WATER QUANTITY AND QUALITY AT BRYCE CANYON NATIONAL PARK

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Groundwater movement and discharge through Bryce Canyon National Park (BCNP) is governed by the relatively uniform "layer-cake" geology, the shallow dipping Bryce Canyon anticline, and the disruption of the laterally consistent geologic units by the Paunsaugunt Fault and the Ruby's Inn Thrust Fault. Groundwater movement was examined using spring discharge measurements and water quality data collected in November 1998 to develop a simple hydrologic budget and refine the conceptual model for water movement in the basin proposed by Marine (1963). The conceptual model is used to interpret the general direction and distribution of groundwater flow at BCNP and to answer two specific questions relevant to Park management: Where does the water that discharges at Mossy Cave spring originate? What is the basis for the poor quality of water in the well drilled near Yellow Creek? The study site is shown in Figure 1.

Water movement and discharge through the Park has become more important with the increasing demands for water in this arid part of the southwestern United States. The focus on the water resources of BCNP has increased due to heightened visitor usage of the Park, and the growing water supply needs of the surrounding communities. The Park lands straddle the drainage divide between the Paria River and the East Fork of the Sevier River. The Paria.River drains to the Colorado River Basin. Water rights for BCNP under the Federal Reserved Water Rights Doctrine were claimed in the Colorado River Adjudication within Kane, Garfield, Wayne and Piute, Emery, Sevier and Sanpete counties in 1983. To the west, streams originating in the Park drain to the Sevier River basin, whose waters have been under adjudication since 1936 (Czarnowski 1991). The water supply for BCNP is drawn from wells on the west side of the Park, from East Creek, a tributary to the East Fork Sevier River. At the southern end of the Park, water is also drawn from Yovimpa Spring, which also discharges to the west of the Park, to the East Fork Sevier River.

Geology

The Park's geologic formations both create the beautiful views from the Park and influence the movement of groundwater through the Park. The axes are described as follows, and are shown in Figure 2, taken from Marine (1963). The Claron Formation, which forms the renowned Bryce hoo-doos, has a maximum thickness of 800 ft and is composed of limey sands and shales. It is underlain by the Kaiparowits Formation, which was mostly eroded away in the vicinity of BCNP before the deposition of Claron sediments. The Kaiparowits Formation is mostly sandstone, with interbedded mudstones. The Wahweap Formation underlies the Kapairowits, also composed of sandstone and smaller amounts of mudstone, with thicknesses in the BCNP area of 200–400 ft. It is underlain by the Straight Cliffs Formation, about 1,500 ft in thickness, composed of four distinct members of marine and alluvial origin. The Straight Cliffs Formation is primarily sandstone, with mudstone and coal present in the upper part, which ranges in thickness from 1,000 to 1,100 ft. The lower Straight Cliffs ranges in thickness from 320 to 400 ft, and is composed of sandstone mudstone, carbonaceous mudstone, and coal. Underlying the Straight Cliffs is the Tropic Shale, present regionally at thicknesses ranging from 700 to 1,000 ft, composed of gray claystone, with some fine interbedded sandstone and mudstone (Bowers 1990). The Tropic Shale rests on the Dakota Formation and underlying Jurassic Rocks. The Dakota Forma-

