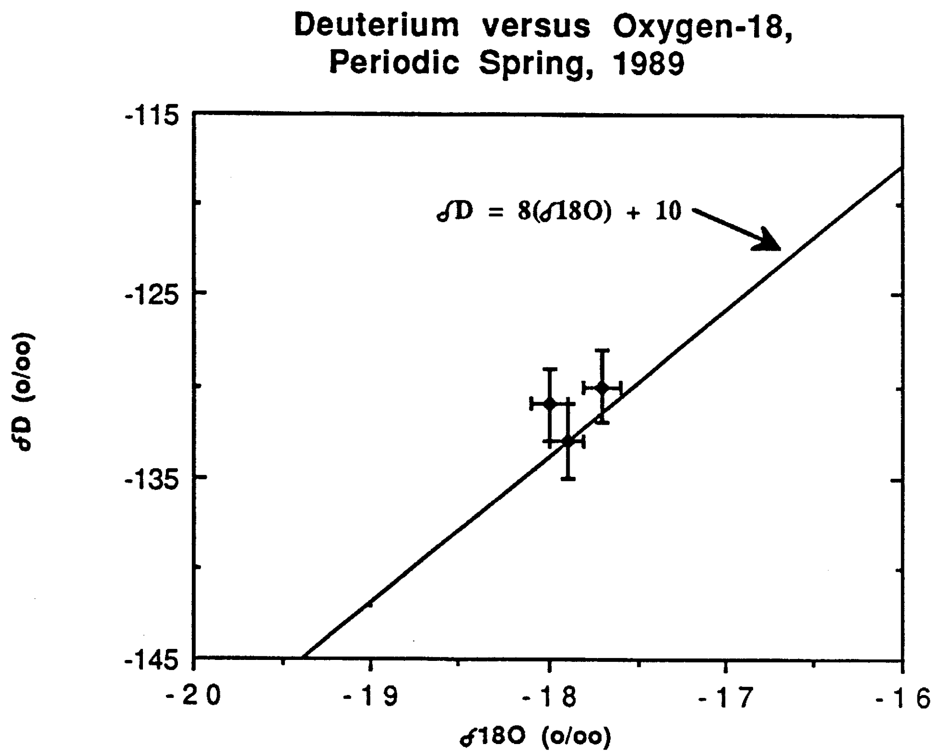


Fig. 15. Deuterium versus oxygen-18 plot for three Periodic Spring samples taken between mid-June and mid-September 1989. All three fall on the meteoric water line within the error of measurement.

June and August samples are not significantly different - the analytical error was plus or minus 2.7 TU. These values indicate that the water is post-1960 (Freeze and Cherry, 1979). Thus the effective age of water in the Madison is 28 years.

Unfortunately, the precipitation values necessary to calculate mixing percentages between recharge water and storage water are not readily available. However, the fact that the tritium concentration doubled from June to September strongly supports the conclusion made from examination of major ions that midsummer water is different from spring and fall water.

EFFECTS ON WATER CHEMISTRY OTHER THAN CARBONATE DISSOLUTION

EVAPOTRANSPIRATION. The effect of evapotranspiration in the recharge area can be determined by a consideration of the degree of concentration of the conservative ion chloride. Within the error of the calculation the ratio of chloride concentration in Periodic Spring discharge to the concentration in Corral Creek Lake water, the lowest value of chloride recorded, is unity (Table 2). This means that the effect of evapotranspiration on recharge water is negligible.

	Cl	K	Na
	meq/l	meq/l	meq/l
1989			
05/19	0.010	0.004	0.017
06/10	0.007	0.000	0.007
07/15	0.005	0.041	0.013
07/24	0.004	0.035	0.012
07/24	0.004	0.036	0.012
07/24	0.004	0.036	0.012
08/19	0.005	0.040	0.015
09/12	0.027	0.000	0.051
09/20	0.005	0.000	0.012
09/20	0.005	0.000	0.012
09/20	0.005	0.000	0.012
Average	0.007	0.017	0.016
Std Dev	0.007	0.019	0.012
Low	0.004	0.000	0.007
High	0.027	0.041	0.051
1990			
04/20	0.008	0.010	0.020
05/27	0.006	0.009	0.018
05/30	0.006	0.009	0.016
06/08	0.005	0.008	0.014
06/09	0.005	0.010	0.019
06/10	0.005	0.010	0.017
06/11	0.005	0.009	0.015
06/19	0.010	0.006	0.016
06/21	0.008	0.005	0.014
06/30	0.008	0.008	0.013
07/03	0.004	0.016	0.018
07/12	0.006	0.009	0.015
07/17	0.004	0.007	0.012
07/27	0.004	0.009	0.015
08/12	0.008	0.009	0.016
08/28	0.006	0.008	0.019
09/15	0.006	0.008	0.020
Average	0.006	0.009	0.016
Std Dev	0.002	0.002	0.002
Low	0.004	0.007	0.012
High	0.010	0.016	0.020
Corral Creek Lake	0.009	0.009	0.013
Ratio 89	0.44 - 3.0	0 - 4.6	0.54 - 3.9
Average	0.78	1.89	1.20
Deviation	0.78	2.11	0.92
Ratio 90	0.44 - 1.1	0.78 - 1.78	0.92 - 1.5
Average	0.67	1.00	1.20
Deviation	0.22	0.22	0.15

Table 2. Calculation of concentration of chloride, potassium, and sodium caused by evapotranspiration. For each ion the ratio of the concentration in Periodic Spring water to the concentration in Corral Creek Lake water is essentially unity, indicating that evapotranspiration has a negligible effect on water chemistry.

Table 2 also presents the calculations for sodium and potassium, which give the same results as chloride.

CATION EXCHANGE. The concentrations of sodium and potassium do not increase significantly between the recharge area and Periodic Spring (Table 2) In addition to indicating that evapotranspiration has a negligible effect, this indicates that cation exchange also has a negligible effect on water chemistry.

COMPARISON TO UPPER STRAWBERRY CREEK SPRINGS

Beaver Dam Spring and Strawberry Creek Upper Rise Spring discharge from the Madison aquifer in the upper reach of Strawberry Creek. The differences between these two springs and Periodic Spring were discussed in the hydrologic setting section. These springs were sampled 12 times between April 1990 and September 1990 to provide a comparison to Periodic Spring. Data are reported in Appendix A.

Figures 16 through 20 show the results of the 1990 sampling. In contrast with Periodic Spring, the composition diagrams (Fig. 16) and fingerprint diagrams (Fig. 17) indicate that the same water chemistry was maintained throughout the study period. Neither of these springs has significant seasonal variation in chemistry

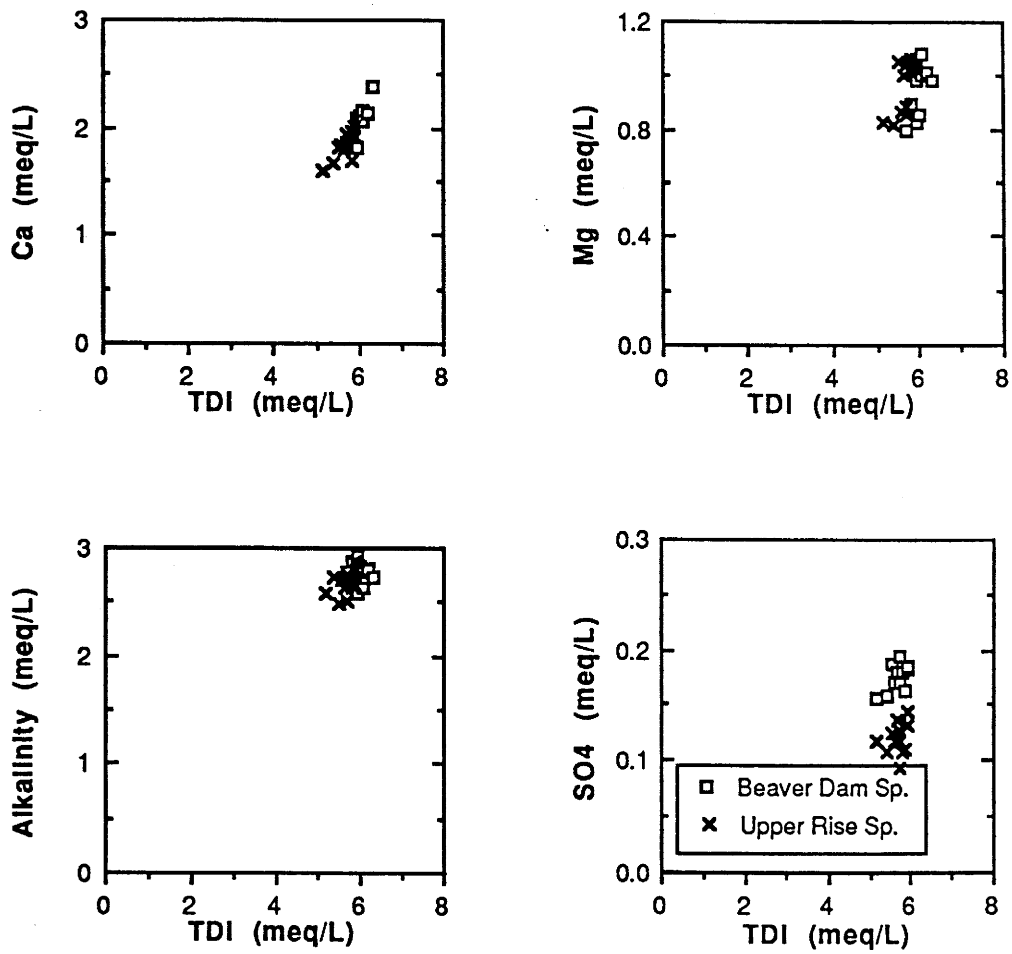
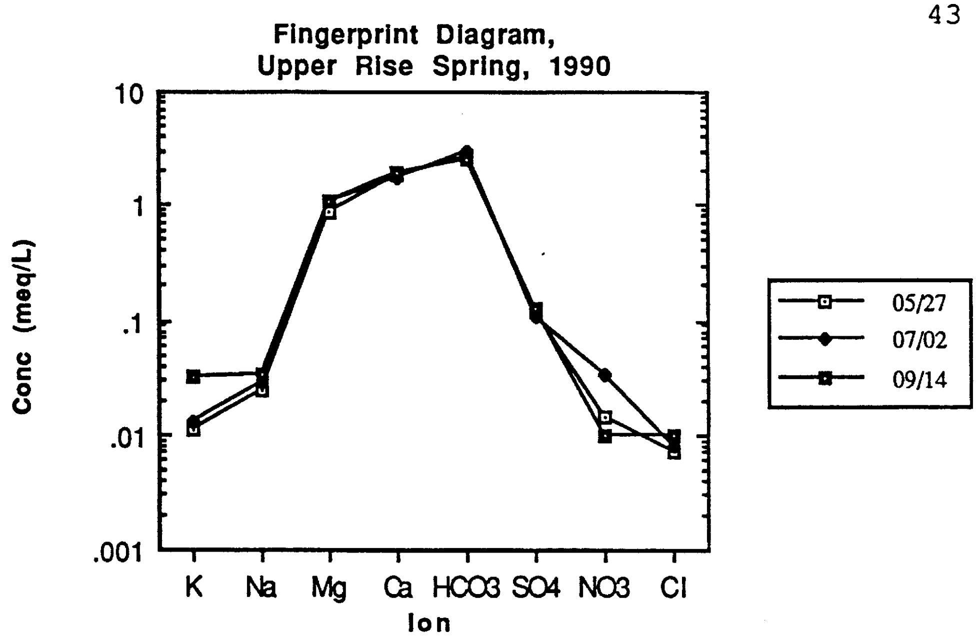


Fig. 16. Composition diagrams for Beaver Dam and Upper Rise springs. Data are clustered, indicating one water type.