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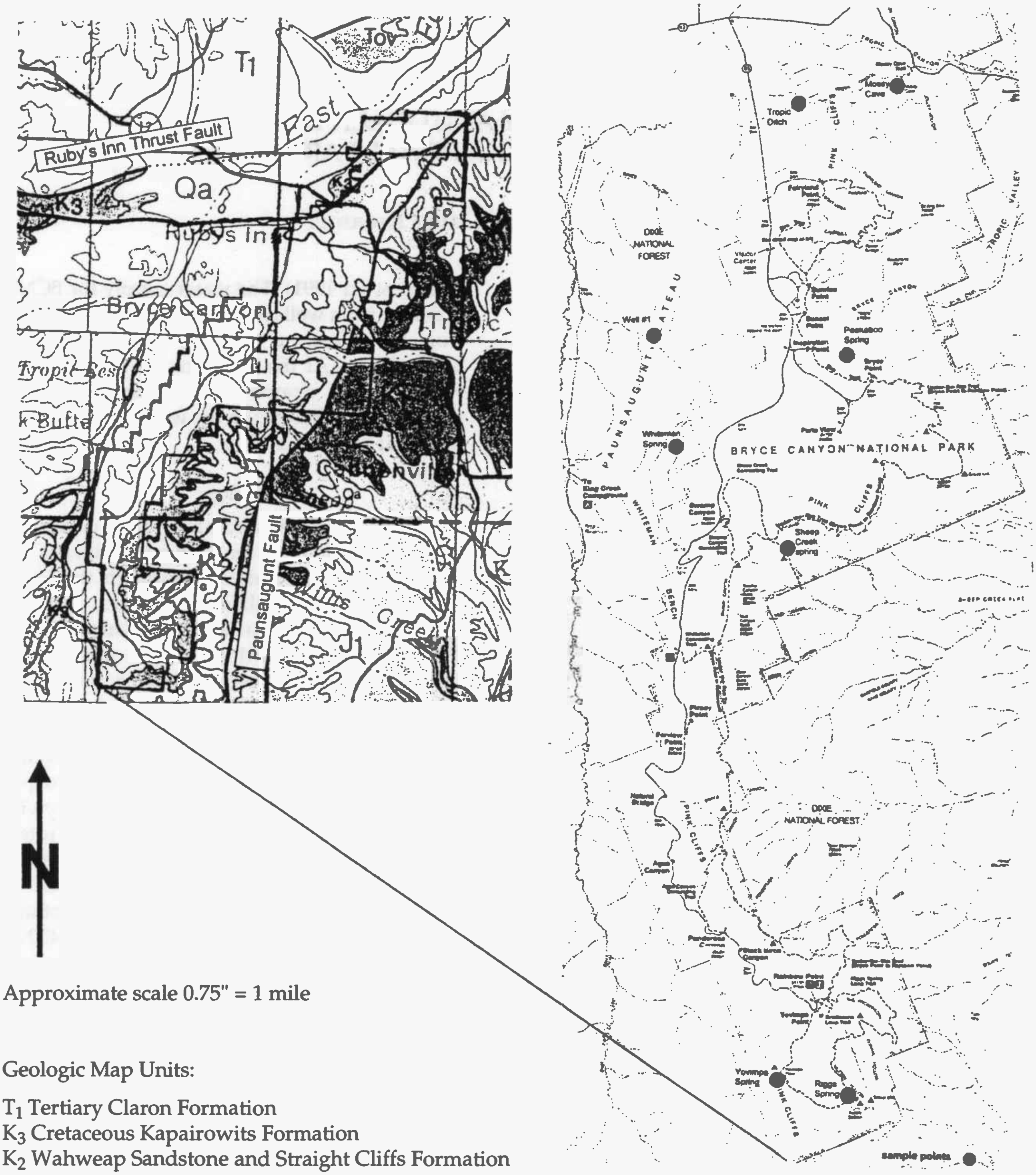
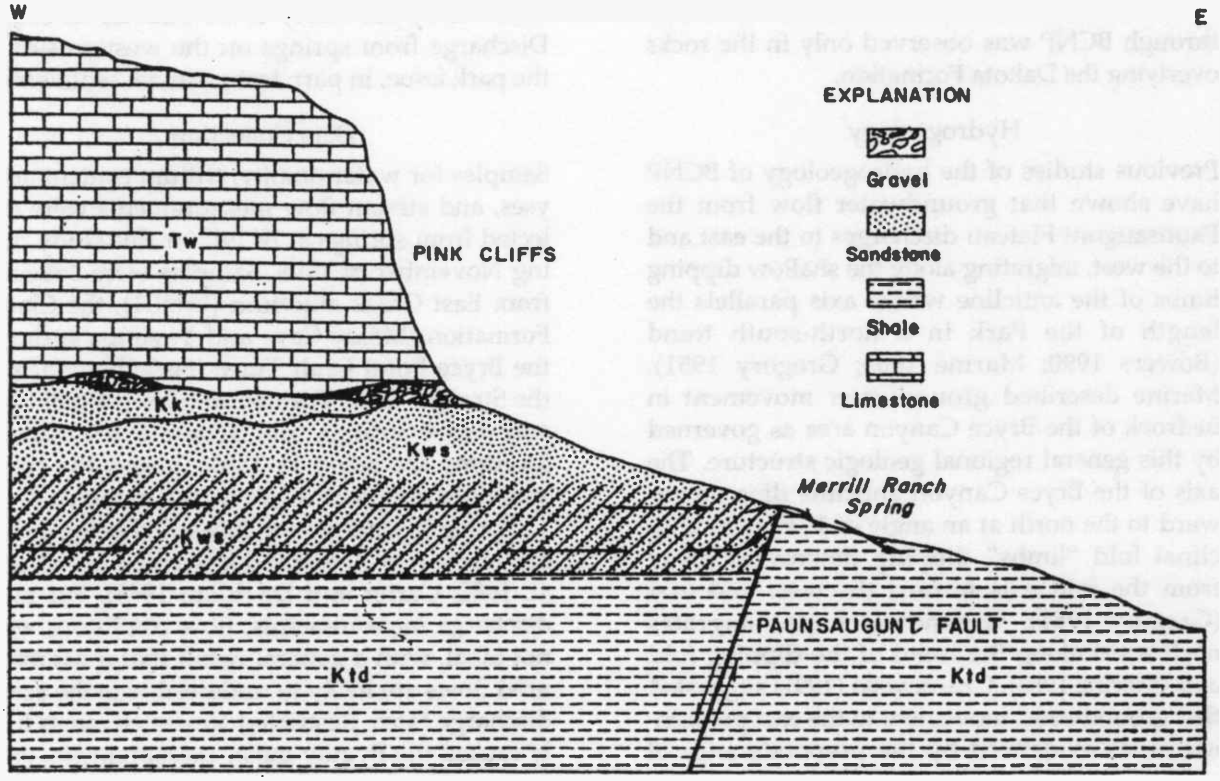


Approximate scale 0.75" = 1 mile

Geologic Map Units:

T_1 Tertiary Claron Formation
K_3 Cretaceous Kapairowits Formation
K_2 Wahweap Sandstone and Straight Cliffs Formation
K_1 Tropic Shale

Figure 1. Bryce Canyon regional geology and data collection locations.



Geologic Map Units:

Tw = T_1 Tertiary Claron Formation
Kk = K_3 Cretaceous Kapairowits Formation
Kws = K_2 Wahweap Sandstone and Straight Cliffs Formation
Ktd = K_1 Tropic Shale

Figure 2. Generalized diagram of Bryce Canyon National Park geology and Paunsaugunt Fault–induced spring discharge (after Marine 1963).

tion and underlying rocks were not the subject of examination for this study because they are not exposed at the ground surface within the Park boundaries, and movement of water through BCNP was observed only in the rocks overlying the Dakota Formation.

Hydrogeology

Previous studies of the hydrogeology of BCNP have shown that groundwater flow from the Paunsaugunt Plateau discharges to the east and to the west, migrating along the shallow dipping limbs of the anticline whose axis parallels the length of the Park in a north-south trend (Bowers 1990; Marine 1963; Gregory 1951). Marine described groundwater movement in bedrock of the Bryce Canyon area as governed by this general regional geologic structure. The axis of the Bryce Canyon anticline dips downward to the north at an angle of 1–3°, with anticlinal fold "limbs" dipping downward away from the fold axis toward the west and east (Gregory 1951). Groundwater also migrates northward along the trend of the dipping fold axis (Marine 1963). Czarnowski (1991) suggested that groundwater movement to the east predominates, as evidenced by the preponderance of springs formed on the eastern margin of the Park along the slopes descending from the Paunsaugunt Plateau. Springs are also present along the western and southern margin of the Park, likely resulting from lateral movement of groundwater intercepted by the sloped ground surface.

The hydrogeology east of the Park is also impacted by the presence of the Paunsaugut Fault. Rock formations along the eastern side of the fault have been uplifted 1000–1500 ft in relation to those on the western side (Gregory 1951). Consequently, the Tropic Shale on the eastern side abuts against the higher permeability sediments of the Claron, Wahweap, and Straight Cliffs formations on the western side. The rate of water migrating from BCNP toward the east in the higher permeability sediments is significantly reduced when the fault zone is encountered, and it moves upward to discharge at the ground surface in the vicinity of the fault zone. Springs likely to result from Paunsaugut Fault–induced discharge are the Dr. Goode (Tropic City), Campbell Canyon, Merrill Ranch, and Bryce springs (Marine 1963).

Shallow subsurface water flow occurs in alluvial sediments deposited in more recent geologic time by the streams and rivers in the Park area (Czarnowski 1991). Czarnowski has suggested that the springs emitting in the East Fork valley are likely to be alluvial in origin. Discharge from springs on the western side of the park issue, in part, from alluvial sediments.

Data Collection

Samples for water quality, tritium content analyses, and stream flow measurements were collected from springs at BCNP for this study during November of 1998. Samples were collected from East Creek alluvium (Well 1), the Claron Formation (Mossy Cave and Yovimpa springs), the Bryce Point Fault Trace (Peekaboo Spring), the Straight Cliffs Formation (Sheep Creek seep and Riggs Spring), and Tropic Ditch. Sample locations are listed in Table 1, and the corresponding sample sites are shown in Figure 1.

Spring discharge was measured using a Pygmy meter (USGS method described in Rantz et al. 1982; Carter and Davidian 1968). For most discharge measurements, flow conditions were not ideal, with a general result that most measured flows are likely to underestimate the actual discharge rates. Restricted stream channels likely caused the Pygmy meter measurements to be impacted by friction between water and streambed; as a result, these measurements may underestimate the actual flow rate by up to 50%.

Samples for laboratory analyses were collected using a clean bucket and funnel from springs and Tropic Ditch, and from a tap in the well housing from Well 1. Samples for chemical analyses were preserved with acid, and were not filtered at the time of collection. Care was taken to ensure that particles were not included in sample bottles. Water samples were immediately placed on ice and transported to a cooler with ice. Samples were shipped to the North Creek analytical laboratory in Bothell, WA via overnight express within 48 hours of collection. The cation and anion contents analyzed are listed in Table 2. Ferrous iron content was measured in the field immediately after sample collection using a Hach colorimetric field kit, with an accuracy of 0.1 mg per liter. Geochemical parameters of pH, dissolved oxygen, redox potential, and temperature were measured at sample collection sites using an Orion Model 1230 Multiparameter Meter. However, the meter malfunctioned during the field data collection, and only temperature was consistently collected at sample sites. Tritium content analyses were performed on

Table 1. Sample collection locations.

Sample Name	Sample Location	Date	Source	Lithologic Unit	Elevation (ft)
Whiteman	Whiteman Spring	11/2/98	Diffuse spring	Claron Formation	8160
Tropic	Tropic Ditch	11/2/98	E. Fork Sevier River	NA	7640
Well 1	East Creek drainage	11/3/98	Groundwater	Alluvium/ Claron Formation	7695–7775
Yovimpa	Yovimpa Spring	11/3/98	Spring	Claron Formation	8320
Riggs	Riggs Spring	11/3/98	Spring	Straight Cliffs Formation	7500
Mossy Cave	Mossy Cave Spring	11/4/98	Diffuse spring	Claron Formation	6980
Water Canyon	Water Canyon stream	11/4/98	Stream flow	Claron Formation	6880
Falls Pool	Water Canyon stream	11/4/98	Stream flow	Claron Formation	6840
Peekaboo	Peekaboo Spring	11/4/98	Spring	Claron Formation	7600
Sheep Creek	Sheep Creek seep	11/5/98	Seep	Straight Cliffs Formation	7560
Still Spring*	Tropic Ditch	11/5/98	E. Fork Sevier River	NA	7640

*Sample collected at same location as Tropic sample for QA purposes

three samples using the same methods as for the water quality samples. Samples were not preserved, and were analyzed within 2 weeks of sample collection.

Spring Discharge Rates

Spring flow from the Claron Formation was measured during November 1998 at Peekaboo (6 gallons per minute, gpm), Whiteman (0.1 gpm), Yovimpa (61 gpm), and Mossy Cave (264 gpm). The flow at Whiteman was from a diffuse seep, and was estimated visually; the estimate was not used for further analysis. Flows from Peekaboo were also diffuse, and previously published discharge rates were not available for comparison. Flows from Mossy Cave and Yovimpa had both been measured previously, at 200 gpm and 1 gpm respectively, and the flow measured in November 1998 was higher in both springs than the previously published values.

Stream discharge measured at four points in Water Canyon showed a gaining stream reach from the falls above the Mossy Cave area to the eastern Park boundary, about half a mile in length. The four measured flow values were from just below the falls in Water Canyon at 119 gpm, just above and below the Mossy Cave spring confluence at 317 and 581 gpm respectively, and at the path crossing approximately 1/4 mile downstream of Mossy Cave at 925 gpm. The difference between the closest measurement points upstream and downstream of the confluence were subtracted to derive the discharge measurement for Mossy Cave spring (950 gpm).

Springs emitting from the Straight Cliffs Formation that were measured in November 1998 are Riggs and Sheep Creek at 0.8 and 33 gpm respectively. Measurements from both springs have been reported previously (Table 3). The Riggs Spring discharge was equivalent to that measured by Ott in the summer of 1996 at 0.9 gpm. The discharge measured in Sheep Creek was between previous measurements by Ott (1996) at 18 gpm and Marine (1963) at 48 and 34 gpm during the spring and fall of 1957 respectively.

Water Chemistry

The water chemistry from all springs reflected the carbonate lithology of the Claron Formation, with some small but notable variations (see Table 2). Calcium and magnesium concentrations (calcium 29–110 mg/l and magnesium 21–30 mg/l) were the highest cations. Sodium and potassium had the next highest cation abundances, with concentrations averaging an order of magnitude less than calcium and magnesium (sodium 2.4–10 mg/l and potassium 0.3–9.8 mg/l). Additional metals detected in trace amounts (all less than 1 mg/l) were aluminum, barium, copper, manganese, titanium, vanadium, and zinc. Titanium was detected, at very low concentrations, only in the Tropic Ditch samples. Barium was detected in every sample (0.02–0.42 mg/l), as was iron. Ferrous iron was detected in field measurements in water collected from Well 1 (at 1 mg/l), from Riggs Spring (1 mg/l), and in Sheep Creek streamflow (0.6 mg/l). Laboratory analysis showed that the

Table 2. Water chemistry measured in 1998 samples, laboratory analyses and field measurements (mg per liter).