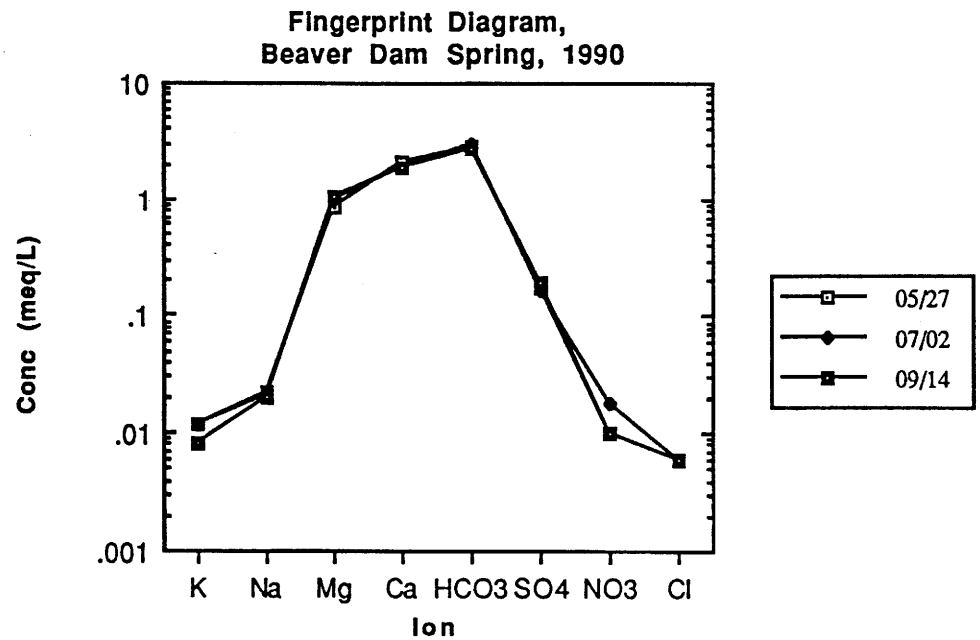


Fig. 17. Fingerprint diagrams for Beaver Dam and Upper Rise springs. One water type is shown.

or temperature (Figs. 18 & 19). Variation in discharge was not measurable in the field. The waters are essentially saturated with respect to calcite (Fig. 20). Thus the water discharging from the Madison reach of Strawberry Creek represents water derived from storage.

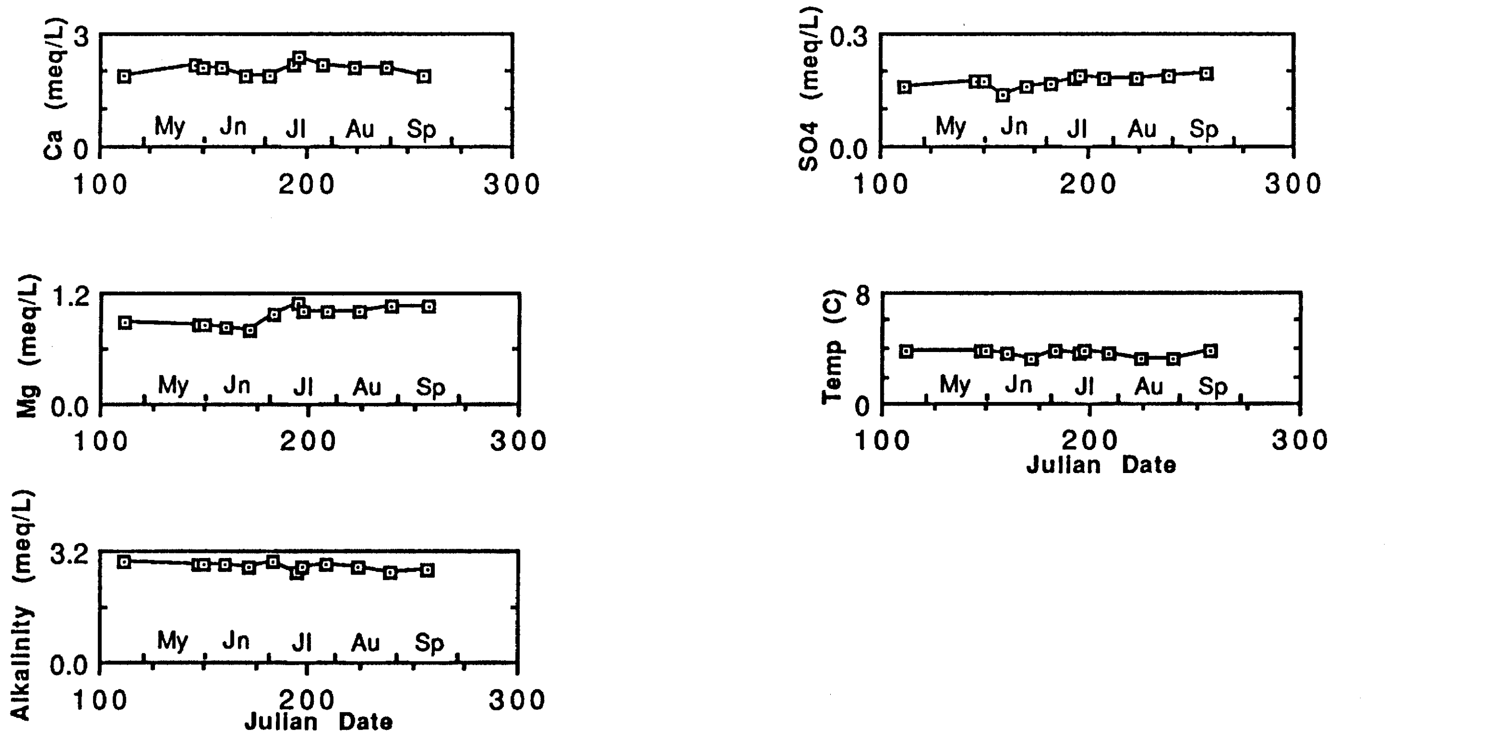


Fig. 18. Time series plots of 1990 Beaver Dam Spring data.

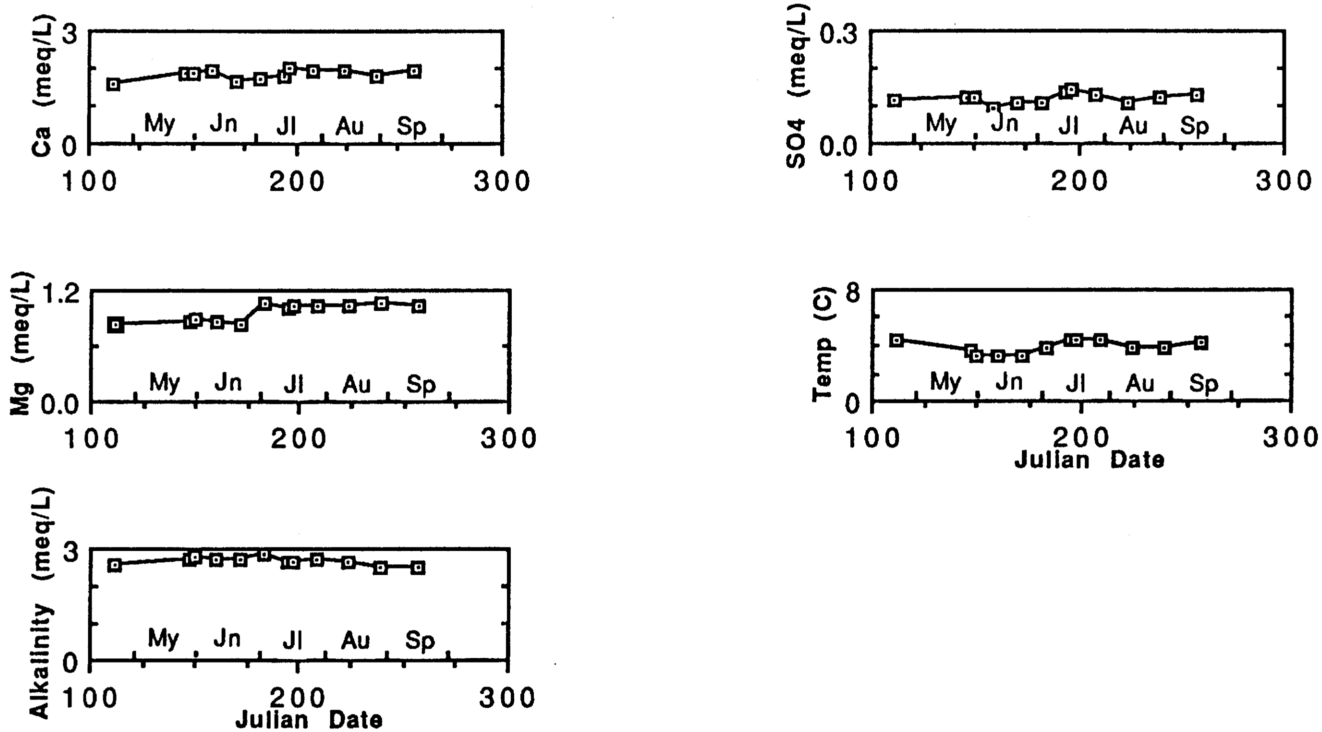
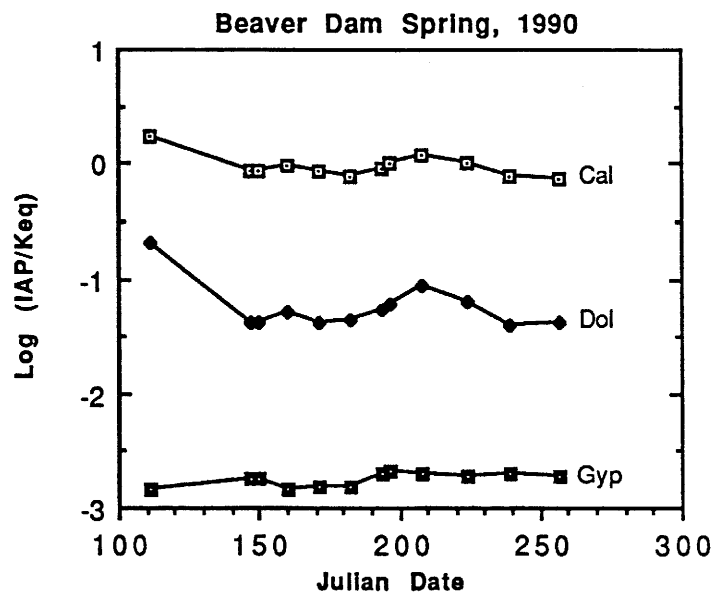


Fig. 19. Time series plots of 1990 Upper Rise Spring data.



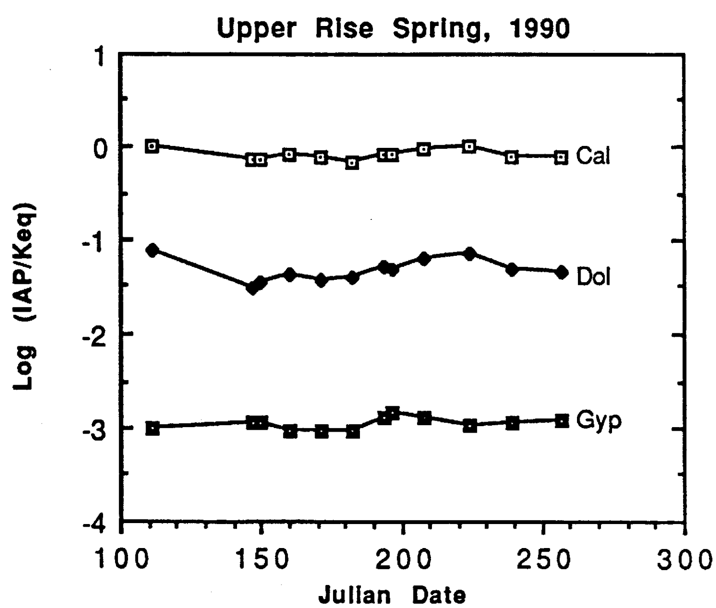


Fig. 20. Time series of saturation data calculated by WATEQ4F (Plummer et al., 1976) for Beaver Dam and Upper Rise springs. Waters are saturated with respect to calcite.

CHAPTER IV

COMPARISON AND INTEGRATION WITH OTHER CARBONATE FLOW MODELS

DIFFUSE AND CONDUIT FLOW

Shuster and White (1971, 1972) coined the terms diffuse flow and conduit flow as endmembers of carbonate flow systems (Fig. 21). In a conduit flow system water moves through an integrated system of large conduits; that is, a well developed karst system. In a diffuse flow system, water moves through small interconnected openings such as joints, fractures, and bedding planes. This is simply flow through a saturated porous medium.

The diffuse/conduit terminology focuses on the physical setting of the aquifer; that is, the rocks and flow openings. The pulse/flow-through terminology focuses on water movement. While the latter can refer to the physical setting, as in the term "flow-through system," the basis of the concept is process oriented. That is, without beginning with the idea of a "flow-through event" or "flow-through process," there is no need to refer to the "flow-through system."

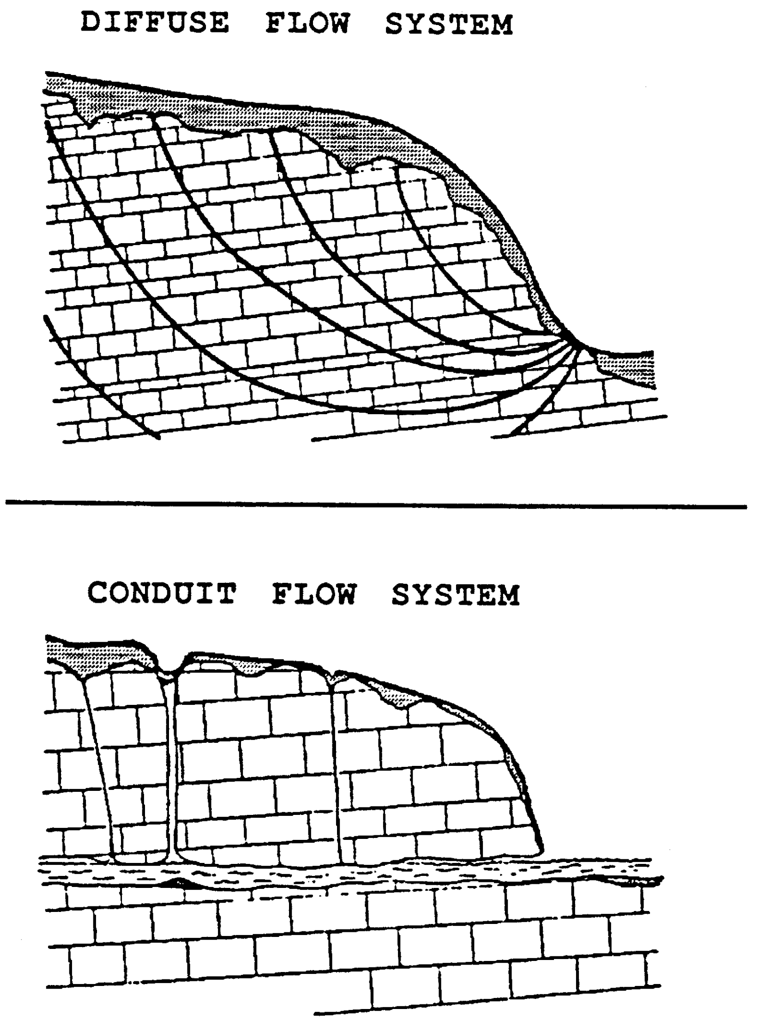


Fig. 21: Diffuse and conduit carbonate flow systems. Water flows through saturated rock in diffuse system, but through integrated conduits in conduit system. From Shuster and White (1971).

Shuster and White (1971) characterized the water chemistry patterns of spring systems known to be either diffuse or conduit systems. Conduit systems show much more seasonal variability in water chemistry because the water has not had as much time to equilibrate with the aquifer wall rock as in a diffuse system. Water in diffuse systems was usually close to saturation with respect to calcite, whereas water in conduit systems was undersaturated by a factor of 2-5 (Shuster and White, 1971, 72). In the springs studied by Shuster and White the saturation index of calcite was -1.0 to -0.3 for conduit systems, but -.01 to +0.07 for diffuse systems.

Two other parameters useful in distinguishing the flow systems are the variations in temperature and hardness. Temperature fluctuates very little in a diffuse system. Shuster and White (1971, 72) found that while hardness itself is not a good indicator, the coefficient of variation of hardness is. This coefficient tends to be greater than 10% in conduit systems but less than 10%, and often less than 5%, in diffuse systems.

The saturation indices of calcite for the 1989 and 1990 Periodic Spring data are closer to those indicative of a conduit system than those of a diffuse system. For

1989 they range from -1.0 to -0.1 and for 1990 from -0.6 to -0.02. The high numbers overlap somewhat with the diffuse system range, but overall the numbers tend toward the conduit range.

The waters of Beaver Dam Spring and Upper Rise Spring are closer to saturation with respect to calcite than those of Periodic Spring. Beaver Dam Spring ranges from -0.25 to -0.15; Upper Rise ranges from -0.16 to -0.01.

The coefficient of variation of hardness provides a clearer distinction than does the saturation index of calcite. For Periodic Spring this was 14% in 1989 and 12% in 1990. For both Beaver Dam and Upper Rise springs it was 7% in 1990.

Periodic Spring shows the seasonal variation and degree of undersaturation characteristic of a conduit system. Therefore there must be a conduit system within the Madison Limestone feeding Periodic Spring.

In contrast, Beaver Dam and Upper Rise springs show no significant seasonal variation and are close to saturation with respect to calcite and dolomite. Therefore the Madison Limestone feeding Strawberry Creek is a diffuse flow system.

DREISS TWO-COMPONENT FLOW MODEL

Dreiss (1989a, 1989b) developed a two-component flow model from her work in the Missouri karst. Figure 22 is a schematic drawing adapted from her work which shows a conduit within a saturated carbonate aquifer (Dreiss, Pers. Comm., 1990). The conduit grade line, which represents the hydraulic head within the conduit, is analogous to the water table of the saturated rock. The comparison then, is one of potential energies.

During a recharge event, conduits within the karst fill rapidly. This raises the conduit grade line, producing rapid flow through the conduit. Some water in the conduit also moves into the saturated rock because the conduit grade line exceeds the water table. Later, when the conduit grade line drops below the water table, water drains from the saturated rock into the conduit.

Dreiss' rapid flow of water through the conduit is a flow-through event. In the Missouri karst, this process was completed on the scale of hours to days. An analogous process, but on the order of weeks, occurring in the Madison Limestone feeding Periodic Spring would explain the chemistry and temperature patterns of Periodic Spring discharge. Spring snowmelt is the rapid input of recharge water. This influx causes both a flow-

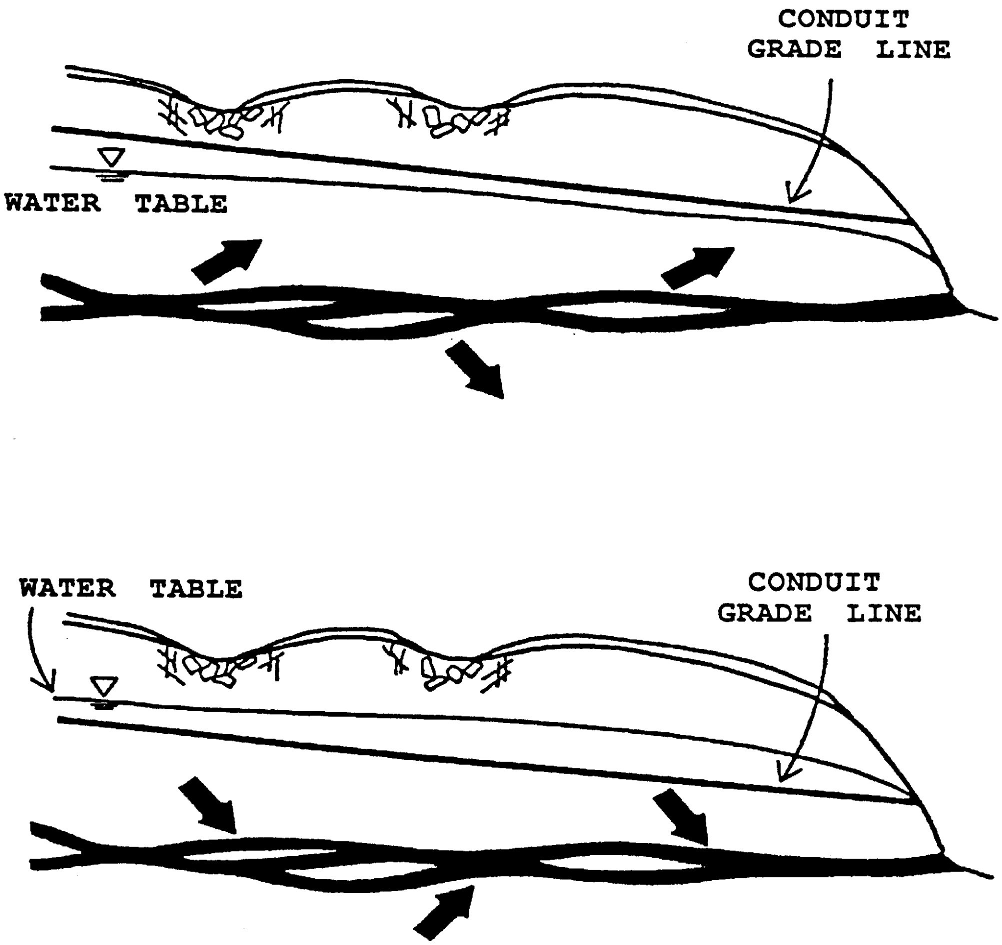


Fig. 22. Two-component carbonate flow model developed by Dreiss (1990). Conduit grade line is analogous to water table line but reflects water in conduit. During rapid recharge (upper) water moving through the conduit replenishes storage because the conduit grade line exceeds the water table. Subsequently the conduit grade line drops and water drains from storage to sustain spring discharge (lower).

through event and the replenishment of aquifer storage. By the end of the summer the spring is again discharging water from storage.