Spring Name	Tropic	Still Spring	Mossy Cave	Water Canyon	Falls Pool	White-man	Well 1	Peeka-boo	Sheep Creek	Riggs	Yovimpa
Analyte											
Ca	50	51	34	39	29	55	42	37	110	87	42
Mg	30	30	25	30	29	30	29	30	30	30	21
Na	9.3	10	3.5	3.7	3.4	1.7	2.4	3.4	2.9	4.5	1.4
K	9.1	9.8	1.0	1.3	1.7	0.5	0.4	0.7	1.1	2.4	0.3
Fe total	0.58	0.61	0.23	0.34	0.22	0.57	0.30	0.30	0.58	0.74	0.26
Fe2+	0.0	NA	0.0	0.0	0.0	0.0	1.0	0.0	0.0	1.0	0.0
Fe3+ *	0.6	NA	0.2	0.3	0.2	0.6	0.0	0.3	0.6	0.0	0.3
Al	0.17	0.17	< 0.01	< 0.01	< 0.01	0.2	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Ba	0.37	0.41	0.42	0.33	0.23	0.33	0.28	0.44	0.020	0.063	0.22
Cd	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Cu	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.01	< 0.01	< 0.01	< 0.01	< 0.01
Pb	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Mn	0.02	0.02	< 0.01	0.01	< 0.01	0.01	< 0.01	0.01	< 0.01	0.14	< 0.01
Ni	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Ti	0.01	0.02	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Va	< 0.01	0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.01	< 0.01
Zn	< 0.01	0.01	0.04	< 0.01	< 0.01	< 0.01	0.05	< 0.01	< 0.01	< 0.01	< 0.01
NO2-	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
NO3-	< 0.1	< 0.1	0.4	0.3	0.2	< 0.1	< 0.1	0.3	< 0.1	< 0.1	< 0.1
SO4-	12.8	14.0	5.8	6.8	7.7	3.7	5.3	5.6	296	49.1	4.5
S2-	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5
Alkalinity	383	425	242	240	233	294	272	245	391	441	240
Br	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Cl	41.4	44.7	6.1	6.7	6.8	1.8	2.1	4.1	4.9	6.3	1.6
Fl	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.3	0.4	< 0.1	0.1
Orthophosphate	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
Flow rate (liters/min)	NA	NA	1,000	1,200	450	NA	NA	23	120	3.2	230
Temperature °C	4.5	NA	7.4	5.9	5.8	4.2	6.1	1.1	NA	6.1	5.8
pH (field)	8.4	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

* Fe3+ derived by subtraction of Fe2+ content from total Fe detected. Fe2+ measurements only accurate to 0.1 mg/l, implying the same accuracy for Fe3+ content.

total iron content in the Sheep Creek sample was 0.58 mg/l, suggesting that at the sample collection point all dissolved iron was in the ferrous ionic state.

Alkalinity was significantly higher in concentration than any other anions present in samples collected for this investigation, with the exception of sulfate concentration in the Sheep Creek spring. Sulfate was present in all water samples collected, with the highest concentrations detected in springs discharging from the Straight Cliffs Formation: Riggs Spring at 296 mg/l and Sheep Creek at 49.1 mg/l. The sulfate concentration in remaining samples ranged from 3.7 to 14 mg/l. Chloride concentrations ranged from 1.6 to 44.7 mg/l, with the Tropic Ditch concentrations an order of magnitude greater than the other samples analyzed. Fluoride was detected

Table 3. Comprehensive summary of measured discharge rates, Bryce Canyon National Park (gpm).

	Nov 2–4 98	Jun 18–28 96	Jul 1–4 96	Jun 16 88	May 23 82	Oct 18–22 81	Nov 15 81	Sep 23 81	Jul 24 81	Sep 9 60	Sep 16 60	Aug 26 60	Aug 29 60	Jun 20–21 58	Sep 24–25 57	Jun 21 57	May 15–20 57
References:	1	B	B	A	C	C	C	C	C	D	D	D	D	D	D	D	D
WEST SIDE SPRINGS																	
Alluvium																	
Bridge Hollow (8020)*					216			48	34								
USGS C37-4-31CBB-S1																	
Straight Cliffs Fm																	
Riggs Spring (7500)	0.9	0.9															
Claron Formation																	
Yovimpa Spring (8320)	61			1		1											
USGS C38-4-31AAA-S1																	
EAST SIDE SPRINGS																	
Water Canyon Discharge																	
Mossy Cave (6980)	264.2					200											
USGS C36-3-21AAC-S1																	
Water Canyon (6900)	951																
Straight Cliffs Fm Discharge																	
Sheep Creek (7560)	32	18													34		48
Yellow Creek (7220)		40								40	50	50	48	32	53	42	79
Rt Fk Yellow Crk (7040)		7.4														75	
Upper Yellow Cr Wash (7200)															120	140	120
2nd Yellow Cr wash (7200)																190	
3rd Yellow Cr wash (5800)															61		
Claron Formation Discharge																	
Peekaboo Spring (7600)	61		very low														
Swamp Spring (7880)		3.7													2		11
Trough Spring (8340)			no flow			0.9											
USGS C37-4-16DCB-S2																	
Iron Spring (7820)			0.3														
Natural Bridge (8020)			0.66														
PAUNSAUGUNT FAULT SPRINGS																	
Claron Formation Discharge																	
Campbell Creek (6800)							1								28		17
C36-3-33BCA-S1																	
Tropic (Dr. Goode) Spring (6740)						238											
USGS C36-3-22BDB-S1																	
Jolley Hollow (7400)		20															
Merrill Ranch Spring (6980)						5.5								12	24	12	17
USGS C37-3-9BCB-S1																	

*Elevation in feet.

References: 1 This study; A Thiros and Brothers (1993); B Ott (1996); C Plantz (1983); D Marine (1963).

in all samples at concentrations of 0.1–0.4 mg/l, except for a non-detection at Riggs Spring. Nitrate was detected in all Water Canyon samples (Mossy Cave, Water Canyon, Falls Pool) and at Peekaboo Spring, with concentrations ranging from 0.2 to 0.4 mg/l.

Tritium Analyses

Measurement of tritium content in groundwater is used to estimate the length of time that groundwater has been in the subsurface. This age dating of groundwater, using tritium content, derives from the fact that atmospheric testing of high-yield thermonuclear devices conducted from 1952 through 1964 released a spike of tritium to the atmosphere. Subsequent to the bomb-pulse spike, tritium content in the atmosphere has gradually decayed, with a half-life of approximately 12.42 years.