COMBINING THE MODELS

The pulse-through/flow-through model describes the relation of the passage of hydraulic energy to the passage of the recharge water that produces that energy through a carbonate system. Flow-through can occur in a conduit flow system, but neither a pure conduit nor pure diffuse system can account for both rapid flow and year-round sustained flow. The Dreiss model is essentially a system that lies between the diffuse and conduit endmembers. This model allows a flow-through event, yet accounts for enough storage to provide sustained flow.

There are two forms which the conduit system feeding Periodic Spring may take. The first possibility is that a conduit system has developed all the way from the recharge area to the spring. When snowmelt loads the system the head in the conduit is greater than in the saturated rock and this water moves completely through the system.

The second possibility is that a short circuit exists which is only utilized when the potentiometric surface of the aquifer rises above a certain level. This will allow flow-through to occur during high flow and pulse-through during low flow. This short circuit would have to be near the spring, along Periodic Anticline, because the aquifer is confined between the recharge area and the anticline.

IMPLICATIONS FOR POLLUTION

Flow-through occurs in the Madison aquifer because of open conduits. Contamination in the recharge area could potentially reach Periodic Spring as fast as this flow occurs - a matter of weeks during the summer. Thus not much reaction time would exist if a problem arose.

The initial implication for a rapid flow system is that the contamination will flush through in a relatively short time. However, this is not the case in the Madison Limestone because of the dual nature of the system. While some pollution would flush through quickly, some would enter storage. Thus both short term and long term effects could be significant.

CHAPTER V

CONCLUSIONS

The following conclusions can be made from examination of seasonal patterns in the chemistry and temperature of spring water.

1. The carbonate system is the main control on the chemistry of water in the Madison aquifer. Evapotranspiration and cation exchange have negligible effects.

2. Flow-through of spring snowmelt causes seasonal variation in the chemistry and temperature of Periodic Spring. In contrast, pulse-through of storage water produces a constancy of chemistry and temperature in the discharge of Beaver Dam and Upper Rise springs.

3. Water chemistry and temperature fluctuations in the discharge of Periodic Spring indicate the existence of a karstic conduit system in the Madison Limestone that is not apparent from field observations in the Salt River Range.

4. Periodic Spring discharge represents both rapid flow and year-round flow because the flow system in the Madison Limestone is a combined diffuse and conduit system (Shuster and White, 1971, 72) similar to that described by Dreiss (1989a, 89b) in the Missouri karst.

5. Recharge to the system feeding Periodic Spring occurs in the cirques along the east side of the topographic divide of the Salt River Range. This recharge area is bounded to the south by Corral Creek. The northern boundary is less certain. It lies in the area lacking extensive cirque development between Mt. Fitzpatrick and Lake Barstow.

6. Contamination in the recharge area of Periodic Spring would pose both immediate and long term problems. Flow-through would bring contamination to Periodic Spring in a matter of weeks, while aquifer storage could prevent the system from flushing clean for years.

APPENDICES

APPENDIX A

Water chemistry and temperature data from 1989 and 1990 sampling of Periodic Spring and 1990 sampling of Beaver Dam and Upper Rise springs

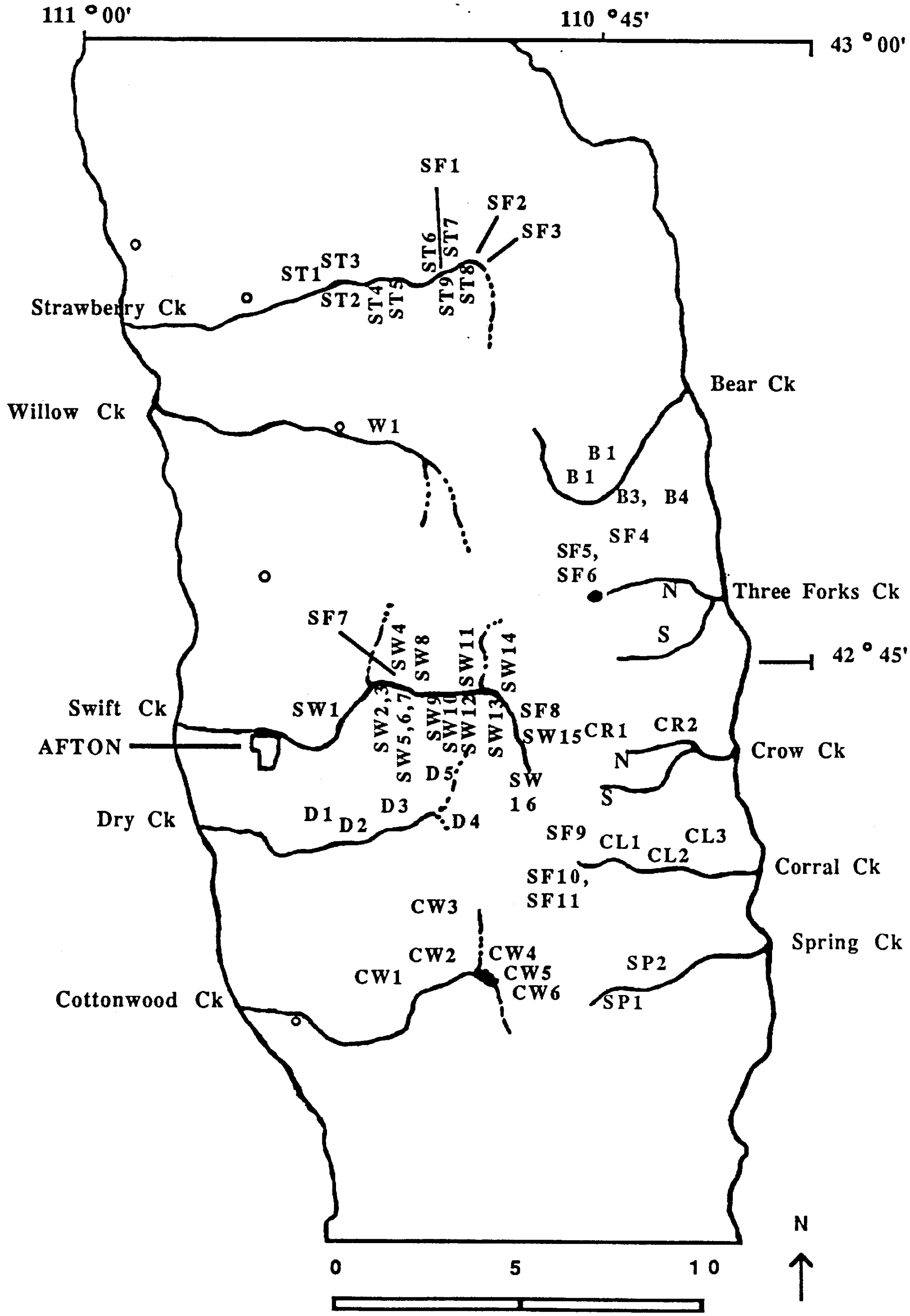
	PERIODIC SPRING DATA														
DATE	TEMP	pH	Ca	Mg	Na	K	Cl	SO4	NO3	PO4	Alkalinity	TDI	SiO2	HARDNESS	Charge
	C	(Lab)	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	(meq/L)	ppm	ppm	Balance (%)
1989															
05/19	6.0	7.65	1.450	0.700	0.017	0.004	0.010	0.080	0.018	0.000	2.030	4.31	1.48	108	0.7
06/10	5.5	7.67	1.430	0.610	0.007	0.000	0.007	0.044	0.016	0.000	1.940	4.05	1.12	102	1.0
07/15	4.5	7.57	1.070	0.499	0.013	0.041	0.005	0.087	0.110	0.000	1.568	3.39	1.26	78	-4.4
07/24	4.2	7.77	1.073	0.512	0.012	0.035	0.004	0.105	0.060	0.000	1.548	3.35	1.39	79	-2.7
07/24	4.2	7.74	1.075	0.503	0.012	0.036	0.004	0.106	0.066	0.000	1.548	3.35	1.26	79	-2.7
07/24	4.2	7.76	1.074	0.508	0.012	0.036	0.004	0.106	0.063	0.000	1.548	3.35	1.33	79	-2.7
08/19	4.4	7.83	1.227	0.620	0.015	0.040	0.005	0.169	0.030	0.000	1.787	3.89	1.80	92	-2.3
09/12	4.7	7.81	1.393	0.721	0.051	0.000	0.027	0.219	0.011	0.000	1.850	4.27	2.06	106	1.4
09/20	5.0	7.96	1.425	0.726	0.012	0.000	0.005	0.228	0.009	0.000	1.860	4.27	2.11	108	1.4
09/20	5.0	8.09	1.372	0.732	0.012	0.000	0.005	0.226	0.010	0.000	1.860	4.22	2.20	105	0.5
09/20	5.0	8.03	1.399	0.729	0.012	0.000	0.005	0.227	0.010	0.000	1.860	4.24	2.16	106	0.9
1990															
04/20	6.1	8.03	1.390	0.790	0.020	0.010	0.008	0.268	0.011	0.000	2.110	0.28	2.34	109	-4.1
05/27	5.6	7.85	1.601	0.902	0.018	0.009	0.006	0.172	0.011	0.000	2.280	0.18	-	125	1.2
05/30	5.0	7.84	1.764	0.875	0.016	0.009	0.006	0.126	0.012	0.000	2.408	0.14	-	132	2.1
06/08	3.9	7.78	1.759	0.731	0.014	0.008	0.005	0.043	0.013	0.000	2.272	0.06	-	125	3.7
06/09	3.9	7.83	1.719	0.712	0.019	0.010	0.005	0.045	0.014	0.000	2.351	0.06	-	122	0.8
06/10	3.6	7.82	1.707	0.706	0.017	0.010	0.005	0.043	0.014	0.000	2.309	0.06	-	121	1.5
06/11	3.3	7.82	1.674	0.671	0.015	0.009	0.005	0.044	0.015	0.000	2.219	0.06	-	117	1.9
06/19	3.6	7.80	1.627	0.711	0.016	0.006	0.010	0.064	0.012	0.000	2.124	0.08	-	117	3.3
06/21	3.3	7.94	1.538	0.658	0.014	0.005	0.008	0.046	0.012	0.000	2.039	0.06	-	110	2.5
06/30	3.3	7.81	1.382	0.578	0.013	0.008	0.008	0.046	0.012	0.000	1.849	0.06	-	98	1.5
07/03	3.3	7.98	1.076	0.520	0.018	0.016	0.004	0.044	0.010	0.000	1.824	0.05	-	80	-7.1
07/12	3.9	7.92	1.381	0.638	0.015	0.009	0.006	0.098	0.012	0.000	1.657	0.11	-	101	7.1
07/17	3.9	7.91	1.343	0.627	0.012	0.007	0.004	0.098	0.012	0.000	1.641	0.11	-	99	6.1
07/27	4.4	7.80	1.418	0.635	0.015	0.009	0.004	0.130	0.012	0.000	1.762	0.14	-	103	4.3
08/12	4.4	7.94	1.460	0.721	0.016	0.009	0.008	0.168	0.012	0.000	1.809	0.18	-	109	5.0
08/28	4.7	7.74	1.536	0.777	0.019	0.008	0.006	0.190	0.011	0.000	1.795	0.20	-	116	7.8
09/15	5.0	7.91	1.521	0.839	0.020	0.008	0.006	0.219	0.012	0.000	1.891	0.23	-	118	5.8