Tritium in the atmosphere is incorporated into water that falls to the ground surface as precipitation. The atmospheric tritium ratio is preserved exactly in the tritium ratio for precipitation, and therefore in the precipitation that infiltrates and recharges groundwater. Tritium content measured in groundwater is not only a function of the atmospheric concentration at the time of infiltration, but is also a function of mixing with more recently infiltrated water.

The atmospheric tritium to hydrogen ratio has been monitored by the International Atomic Energy Agency (IAEA) since 1952 (tritium content relates linearly to the tritium to hydrogen ratio, by a factor of 0.31). The atmospheric ratios measured by the IAEA at Flagstaff and Albuerquerque are shown in Table 4. Also shown in Table 4 are the calculated equivalent tritium ratios that would be found in water that infiltrated at that monitoring date and discharged from the ground surface during sampling in 1998.

The present-day tritium ratios were compared with the tritium ratios detected in samples, using the method described by Fitzgerald (1996). Tritium content detected in the three springs samples collected at BCNP and their corresponding tritium ratios are listed in Table 5. Comparing the tritium ratios of spring samples with the ratios shown in Table 4 yields a likely date of infiltration for sampled water. In comparing these values for this study, we assumed no mixing of more recently infiltrated groundwater with older groundwater.

Table 4. Historic tritium ratio data and corresponding present-day ratios.

Year	Monitored Tritium Ratio in Atmosphere*	Present-Day Tritium Ratio After Decay
Flagstaff, Arizona		
1962	952	121
1963	1,415	190
1964	980	139
1965	455	68
1966	572	91
1967	344	58
1968	115	20
1969	153	29
1970	97	19
1971	100	20
1972	47	17
1973	136	32
1974	68	30
Albuquerque, New Mexico		
1975	60	28
1976	60.3	29
1977	49.7	15
1978	45.4	14
1979	22.9	8
1980	23.3	8
1981	35.7	13
1982	28.9	11
1983	16.2	7
1984	16.5	7
1985	19.7	9
1986	17.3	8
1987	11.2	6
1988	18.9	10
1989	10	6
1990	11.4	7
1991	8.6	6
1995	10.7	9

*Monitored by the International Atomic Energy Agency.

Tritium ratios for Mossy Cave (2.5) and Sheep Creek (1.9) springs are lower than any values calculated for precipitation that infiltrated since initiation of atmospheric testing (1952). The minimum calculated tritium ratio since atmospheric testing was initiated is 6 (shown in Table 4). Water with these tritium ratios was not exposed to atmospheric tritium associated with nuclear testing and therefore infiltrated prior to the initiation of testing in 1952. Water emitting from both these springs has likely been in the subsurface for at least 50 years.

Table 5. Tritium content detected in spring water.

Sample	Tritium Content (picoCuries/liter)	Tritium Ratio
Yovimpa Spring	57	17.7
Mossy Cave	1.9	1.9
Sheep Creek Spring	2.5	2.5

The tritium ratio calculated for Yovimpa Spring is 17, which is close to the tritium ratios for water that would have infiltrated in the 1970s. This suggests an infiltration date approximately 15–30 years ago, and a commensurate subsurface travel time of 15–30 years for groundwater that discharges from Yovimpa Spring.

Discussion of Chemical and Spring Flow Data

Precipitation during the month of October in 1998 was higher than any monthly precipitation for October on record, and total annual precipitation for 1998 was the second highest year on record. Consequently, water samples and measurements collected for this project during the first week of November in 1998 represent some of the highest hydrologic discharge conditions for BCNP.

The higher than previously reported spring discharge rates measured in 1998 for the Claron Formation springs (Yovimpa and Mossy Cave) are evidence that these springs respond rapidly to changes in recharge. The relatively consistent discharge rates measured for the Straight Cliffs Formation springs (Sheep Creek and Riggs) suggest that they discharge from a more isolated hydrogeologic system that does not reflect the seasonal fluctuations in precipitation and infiltration that the Claron Formation springs do.

In general, the measurements collected for this study and those reported by other investigators show that spring discharge rates from the eastern margin of BCNP are highest to the north, gradually decreasing to the southernmost extent of the Park, at Riggs Spring. The numerous exceptions to this statement are the small seeps present along the length of the Park, which discharge intermittently at low flow rates. These seep locations did not correlate with a specific elevation or lithology within either the Claron or Straight Cliffs formations; neither did the measured spring discharge rates.

Springs emitting from the Claron Formation and the underlying Straight Cliffs Formation can be differentiated chemically with respect to sulfate and ferrous iron content. The higher sulfate concentrations detected in springs issuisng from the Straight Cliffs Formation suggest that flow through the marine-derived sediments in this formation contributes sulfate to the groundwater. Previous chemical analyses of springs issuing from the Straight Cliffs Formation (Riggs, Iron, Yellow Creek, and Sheep Creek) detected sulfate concentrations ranging from 49 to 900 mg/l (Marine 1963; Plantz 1993). Discrete depth sampling from the well installed by Marine at locations intersecting the Straight Cliffs Formation showed sulfate concentrations ranging from 6 to 512 mg/l, with maximum concentrations at 860 ft depth or 7,150 ft elevation (364 mg/l) and 1,100 ft depth or 6,900 ft elevation (512 mg/l). For springs emitting from the Claron Formation, sulfate is consistently detected at concentrations less than 10 mg/l.

Ferrous iron detected in field measurements of Straight Cliffs samples suggests that reducing conditions are present in this formation. Ferrous iron was also detected in samples collected from Well 1. These three samples were all captured immediately after issuing from their groundwater source, and were analyzed for ferrous iron content, allowing detection of ferrous iron before it was oxidized.

The reducing conditions in springs emitting from the Straight Cliffs Formation and the high sulfate detections in Riggs Spring and Sheep Creek samples, reported by Marine (1963) and Ott (1996), suggest that sulfate may be present in a reduced state within the formation, where water is isolated from oxygen reaction. The reduced sulfur may explain the "stinky" well water referred to by Park Service staff. The well was drilled by the USGS at a location above the headwaters of Yellow Creek to a depth of 800 ft. Well sample chemistry data and lithology was reported by Marine (1963).