DATE	TEMP	pH	Ca	Mg	Na	K	Cl	SO4	NO3	PO4	Alkalinity	TDI	HARDNESS	Charge
	C	(Lab)	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/L	ppm	Balance (%)
Beaver Dam Spring														
04/21	3.9	8.17	1.840	0.900	0.017	0.007	0.007	0.155	0.010	0.000	2.888	5.82	137	-5.1
05/27	3.9	7.82	2.111	0.856	0.022	0.012	0.006	0.171	0.010	0.000	2.820	6.01	148	-0.1
05/30	3.9	7.83	2.082	0.847	0.020	0.009	0.007	0.170	0.010	0.000	2.812	5.96	147	-0.7
06/09	3.6	7.88	2.100	0.829	0.017	0.009	0.007	0.135	0.008	0.000	2.850	5.95	147	-0.7
06/20	3.3	7.88	1.878	0.800	0.031	0.015	0.012	0.158	0.008	0.000	2.780	5.68	134	-4.1
07/02	3.9	7.83	1.823	0.979	0.021	0.012	0.006	0.164	0.018	0.000	2.919	5.94	140	-4.6
07/13	3.6	7.87	2.160	1.081	0.019	0.012	0.008	0.180	0.010	0.000	2.622	6.09	162	7.4
07/16	3.9	7.87	2.376	0.987	0.019	0.011	0.008	0.184	0.010	0.000	2.732	6.33	168	7.3
07/27	3.6	7.96	2.144	1.014	0.020	0.012	0.008	0.182	0.010	0.000	2.791	6.18	158	3.2
08/12	3.3	7.91	2.069	1.000	0.019	0.011	0.008	0.180	0.008	0.000	2.775	6.07	154	2.1
08/27	3.3	7.83	2.058	1.058	0.022	0.009	0.010	0.186	0.008	0.000	2.580	5.93	156	6.1
09/14	3.9	7.84	1.872	1.053	0.020	0.008	0.006	0.194	0.010	0.000	2.639	5.80	146	1.8
Upper Rise Spring														
04/21	4.4	8.03	1.600	0.830	0.019	0.007	0.006	0.117	0.013	0.003	2.571	5.17	122	-4.9
05/27	3.6	7.81	1.836	0.864	0.024	0.011	0.007	0.118	0.014	0.003	2.709	5.59	135	-2.1
05/30	3.3	7.83	1.861	0.884	0.025	0.012	0.008	0.118	0.014	0.005	2.762	5.69	137	-2.2
06/09	3.3	7.87	1.943	0.859	0.030	0.012	0.006	0.093	0.012	0.000	2.739	5.70	140	-0.1
06/20	3.3	7.88	1.670	0.816	0.028	0.009	0.012	0.108	0.010	0.000	2.719	5.37	124	-6.1
07/02	3.9	7.81	1.700	1.065	0.029	0.013	0.008	0.110	0.034	0.000	2.888	5.85	138	-4.0
07/13	4.4	7.88	1.804	0.999	0.025	0.011	0.008	0.136	0.012	0.000	2.619	5.62	140	1.1
07/16	4.4	7.84	2.012	1.028	0.026	0.012	0.010	0.144	0.012	0.000	2.649	5.89	152	4.5
07/27	4.4	7.89	1.930	1.040	0.025	0.012	0.008	0.132	0.012	0.000	2.724	5.88	149	2.2
08/12	3.9	7.94	1.957	1.017	0.024	0.011	0.008	0.108	0.012	0.000	2.657	5.79	149	3.9
08/27	3.9	7.89	1.816	1.051	0.026	0.009	0.008	0.124	0.012	0.000	2.490	5.54	143	4.9
09/14	4.2	7.86	1.935	1.042	0.033	0.031	0.010	0.126	0.010	0.000	2.512	5.70	149	6.7

APPENDIX B

Inventory of 1989 and 1990 spring and surface site data in the Salt River Range, Wyoming

LOCATION	ABBREVIATION
Bear Creek	B
Corral Creek	CL
Cottonwood Creek	CW
Crow Creek	CR
Dry Creek	D
Spring Creek	SP
Strawberry Creek	ST
Surface Water	SF
Swift Creek	SW
Willow Creek	W


111 ° 00'
110 ° 45'
43 ° 00'
42 ° 45'
SF1
SF2
SF3
ST1
ST3
ST2
ST4
ST5
ST6
ST7
ST8
ST9
Strawberry Ck
Willow Ck
W1
Bear Ck
B1
B1
B3, B4
SF4
SF5,
SF6
N
S
Three Forks Ck
SF7
SW4
SW8
SW11
SW14
Swift Ck
SW1
SW2,3
SW5,6,7
SW9
SW10
SW12
SW13
SF8
SW15
CR1
CR2
N
S
Crow Ck
AFTON
D5
SW
16
Dry Ck
D1
D2
D3
D4
SF9
CL1
CL2
CL3
Corral Ck
SF10,
SF11
CW3
Spring Ck
CW2
CW4
CW5
CW6
CW1
SP2
SP1
Cottonwood Ck
0
5
10
N

SITE	DATE	SOURCE FORMATION	DISCHARGE	TEMP	pH	Ca	Mg	Na	K	Cl	SO4	NO3
	1989		ft3/s	C	(Lab)	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l
CL1	09/16	Madison	0.25	3.3	8.18	1.695	0.958	0.023	0.007	0.006	0.145	0.012
CL2	09/16	Darby	0.25	5.6	8.14	1.750	0.921	0.020	0.005	0.005	0.170	0.002
CL3	09/16	Cretaceous	0.50	6.7	8.05	1.547	0.559	0.027	0.006	0.007	0.024	0.008
CR1	09/15	Bighorn	1.00	8.3	8.06	1.546	0.556	0.022	0.004	0.006	0.037	0.006
CR2	09/15	Cretaceous	0.50	5.6	8.37	2.535	0.905	0.028	0.006	0.007	0.029	0.004
CW1	06/11	Wells	<.05	7.0	7.77	2.690	1.010	0.033	0.006	0.014	0.220	0.017
CW1	07/15	Wells	<.05	5.6	7.79	3.064	1.188	0.039	0.067	0.013	0.208	0.137
CW2	07/15	Ankareh/Nugget	0.50	5.0	7.70	2.002	0.686	0.052	0.081	0.011	0.534	0.018
CW2	08/19	Ankareh/Nugget	-	5.0	7.89	2.038	0.580	0.048	0.064	0.007	0.609	0.009
CW3	07/22	Nugget	1.50	3.1	7.25	0.288	0.145	0.043	0.056	0.006	0.021	0.039
CW4	06/11	Nugget	<.05	9.5	7.66	1.890	0.730	0.048	0.007	0.016	0.423	0.011
CW5	06/11	Nugget	<.05	9.0	7.64	1.900	0.540	0.060	0.008	0.014	0.080	0.009
CW6	06/11	Nugget	<.05	5.5	6.98	0.570	0.130	0.039	0.007	0.010	0.028	0.023
CW6	07/15	Nugget	<.05	6.7	7.55	0.861	0.165	0.059	0.113	0.013	0.029	0.207
D1	07/23	Wells	0.25	5.8	7.66	1.308	0.762	0.032	0.071	0.010	0.072	0.107
D2	06/13	Madison	2.00	4.0	7.77	2.370	1.170	0.060	0.010	0.012	0.835	0.009
D2	07/15	Madison	0.40	3.9	7.68	2.319	1.121	0.059	0.116	0.010	0.849	0.025
D2	07/23	Madison	0.25	3.6	7.83	2.342	1.130	0.059	0.111	0.010	0.826	0.026
D2	08/19	Madison	0.00	5.0	8.11	2.480	0.963	0.060	0.099	0.009	0.705	0.008
D3	06/13	Thaynes	0.25	6.0	7.72	1.660	1.140	0.057	0.007	0.015	0.221	0.013
D3	07/15	Thaynes	0.10	5.6	7.72	1.595	1.014	0.049	0.063	0.008	0.194	0.131
D3	08/19	Thaynes	0.10	5.0	7.89	1.732	1.030	0.051	0.057	0.008	0.208	0.031
D3	09/19	Thaynes	<.05	5.0	8.03	1.768	1.056	0.043	0.006	0.008	0.240	0.013
D4	07/23	Thaynes	0.10	3.1	7.81	2.335	1.033	0.076	0.107	0.011	0.472	0.055
D5	06/13	Nugget	0.25	5.5	7.58	1.310	0.740	0.068	0.008	0.009	0.038	0.018
D5	07/15	Nugget	0.25	5.0	7.61	1.165	0.571	0.065	0.085	0.008	0.036	0.111
D5	08/19	Nugget	0.20	5.0	7.70	0.958	0.403	0.061	0.080	0.007	0.036	0.029
D5	09/19	Nugget	0.20	4.4	7.83	1.178	0.477	0.052	0.007	0.007	0.037	0.014
SF7	06/09	Surface	-	9.5	7.94	1.740	0.970	0.035	0.005	0.013	0.052	0.007
SF7	07/16	Surface	-	7.0	7.95	1.684	0.925	0.037	0.065	0.012	0.053	0.062
SF8	07/21	Surface	-	6.7	7.91	1.358	0.889	0.023	0.053	0.008	0.051	0.062
SP1	09/17	Madison	0.10	7.2	8.18	2.327	1.376	0.024	0.013	0.007	1.192	0.002
SP2	09/17	Bighorn	1.50	3.9	8.10	1.512	0.834	0.023	0.006	0.006	0.145	0.004
SW1	06/09	Thaynes	0.25	11.0	7.92	2.260	1.730	0.124	0.012	0.030	0.869	0.011
SW1	07/16	Thaynes	0.25	7.0	7.95	2.143	1.640	0.133	0.139	0.031	0.845	0.102
SW1	08/19	Thaynes	0.25	6.7	8.07	2.522	1.633	0.130	0.110	0.028	0.805	0.024
SW1	09/14	Thaynes	0.25	5.6	8.42	2.294	1.629	0.120	0.012	0.028	0.826	0.010
SW2	09/14	Amsden	1.00	4.2	7.87	1.659	1.053	0.030	0.010	0.013	0.060	0.012
SW3	09/14	Amsden	0.25	3.9	7.85	1.441	0.938	0.023	0.006	0.008	0.040	0.010
SW4	07/19	Wells	0.25	4.5	7.70	1.636	0.931	0.036	0.068	0.013	0.053	0.039
SW5	09/14	Madison	0.05	5.3	7.91	3.815	1.728	0.024	0.011	0.007	2.716	0.002
SW7	09/14	Madison	0.05	5.3	7.98	3.472	1.596	0.025	0.012	0.007	2.475	0.004
SW9	07/24	Madison	0.25	4.2	7.78	1.220	0.560	0.010	0.030	0.000	0.100	0.060
SW10	Periodic Spring, See Appendix A											
SW11	07/24	Wells	0.50	5.8	7.70	1.857	1.017	0.040	0.070	0.010	0.236	0.048
SW11	09/12	Wells	0.25	5.0	7.91	1.957	1.004	0.039	0.009	0.011	0.249	0.008
SW12	09/12	Wells	0.25	6.7	7.97	2.233	1.349	0.035	0.015	0.011	0.477	0.007
SW13	07/24	Thaynes	1.00	3.6	7.83	2.108	1.025	0.036	0.065	0.007	0.741	0.052
SW13	09/13	Thaynes	0.50	4.4	8.17	2.479	1.135	0.039	0.007	0.007	1.186	0.006
SW14	07/24	Thaynes	0.25	4.2	7.67	2.256	0.994	0.041	0.066	0.007	1.123	0.000
SW15	07/21	Wells	0.25	8.1	7.67	2.295	1.512	0.043	0.070	0.012	0.219	0.000
SW16	07/21	Thaynes	0.05	9.6	7.39	1.165	0.571	0.023	0.025	0.002	0.051	0.000

SITE	DATE	PO4	ALKALINITY	SiO2	TDS	CHARGE
	1989	meq/l	meq/l	ppm	ppm	BALANCE (%)
CL1	09/16	0.000	2.590	2.24	134	-1.3
CL2	09/16	0.003	2.550	1.83	134	-0.6
CL3	09/16	0.000	2.140	2.42	107	-0.9
CR1	09/15	0.000	2.080	0.89	104	0.0
CR2	09/15	0.000	3.550	2.34	173	-1.6
CW1	06/11	0.000	3.550	2.73	189	-0.8
CW1	07/15	0.000	3.547	2.46	207	5.5
CW2	07/15	0.000	2.286	2.34	151	-0.5
CW2	08/19	0.000	2.424	2.47	157	-5.5
CW3	07/22	0.000	0.433	2.58	30	3.2
CW4	06/11	0.000	2.200	2.47	138	0.5
CW5	06/11	0.000	2.330	3.19	124	1.5
CW6	06/11	0.000	0.560	2.96	37	9.1
CW6	07/15	0.000	0.871	2.81	69	3.4
D1	07/23	0.000	2.081	2.23	114	-2.2
D2	06/13	0.000	2.730	3.16	190	0.3
D2	07/15	0.000	2.860	3.14	198	-1.8
D2	07/23	0.000	2.860	3.16	197	-1.1
D2	08/19	0.000	2.957	3.14	193	-1.1
D3	06/13	0.000	2.500	3.18	139	2.0
D3	07/15	0.000	2.624	3.08	147	-4.2
D3	08/19	0.000	2.999	3.03	156	-6.1
D3	09/19	0.000	2.690	3.03	146	-1.3
D4	07/23	0.000	3.044	2.88	186	-0.4
D5	06/13	0.000	2.000	3.72	104	1.5
D5	07/15	0.000	1.814	3.69	102	-2.2
D5	08/19	0.000	1.672	3.72	86	-7.5
D5	09/19	0.000	1.590	3.82	85	2.0
SF7	06/09	0.000	2.570	2.52	131	2.0
SF7	07/16	0.000	2.727	2.57	140	-2.6
SF8	07/21	0.000	2.296	2.13	118	-2.0
SP1	09/17	0.000	2.560	2.46	201	-0.3
SP2	09/17	0.000	2.230	1.95	117	-0.2
SW1	06/09	0.000	3.160	4.78	213	0.7
SW1	07/16	0.000	3.219	4.78	221	-1.7
SW1	08/19	0.000	3.438	4.78	227	1.2
SW1	09/14	0.000	3.310	4.93	215	-1.4
SW2	09/14	0.000	2.790	2.40	138	-2.2
SW3	09/14	0.000	2.440	2.30	119	-1.8
SW4	07/19	0.000	2.675	2.46	136	-2.0
SW5	09/14	0.000	2.620	2.52	310	2.1
SW7	09/14	0.000	2.630	2.62	291	-0.1
SW9	07/24	0.000	1.550	1.33	89	3.1
SW10	Periodic S					
SW11	07/24	0.000	2.798	2.38	154	-1.8
SW11	09/12	0.000	2.830	2.44	153	-1.5
SW12	09/12	0.000	3.180	3.61	185	-0.6
SW13	07/24	0.000	2.501	2.05	174	-1.0
SW13	09/13	0.000	2.510	2.06	200	-0.7
SW14	07/24	0.000	2.286	2.05	186	-0.9
SW15	07/21	0.000	3.711	2.55	193	-0.3
SW16	07/21	0.000	1.784	1.44	89	-1.5

SITE	DATE	SOURCE FORMATION	DISCHARGE	TEMP	pH	Ca	Mg	Na	K	Cl	SO4	NO3
	1990		ft3/s	C	(Lab)	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l
B1	05/29	Madison	0.10	5.6	7.65	2.675	1.466	0.028	0.020	0.008	0.951	0.010
B2	05/29	Madison	0.20	5.0	7.66	2.629	1.203	0.035	0.020	0.008	0.321	0.013
B3	07/13	Madison	0.50	3.9	7.74	2.229	1.198	0.024	0.014	0.016	0.268	0.008
B4	07/13	Madison	0.50	3.9	7.85	2.554	1.231	0.034	0.016	0.014	0.130	0.008
CR1	05/28	Bighorn	0.75	5.0	7.75	2.336	0.727	0.022	0.006	0.008	0.033	0.009
CR1	07/14	Bighorn	0.50	6.1	7.86	1.734	0.571	0.014	0.006	0.008	0.030	0.006
D2	07/17	Madison	<.05	3.3	7.87	2.860	1.162	0.063	0.018	0.012	0.728	0.008
SF1	07/02	Surface	-	5.6	7.79	1.879	1.053	0.023	0.012	0.010	0.222	0.052
SF1	07/13	Surface	-	5.6	8.03	2.148	1.076	0.021	0.011	0.010	0.298	0.008
SF2	07/02	Surface	-	11.1	8.23	1.840	1.078	0.035	0.012	0.010	0.098	0.050
SF3	07/02	Surface	-	11.1	8.20	1.795	1.076	0.036	0.012	0.010	0.096	0.060
SF4	07/15	Surface	-	5.6	8.22	2.231	0.740	0.015	0.011	0.010	0.028	0.006
SF5	07/16	Surface	-	15.6	8.33	1.975	0.903	0.019	0.012	0.016	0.038	0.000
SF6	07/16	Surface	-	16.1	8.33	2.076	0.819	0.018	0.010	0.012	0.040	0.000
SF9	07/01	Surface	-	1.1	7.57	0.762	0.193	0.013	0.009	0.004	0.034	0.034
SF10	07/01	Surface	-	6.7	7.96	1.797	0.415	0.025	0.010	0.016	0.030	0.012
SF11	07/01	Surface	-	10.0	7.71	1.781	0.436	0.033	0.014	0.026	0.030	0.048
ST1	04/21	Gros Ventre	0.10	5.0	8.00	2.150	1.580	0.027	0.033	0.012	0.130	0.002
ST1	05/30	Gros Ventre	0.10	4.7	7.72	2.274	1.492	0.027	0.037	0.010	0.133	0.002
ST1	06/08	Gros Ventre	0.10	5.0	7.72	2.385	1.499	0.037	0.042	0.008	0.108	0.002
ST1	06/20	Gros Ventre	0.10	4.7	7.75	2.121	1.422	0.033	0.039	0.018	0.134	0.000
ST1	07/02	Gros Ventre	0.10	5.3	7.72	2.114	1.856	0.031	0.050	0.010	0.140	0.028
ST1	07/13	Gros Ventre	0.10	5.3	7.82	2.203	1.736	0.028	0.053	0.010	0.158	0.004
ST1	07/16	Gros Ventre	0.10	5.0	7.78	2.487	1.797	0.028	0.053	0.012	0.178	0.004
ST1	07/27	Gros Ventre	0.10	5.0	7.82	2.276	1.818	0.031	0.053	0.010	0.210	0.004
ST1	08/12	Gros Ventre	0.10	5.0	7.84	2.197	1.798	0.033	0.051	0.010	0.228	0.006
ST1	08/27	Gros Ventre	0.10	4.7	7.80	1.924	1.797	0.038	0.036	0.008	0.236	0.006
ST1	09/14	Gros Ventre	0.10	5.0	7.80	2.006	1.887	0.035	0.034	0.008	0.226	0.006
ST2	04/21	Gros Ventre/Bighorn	8.00	5.0	8.10	1.970	1.110	0.020	0.009	0.007	0.650	0.015
ST2	05/30	Gros Ventre/Bighorn	8.00	4.4	7.78	2.221	1.032	0.023	0.012	0.007	0.527	0.011
ST2	06/08	Gros Ventre/Bighorn	8.00	4.4	7.84	2.144	1.020	0.026	0.012	0.006	0.392	0.009
ST2	06/20	Gros Ventre/Bighorn	8.00	4.4	7.88	2.109	1.000	0.027	0.011	0.012	0.472	0.008
ST2	07/02	Gros Ventre/Bighorn	8.00	5.0	7.84	1.973	1.236	0.027	0.015	0.008	0.518	0.026
ST2	07/13	Gros Ventre/Bighorn	8.00	5.0	7.88	2.435	1.280	0.024	0.015	0.010	0.692	0.008
ST2	07/16	Gros Ventre/Bighorn	8.00	5.0	7.85	2.352	1.310	0.023	0.015	0.008	0.736	0.008
ST2	07/27	Gros Ventre/Bighorn	8.00	5.0	7.87	2.236	1.328	0.023	0.014	0.006	0.670	0.008
ST2	08/12	Gros Ventre/Bighorn	8.00	5.0	7.93	2.509	1.371	0.023	0.015	0.010	0.770	0.008
ST2	08/27	Gros Ventre/Bighorn	6.00	4.7	7.86	2.270	1.430	0.026	0.012	0.008	0.798	0.008
ST2	09/14	Gros Ventre/Bighorn	3.00	5.0	7.86	2.330	1.450	0.026	0.012	0.006	0.858	0.008
ST3	04/21	Gros Ventre	0.25	5.0	8.05	1.510	1.540	0.033	0.020	0.006	0.266	0.006
ST3	06/08	Gros Ventre	0.25	5.0	8.07	1.680	1.494	0.062	0.036	0.006	0.241	0.005
ST4	04/21	-	0.50	4.7	8.40	1.870	0.950	0.019	0.007	0.008	0.432	0.005
ST5	04/21	-	-	6.7	7.93	1.970	1.080	0.020	0.009	0.008	0.638	0.013
ST6	04/21	Amsden	0.10	6.7	8.19	2.080	1.150	0.020	0.010	0.011	0.694	0.008
ST7	Beaver Dam Spring, See Appendix A											
ST8	Upper Rise Spring, See Appendix											
ST9	07/13	Madison	0.05	3.9	7.90	1.915	1.121	0.026	0.013	0.012	0.128	0.012
SW5	06/10	Madison	0.05	6.1	8.13	3.251	1.267	0.029	0.014	0.006	2.673	0.005
SW5	08/28	Madison	0.05	6.7	7.70	4.274	2.016	0.030	0.014	0.008	3.002	0.004
SW6	06/10	Madison	0.05	5.6	8.06	3.936	1.583	0.029	0.014	0.006	2.604	0.005
SW6	08/28	Madison	0.05	6.7	7.72	3.987	1.976	0.031	0.015	0.008	2.750	0.002
SW7	06/10	Madison	0.05	5.6	7.89	3.812	1.527	0.032	0.016	0.006	2.481	0.006
SW7	08/28	Madison	0.05	6.7	7.75	3.849	1.928	0.031	0.015	0.008	2.680	0.004
SW8	08/28	Madison	0.25	5.6	7.77	3.341	1.588	0.046	0.015	0.010	1.648	0.006
SW10	Periodic Spring, See Appendix A											
SW11	04/20	Wells	0.25	5.3	7.72	1.750	0.820	0.033	0.009	0.022	0.135	0.016
SW11	06/10	Wells	0.50	5.3	7.79	2.205	0.916	0.042	0.011	0.009	0.171	0.010
SW13	06/10	Thaynes	1.00	3.6	7.83	2.949	1.119	0.046	0.012	0.007	0.705	0.013
W1	07/16	Madison	0.05	6.1	7.78	2.662	1.306	0.039	0.019	0.012	0.578	0.010