The flow in Water Canyon is augmented during the summer months by diversion of water from the Tropic Reservoir (located in the East Creek drainage, west of the Park boundary), and transported via Tropic Ditch through Water Canyon to a collection point east of the Park boundary. This diversion had been terminated and flow in the ditch had significantly decreased shortly before water samples were collected, during the week previous to November 2 (Neighbor 1998).

The chemical constituents in the Tropic Ditch water can be distinguished from those in water discharging from the Mossy Cave spring (discharging in the Water Canyon drainage) to evaluate the contribution of water infiltrated from Tropic Ditch to Mossy Cave spring discharge and the Water Canyon Creek flow. Nitrate was detected in samples collected from Water Canyon, including the Mossy Cave spring. However, nitrate was not found in Tropic Ditch samples. The chloride concentration in Tropic Ditch samples (41.4 and 44.7 mg/l) was an order of magnitude greater than that measured in Water Canyon and Mossy Creek samples (6.1, 6.7, and 6.8 mg/l). Sodium and potassium concentrations were also found to be significantly higher in Tropic Ditch water samples (9.3 and 10.0 mg/l sodium, and 9.1 and 9.8 mg/l potassium) than Water Canyon samples (sodium 3.4–3.7 mg/l and potassium 1.0–1.7 mg/l). Small amounts of titanium and aluminum were detected in Tropic Ditch that were not detected in any of the Water Canyon samples. Together these data suggest a different source for water issuing from springs in Water Canyon than Tropic Ditch.

Tritium data suggest that water issuing from Mossy Cave infiltrated more than 50 years ago, and remained hydrologically isolated traveling in the subsurface until its discharge at Mossy Cave. A significant Tropic Ditch contribution to the water discharging through Mossy Cave would be recognizable, because current atmospheric precipitation contains higher tritium contents than the tritium content detected in this sample. These data also indicate that water discharging from the Mossy Cave spring does not originate from Tropic Reservoir and Tropic Ditch.

Hydrologic Budget

The very generalized hydrologic budget presented here facilitates comparison of the quantity of water discharging from springs with the overall quantity of water that discharges annually from BCNP. The budget is for discussion and conceptualization purposes, not quantitative analysis. A simple hydrologic budget balances the amount of water that enters the hydrologic basin annually with the amount flowing out from the basin and the amount stored in the basin. Water enters as precipitation, leaves the basin as evaporation, transpiration, surface flow, and groundwater flow, and is stored in the basin in groundwater aquifers and surface water lakes. Freeze and Cherry (1979) showed this in equation form as

$$P = Q + E + \delta S_s + \delta S_g$$

where

P = annual precipitation
Q = total annual spring and stream discharge
E = total annual evaporation and transpiration
δS_s = change in surface water storage
δS_g = change in groundwater storage.

This budget is simplified further because of the lack of data with which to estimate surface water storage and groundwater storage. These components are assumed to average to zero over a long time frame (Freeze and Cherry 1979), and terms for storage are not considered further for this hydrologic budget estimate. The high evaporation rate in the BCNP region (Thiros and Brothers 1993) and the lack of standing surface water support the assumption that surface water storage does not occur. Groundwater storage is more likely to occur, although it is not well enough quantified at the time of this study to be incorporated into the budget.

Recharge to the Park via infiltration of precipitation is augmented by infiltration of flow from Tropic Ditch. Removing the groundwater and surface water storage factors and adding the Tropic Ditch contribution to recharge modifies the hydrologic budget equation to

$$P + Q_{TD} = Q + E.$$

Q_{TD} is the amount infiltrating through Tropic Ditch and discharging into Water Canyon (this assumes that water in Tropic Ditch flows completely through Water Canyon and discharges at the eastern Park boundary, without infiltrating further downstream along Water Canyon).

E represents a combined value for evaporation and transpiration (evapotranspiration). Evapotranspiration was estimated to be 95% of measured precipitation (Thiros and Brothers 1993) for the Sevier River valley. This value is incorporated into the hydrologic budget by assuming that the 5% of precipitation that is not evapotranspired infiltrates to recharge groundwater; evapotranspiration is assumed to consume the entire precipitation volume that does not recharge groundwater. To account for some uncertainty in this estimate, values for evapotranspiration of 90 and 95% are used in calculating the hydrologic budget. This quantity of the precipitation is effectively removed from the basin by atmospheric transport. Water estimated to be evapotranspired from the basin is not considered further in the hydrologic budget estimate. The hydrologic budget equation used for this estimate then reduces to

$$R + Q_{TD} = Q$$

where

R is the proportion of precipitation that infiltrates to recharge groundwater.

Recharge was calculated by multiplying the entire area of the Park (35,059 acres) by the average annual precipitation (16.39 inches recorded at the BCNP monitoring station) times an assumed rate of infiltration of either 5 or 10%. For this hydrologic budget estimate, the entire area of BCNP is assumed to be a recharge zone. Using this calculation approach incorporates a number of assumptions. All precipitation is assumed to infiltrate and recharge the aquifer before discharging from springs, streams, and pumping wells; water that runs off to surface water drainages without infiltrating is not accounted for in this hydrologic budget. This assumption reflects the arid conditions present at BCNP during the dry months of summer and fall, when precipitation infiltrates and evaporates rapidly. Recharge calculations are shown in Table 6.

Table 6. Estimated hydrologic budget for Bryce Canyon National Park.

Annual Recharge	Total acre ft/yr	Cubic ft/sec	Gallons per min	Ratios max/min
Precipitation Infiltration Average				
minimum (5%)	2,396	3.31	1,486	
maximum (10%)	4,785	6.61	2,967	200
1998				
minimum (5%)	3,417	4.72	2,118	
maximum (10%)	6,841	9.45	4,241	200
Tropic Ditch Infiltration*				
minimum (10%)	51	0.07	31	
maximum (40%)	507	0.7	314	1,000
Total Recharge				
minimum	2,447	3.38	1,517	
maximum	7,348	10.15	4,555	300
Annual Discharge**				spring/total
West Side Discharge (total)	1,860	2.57	876	32.7
C37-4-31CBB spring	608	0.84	100	5.0
Well #1 Pump Rate	123	0.17	76	2.9
unreported west side springs	1,129	1.56	700	26.2
East Side Discharge (total)	1,060	1.46	1,799	67.2
Measured Spring Flow*				
Water Canyon	404	0.56	950	35.5
Sheep Creek	14	0.02	32	1.2
Yellow Creek (total)	192	0.26	450	16.8
Estimated Spring Flow				
unreported east side springs	34	0.05	80	3.0
Paunsaugunt Fault Springs*				
Dr. Goode (Tropic City)	384	0.53	238	8.9
Merril Ranch	0	0.00	14	0.5
Jolley Hollow	32	0.04	20	0.7
Campbell Creek	0	0.00	15	0.6
Total Discharge	3,980	5.50	2,675	

*Topic Ditch calculations are shown in Table 7.
**Spring discharge measurements are shown in Table 3.

Tropic Ditch transports water from the East Fork of the Sevier River to the City of Tropic (in the Paria River basin) through a canal approximately 12 miles in length. The average annual quantity of water diverted for the years of record is 4,748 acre ft, with a maximum recorded annual diversion of 7,022 acre ft and a minimum of 2,474. The amount of water actually received in the Paria basin was estimated by Thiros and Brothers (1993) at 2,610 acre ft per year (55% of the diverted quantity) based on work by Carpenter et al. (1967). This implies a combined infiltration and evaporation rate of 45% from Tropic Ditch.

Infiltration losses estimated from canals in the Sevier River basin, based on sediment size and genesis of canal beds, ranges from 10 to 40% of the diverted quantity, according to Thiros and Brothers. An estimate of the potential infiltration losses from Tropic Ditch prior to its entrance to Water Canyon is shown in Table 7. These estimates use the assumption that only water infiltrating in the last 2 to 3 miles of Tropic Ditch discharges to Water Canyon, approximately 20% of the length of the canal. The remainder of the infiltration through Tropic Ditch is assumed to infiltrate to drainages topographically isolated from Water Canyon, along the ditch length from Tropic Reservoir to Syrett Hollow. Using these assumptions, the water infiltrating from Tropic Ditch that might discharge to Water Canyon ranges from an annual average of 0.07 cfs (31 gpm) to 0.70 cfs (310 gpm). If the values for annual infiltration are considered in light of the fact that water is diverted to Tropic Ditch only from April to October (for half the year), the actual infiltration rates are twice those calculated at 0.14 cfs (62 gpm) minumum and 1.4 cfs (620 gpm maximum).

Discharge from the Park is calculated from three components: measured and estimated spring discharge within BCNP, pumping from the alluvial aquifer of East Creek as calculated by Martin (1998), and discharge from springs along the Paunsaugunt Fault. These calculations are shown in Tables 3 and 6. For springs with multiple discharge measurements, an average of all measured values was selected to represent the annual discharge rate (Table 6).

Additional discharge measurements were collected in July of 1999 from some of the drainages that discharge west of the Park, including Podunk Creek, Oak Hollow, Long Hollow, Ingram Hollow, and the headwaters of East Fork. These have been included in the hydrologic budget as "estimated spring discharge" from the west side of the Park. In addition to the west-side flow measurements incorporated into this budget, shallow subsurface discharge from the west side of the Park may be significant. The drainages were observed to support grass and green vegetation during July of 1999, in marked contrast to the conditions on the Park's east side. These well-vegetated conditions indicate that more water is being discharged along the west side of the Park than was measured in surface water drainages.

Evaluation of Park Hydrogeology

The maximum and minimum recharge estimates (7,359 and 2,447 acre ft respectively) bracket the discharge estimate (3,637 acre ft), which suggests that most water infiltrating at BCNP discharges to surface water drainages within or near to the Park boundaries. The budget does not account for water that is stored as groundwater and likely discharges along the Paunsaugunt Fault and to the Sevier River and Paria River considerably downstream from the Park boundaries.

The east-west-trending Ruby's Inn Thrust Fault intersects the Paunsaugunt Fault at the northeast corner of the Park. The combined strains on the rock from movement along both faults in this vicinity may have caused stress fracturing over a wide area; such fracture planes can enhance water transport through the formation. Increased groundwater movement in this region may have caused increased mineral precipitation and cementation in the Claron Formation (G. Davis, personal communication, 1999). Increased water movement along fracture planes may continue to influence groundwater discharge in the northeastern portion of the Park, and may contribute to higher discharge through springs in this area, as evidenced by Water Canyon discharge being the largest flow measured for drainages originating in the Park.

Bryce Canyon National Park is situated on a high topographic surface, relative to the surrounding area, that receives and subsequently discharges a large portion of the precipitation in the region. The elongate linear configuration of the park parallels both the Paunsaugunt Fault and the northward-dipping Bryce Canyon Anticline and Syncline. The northward-dipping anticline and the downward slope to the north of the surface topography combine to direct groundwater movement along the length of the

Table 7. Tropic Ditch infiltration estimates.

	Water Diverted Annually from Sevier R.	Total Estimated Ditch Infiltration						Contribution to Water Canyon Flows (20% est. ditch infiltration)			
		10%			40%			10%		40%	
Year	Acre Feet	a–f	cfs	lpm	a–f	cfs	lpm	cfs	lpm	cfs	lpm
1961	2,474	247	0.34	581	990	1.37	2,325	0.07	116	0.27	465
1962	3,273	327	0.45	769	1,309	1.81	3,076	0.09	154	0.36	615
1964	4,104	410	0.57	964	1,642	2.27	3,857	0.11	193	0.45	771
1965	4,528	453	0.63	1,064	1,811	2.50	4,255	0.13	213	0.50	851
1966	4,906	491	0.68	1,153	1,962	2.71	4,611	0.14	231	0.54	922
1967	4,380	438	0.61	1,029	1,752	2.42	4,116	0.12	206	0.48	823
1968	5,141	514	0.71	1,208	2,056	2.84	4,831	0.14	242	0.57	966
1969	6,435	644	0.89	1,512	2,574	3.56	6,048	0.18	302	0.71	1,210
1970	4,891	489	0.68	1,149	1,956	2.70	4,597	0.14	230	0.54	919
1971	4,572	457	0.63	1,074	1,829	2.53	4,297	0.13	215	0.51	859
1972	3,077	308	0.43	723	1,231	1.70	2,892	0.09	145	0.34	578
1973	6,336	634	0.88	1,489	2,534	3.50	5,955	0.18	298	0.70	1,191
1974	3,934	393	0.54	924	1,574	2.17	3,697	0.11	185	0.43	739
1975	6,088	609	0.84	1,430	2,435	3.36	5,721	0.17	286	0.67	1,144
1978	4,831	483	0.67	1,135	1,932	2.67	4,540	0.13	227	0.53	908
1979	5,192	519	0.72	1,220	2,077	2.87	4,879	0.14	244	0.57	976
1980	5,578	558	0.77	1,311	2,231	3.08	5,242	0.15	262	0.62	1,048
1983	5,139	514	0.71	1,207	2,056	2.84	4,830	0.14	241	0.57	966
1988	6,146	615	0.85	1,444	2,458	3.40	5,776	0.17	289	0.68	1,155
1989	3,717	372	0.51	873	1,487	2.05	3,493	0.10	175	0.41	699
1990	3,334	333	0.46	783	1,334	1.84	3,133	0.09	157	0.37	627
1991	3,612	361	0.50	849	1,445	2.00	3,395	0.10	170	0.40	679
1995	7,022	702	0.97	1,650	2,809	3.88	6,599	0.19	330	0.78	1,320
1996	4,542	454	0.63	1,067	1,817	2.51	4,269	0.13	213	0.50	854
1997	5,442	544	0.75	1,279	2,177	3.01	5,114	0.15	256	0.60	1,023
Avg	4,748	475	0.66	1,115	1,899	2.62	4,462	0.13	223	0.52	892