SITE	DATE	PO4	ALKALINITY	TDS	CHARGE
	1990	meq/l	meq/l	ppm	BALANCE (%)
B1	05/29	0.000	3.353	220	-1.5
B2	05/29	0.000	3.812	200	-3.2
B3	07/13	0.000	2.558	151	9.8
B4	07/13	0.000	3.170	170	7.3
CR1	05/28	0.000	3.178	154	-2.2
CR1	07/14	0.000	1.946	103	7.9
D2	07/17	0.000	2.954	198	5.1
SF1	07/02	0.000	2.916	153	-3.7
SF1	07/13	0.000	2.440	145	8.3
SF2	07/02	0.010	2.903	147	-1.7
SF3	07/02	0.010	2.928	148	-3.0
SF4	07/15	0.000	2.608	135	6.2
SF5	07/16	0.000	2.438	127	7.8
SF6	07/16	0.000	2.460	129	7.6
SF9	07/01	0.000	0.968	51	-3.0
SF10	07/01	0.000	2.412	117	-4.7
SF11	07/01	0.000	2.361	118	-4.4
ST1	04/21	0.000	4.211	197	-7.0
ST1	05/30	0.000	4.020	193	-4.3
ST1	06/08	0.000	4.036	195	-2.3
ST1	06/20	0.000	3.998	189	-6.8
ST1	07/02	0.000	4.187	202	-3.8
ST1	07/13	0.000	3.822	191	0.4
ST1	07/16	0.000	3.734	196	5.3
ST1	07/27	0.000	3.831	196	1.5
ST1	08/12	0.000	3.709	192	1.6
ST1	08/27	0.000	3.455	178	1.2
ST1	09/14	0.000	3.543	183	2.3
ST2	04/21	0.000	2.794	170	-5.5
ST2	05/30	0.000	2.792	168	-0.8
ST2	06/08	0.000	2.756	159	0.6
ST2	06/20	0.000	2.764	162	-1.7
ST2	07/02	0.000	2.952	171	-3.7
ST2	07/13	0.000	2.626	178	5.8
ST2	07/16	0.000	2.688	181	3.6
ST2	07/27	0.000	2.809	179	1.6
ST2	08/12	0.000	2.795	190	4.5
ST2	08/27	0.000	2.594	181	4.6
ST2	09/14	0.000	2.679	188	3.7
ST3	04/21	0.000	3.149	158	-5.1
ST3	06/08	0.000	3.299	166	-4.1
ST4	04/21	0.000	2.714	153	-5.2
ST5	04/21	0.000	2.785	169	-5.5
ST6	04/21	0.000	2.905	178	-5.2
ST7	Beaver Dam S				
ST8	Upper Rise S				
ST9	07/13	0.000	2.449	134	8.5
SW5	06/10	0.000	2.938	299	-10.4
SW5	08/28	0.000	2.626	335	5.8
SW6	06/10	0.000	2.972	314	-0.3
SW6	08/28	0.000	2.661	318	5.2
SW7	06/10	0.000	2.893	303	0.0
SW7	08/28	0.000	2.657	311	4.2
SW8	08/28	0.000	2.842	253	5.1
SW10	Periodic Spr				
SW11	04/20	0.000	2.769	137	-5.9
SW11	06/10	0.000	3.075	158	-1.6
SW13	06/10	0.000	3.273	207	1.6
W1	07/16	0.000	3.193	195	3.1

APPENDIX C

A comparison of two lower Strawberry Creek springs

Erickson (Unpub. data) sampled W and Big springs, located on the south side of the lower reach of Strawberry Creek (See Appendix B location map, W = ST1, Big = ST2), several times during summer 1989. Though the springs are within several hundred feet of each other and appear to be discharging from the same Cambrian unit, he noted a difference in chemistry. These springs were sampled 12 times from April 1990 to September 1990. Data are reported in Appendix B.

The two springs form distinct groups on composition diagrams (Fig. C1). W Spring samples tend to cluster, whereas Big Spring samples form a line. Big Spring has a noticeably lower magnesium and alkalinity concentration, but a higher sulfate concentration. Figure C2 is a fingerprint diagram of representative samples showing that the two have different overall patterns.

Time series plots (Figs. C3 and C4) show a midsummer step increase of magnesium and sulfate concentrations for both springs. In W Spring this is accompanied by a slight step decrease in alkalinity concentration.

Two factors produce the changes and differences in the chemistry of these springs. The concentrations of magnesium and sulfate are lower in the first part of the summer because local snowmelt infiltrates the soil and dilutes spring discharge. This snowmelt flushes through by midsummer.

Secondly, the chemistry of Big Spring differs from that of W Spring because water from Strawberry Creek contributes to the discharge. W Spring is located 150 to 200 feet (45-60 m) farther from the river and 20 feet (6 m) higher in elevation than Big Spring. The influence of the creek is shown in figure C5, a fingerprint diagram which shows a sample of each spring and the creek. Strawberry creek water decreases the alkalinity and magnesium concentrations and increases the sulfate concentration of Big Spring. The contribution of the creek changes over the sampling period, thus producing the line in the composition diagrams.

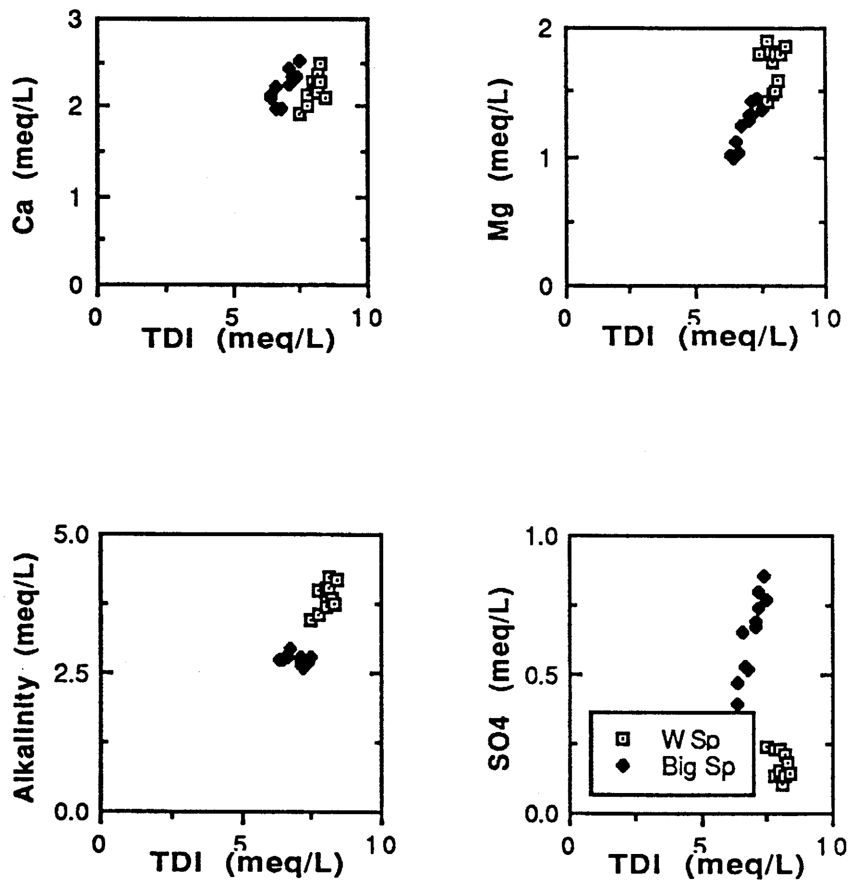


Fig. C1. Composition diagrams of 1990 Big and W springs data. The two springs form distinct groups.

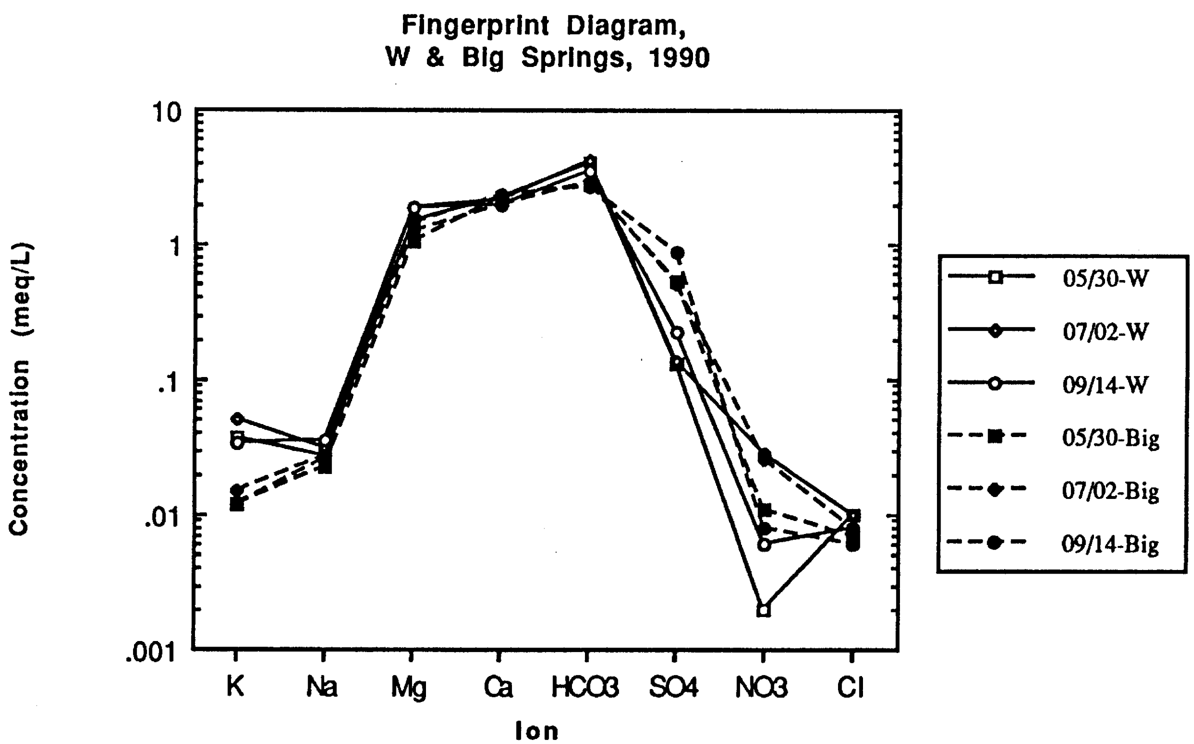


Fig. C2. Fingerprint diagram of representative 1990 samples of W and Big springs, Strawberry Creek, Salt River Range, Wyoming.