Park from south to north. The Bryce Canyon Anticline continues its northward-dipping trend in the next syncline to the north. The syncline axis intersects Water Canyon, possibly acting as a subsurface funnel that drains into Water Canyon.

Hydraulic conductivity for the Claron Formation was calculated by Martin (1998) from a pump test conducted in Well 1 at 8,900 ft^2 per day, which corresponds to a Claron Formation hydraulic conductivity of 150 ft per day for the 60 ft of Claron Formation intersected by the well. Using the hydraulic gradient of the East Creek Valley calculated by Martin at .0042 and an estimated porosity of 0.35, the average linear groundwater velocity is about 2 ft per day. Water discharging through the Claron Formation from Mossy Cave spring water, traveling at this velocity over 50 years (interpreted from the tritium age-date), would have infiltrated at least 6.2 miles from Mossy Cave. The Claron Formation is truncated to the east and north by topographic relief and faulting along the Paunsaugunt Fault and Ruby's Inn Thrust Fault. Groundwater movement from 6.2 miles west of Mossy Cave would have originated in the East Fork Sevier River drainage, and would discharge to the East Fork. Using this calculated velocity, and a 50 year plus travel time, the most plausible direction from which groundwater could have originated is south of Mossy Cave.

The Paunsaugunt Fault also provides a preferred groundwater flow path, with springs discharging along the intersection of the fault with the ground surface, along the northeastern margin of BCNP. The proposed mechanism for fault influence of spring discharge (Marine 1963) is illustrated in Figure 2. Springs generated by flow along the Paunsaugunt Fault are listed by Marine as Merrill Ranch, Bryce, Campbell Creek, and Dr. Goode (Tropic City) springs, all located north and east of Yellow Creek. The fact that the observed springs are located at the northern extent of the fault trace suggests that the northward-dipping fold axes and topography directs groundwater flow to fault-related springs at the north end of BCNP as well as to springs discharging at higher elevations at the north end of the Park.

The water chemistry of the fault-related springs suggests deeper infiltration depths and longer subsurface travel times. High sulfate concentrations are associated with water infiltrating to and issuing from the Straight Cliffs Formation. Springs associated with Paunsaugunt Fault have sulfate concentrations between the higher values for the Straight Cliffs Formation and the lower values for the Claron Formation. These data suggest that discharge from the fault-related springs derives from a combination of shallow infiltrated water from the Claron Formation and deeper infiltrated water that traveled at least in part through the Straight Cliffs Formation.

Previous investigators have emphasized discharge from the eastern side of the Park (Marine 1963; Czarnowski 1991), and previous hydrologic investigations have focused on the eastern side. The steeper topography of the highly eroded Claron Formation basins likely produces steeper hydrologic gradients and enhances discharge on the eastern side of the Park. However, flow measurements on the western side of the park and the abundance of vegetation suggest that groundwater discharge to the west likely equals or exceeds that on the east. Although the topographic gradients on the east side of the Park exceed those on the west side, the discharge from the alluvium-filled East Fork Sevier River tributaries on the Park's west side likely matches or exceeds that discharged from the east side springs. A high rate of groundwater movement on the west side is also indicated by the production capacity measured in Well 1 (Martin 1998).

Summary and Conclusions

The discharge from Water Canyon (1998 measurement) constitutes almost one third of the annual discharge from the BCNP. The fault orientations and potential stress factures, and the northward-dipping structure and topography, provide compelling evidence that a significant proportion of groundwater migrates northward and is released at Water Canyon. Contribution from infiltration though Tropic Ditch (shown in Table 7) to Water Canyon and the surrounding area springs (estimated at 0.7 cfs or 314 gpm) is also likely. This estimated infiltration rate is almost one third of the flow measured in Water Canyon; however, the chemical constituents in Tropic Ditch water samples and Water Canyon samples indicate that water from Tropic Ditch does not contribute one third of the flow in Water Canyon. Additionally, the age date of water discharging from Mossy Cave spring indicates a travel time of more than 50 years for groundwater discharging at the spring. Although it is likely that a proportion of water from Tropic Ditch does infiltrate and discharge to Water Canyon, it is more likely that the minimum infiltration estimate of 0.7 cfs (31 gpm) more accurately represents the contribution of Tropic Ditch to Water Canyon flows.

Although discharge along the Paunsuagunt Fault was postulated by Marine (1963) and other investigators to be the primary path for groundwater discharge from BCNP, this investigation did not find data with which to support this. The Merrill Ranch seep, Bryce Spring, and Campbell Spring were observed in July of 1999 to be discharging at a rate of 1 gpm or less.

The relative magnitude of the groundwater flow through the Claron Formation to the west and to the East Fork Sevier River, the discharge from the springs in the Claron Formation on the east side of BCNP, and the quantity of water that infiltrates to the underlying Straight Cliffs Formation and laterally out of BCNP to the east is completely undefined. At this time, the discharge from the Straight Cliffs Formation on the east side of BCNP appears to be less than that from the Claron Formation (based on the comparison of discharge from Water Canyon with the discharges from Sheep Creek and Yellow Creek springs). However, further study is required to better evaluate this distribution of groundwater and the deeper infiltration to and discharge from the Paunsaugunt Fault.

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