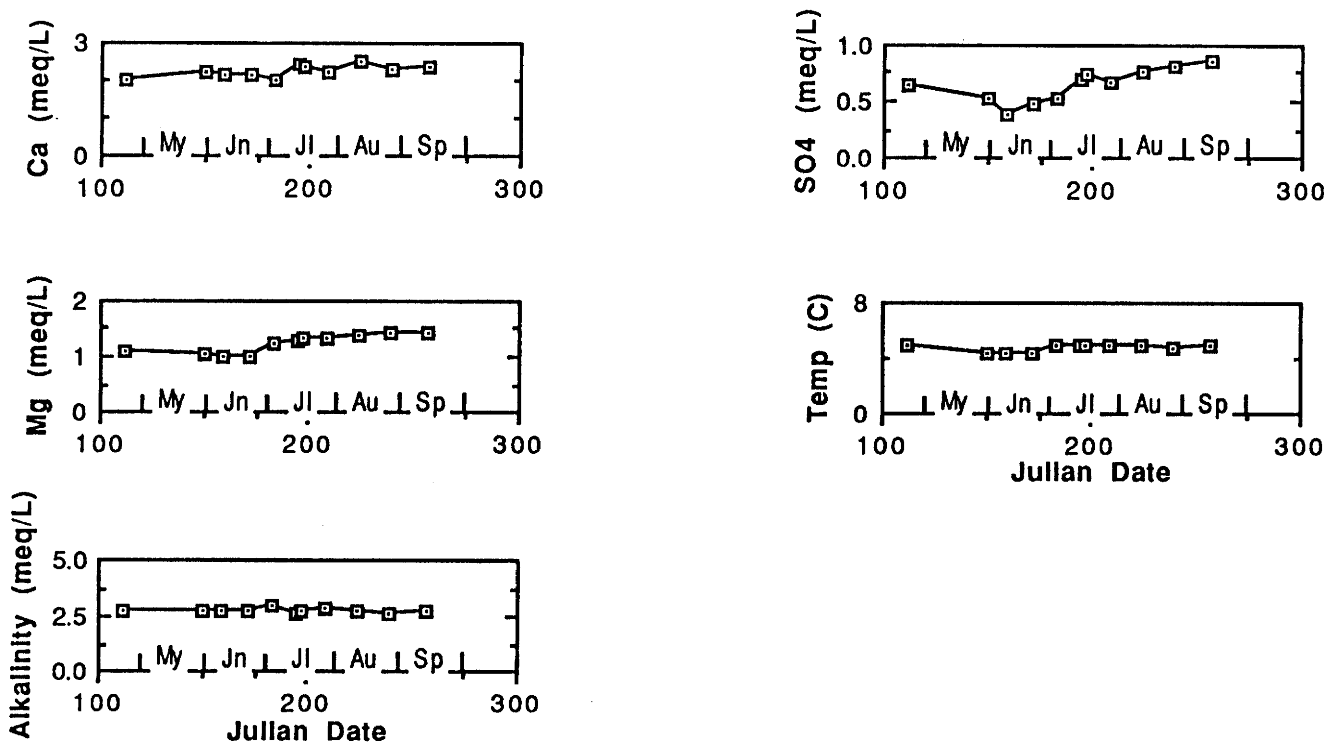


Fig. C3. Time series plots of 1990 Big Spring data.

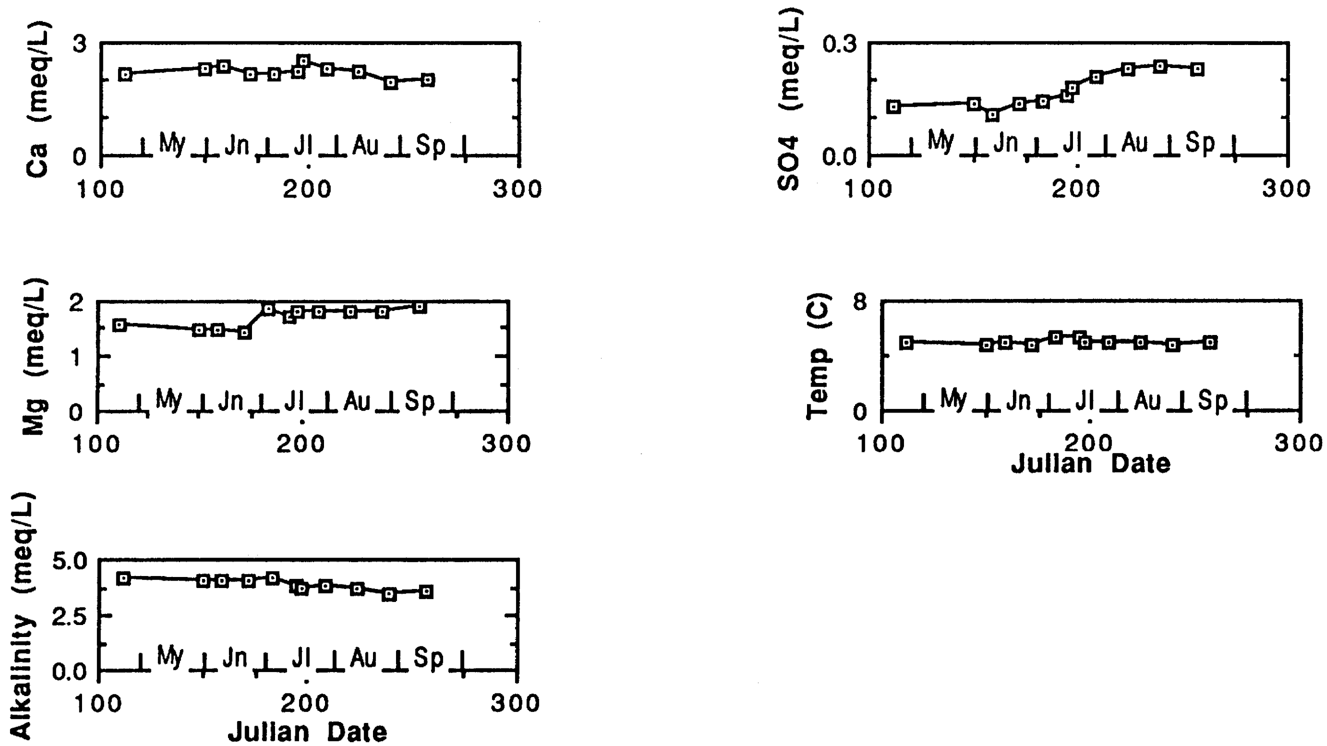


Fig. C4. Time series plots of 1990 W Spring data.

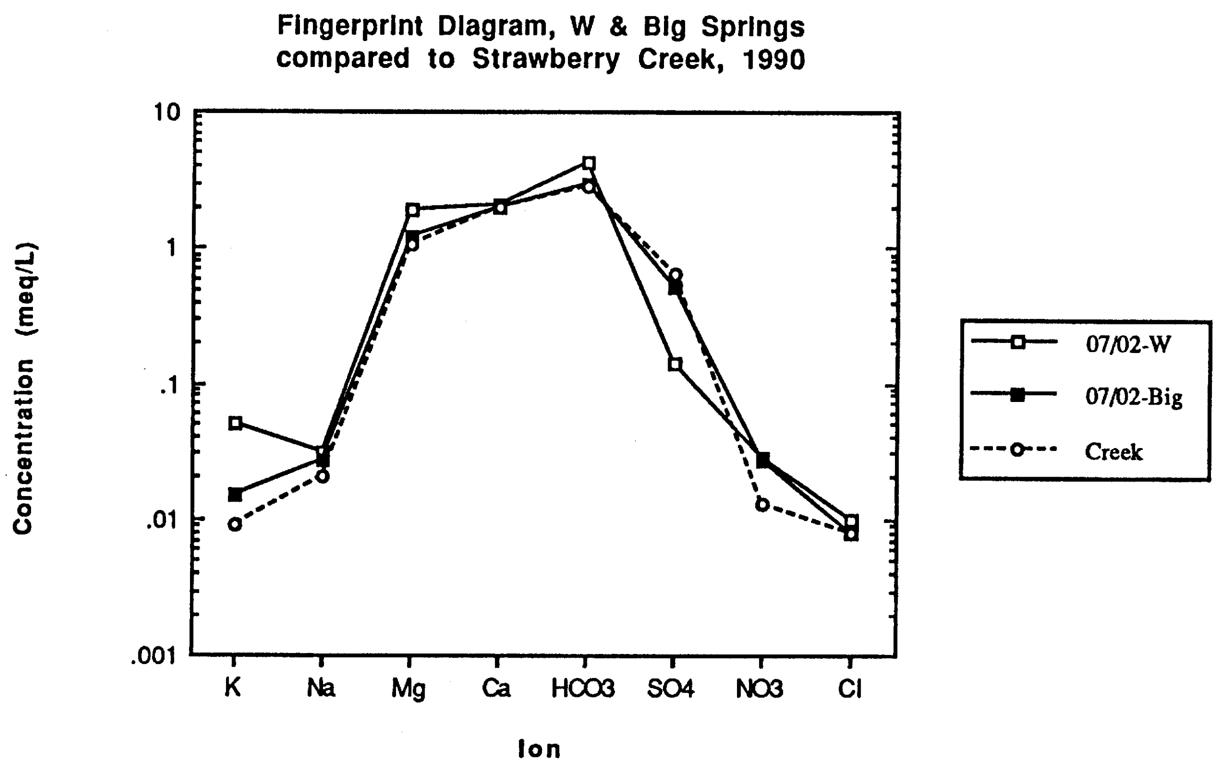


Fig. C5. Fingerprint diagram comparing W and Big springs to Strawberry Creek, Salt River Range, Wyoming. A portion of Big Spring discharge is actually water from Strawberry Creek, causing the fingerprint of Big Spring to follow that of Strawberry Creek.

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