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Influence of rock glaciers on stream hydrology in the La Sal Mountains, Utah

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Abstract

While valley glaciers have received considerable attention for their contributions to summer runoff during the past decade, the contributions of rock glaciers to summer runoff patterns have largely been ignored, especially in the western United States. This article examines summer runoff from two basins in the La Sal Mountains, Utah: the non–rock glaciated Wet Fork and rock glaciated Gold Basin. Runoff events were analyzed for volume of stormflow, stormflow duration, and peak flow duration. Four events were recorded in Wet Fork ($n = 4$), five events were recorded in Gold Basin ($n = 5$), and six events at a flume immediately adjacent to the Gold Basin rock glacier ($n = 6$). Wet Fork hydrographs are dominated by baseflow throughout the summer and a small proportion (0.13%–0.31%) of precipitation leaves the basin as stormflow during storms. Gold Basin hydrographs are characterized by early season snowmelt with flood peaks associated with summer storms. Runoff from the gaged rock glacier represents 15%–30% of total basin runoff and is inversely related to precipitation and directly related to rainfall intensity. Removal of rock glacier hydrographs from total basin hydrographs indicates that there is increased surface runoff from alpine drainage basins that contain rock glaciers, suggesting rock glaciers act as impervious surfaces. This short-term study in Utah suggests that alpine drainage basins with rock glaciers could have greater surface runoff and higher flood peaks than drainage basins that lack rock glaciers. While the long-term effects of rock glaciers on summer water resources is still unknown, this investigation demonstrates rock glaciers may profoundly influence hydrographs in alpine drainage basins.

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Introduction

The initiation of research on rock glaciers can be traced to a paper in Danish by Steenstrup in 1883 (Humlum, 1982). At the beginning of the twentieth century, rock glaciers were considered a peculiar form of talus (Spencer, 1900). Capps (1910) introduced the term *rock glacier* to describe these landforms. Wahraftig and Cox (1959) demonstrated that the landforms had a tendency to creep downslope in the manner of a glacier, apparently as a result of the inclusion of ice within the talus. A more complete description of a rock glacier identifies the shape and some of the features associated with the landform. These include tongue- or lobate-shaped bodies of frozen material with steep face and side slopes that are at or near the angle of repose; sharp angles between the face and upper surfaces; and longitudinal and transverse furrows and ridges on the upper surface (Wahraftig and Cox, 1959; White, 1976; Shroder, 1987; Giardino et al., 1987; Burger et al., 2000).

Rock glaciers have an important role in sediment (Barsch, 1988, 1996; Barsch and Jakob, 1998; Burger et al., 2000; Corte, 1978; Gärtner-Roer, 2012; Giardino et al., 1987; Humlum, 2000) and hydrologic budgets of alpine drainage basins (Caine, 1974). Sediment is entrained from cirque and valley headwalls and transported down-valley by the rock glacier. Sediment ranging in size from silt to coarse gravel is moved by gravity and water downslope to the drainage network below. Discharge from meltwater springs located at the base of rock glaciers is likely responsible for transporting a majority of suspended and dissolved load within channels downstream. Improved understanding of rock glacier hydrology will help better quantify sediment transport rates in downstream watersheds.

Rock glaciers are hydrologically significant because they contribute meltwater to the fluvial system, usually through springs at the rock glacier toe. Potter (1972) characterized these flows as being largely sediment free, unlike the sediment-laden discharge of glacial meltwater streams. In addition, rock glacier meltwater streams do not exhibit marked diurnal fluctuations in discharge. Potter (1972) attributed these differences to rock glacier debris mantles that filter fine material from meltwater and insulate ice (interstitial or massive) from direct solar radiation, limiting the intensity of daily meltwater cycles.

Discharge from rock glaciers is generally similar to or greater than discharge from ice glaciers of similar size (Corte, 1978; Gardner and Bajewsky, 1987). Corte (1978), working in the Mendoza Andes of Argentina, found that rock glaciers provided 56% of the total annual discharge of the Cuevas River, while ice glaciers provided only 44% of discharge, despite the fact that ice glaciers occupy more area. Working on the Hilda rock glacier in the Canadian Rocky Mountains, Gardner and Bajewsky (1987) observed Hilda rock glacier peak discharge of 0.27 $m^3 s^{-1}$ and a minimum of 0.09 $m^3 s^{-1}$. Boundary glacier, located 1 km away, had slightly higher peak discharge but also exhibited a higher range (maximum 0.33 $m^3 s^{-1}$, minimum 0.004 $m^3 s^{-1}$). Gardner and Bajewsky (1987) found that daily climatic conditions including temperature, precipitation, and incident solar energy had a prominent effect on the hydrograph of a glacial meltwater stream, but played a relatively insignificant role in meltwater

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from the Hilda rock glacier. They concluded that the debris cover of rock glaciers insulates them from meteorological changes that create pronounced daily variability in an ice glacier of similar size. Gardner and Bajewsky (1987) also measured suspended sediment concentration of Hilda rock glacier (1–3 mg L^{-1}) and Boundary glacier (600–800 mg L^{-1}) outflow. This finding supports the hypothesis that rock glaciers are conservative contributors of suspended sediment to the fluvial system.

Several research articles have recognized rock glaciers as potential storage reservoirs for water (Corte, 1976, 1978; and Barsch, 1988). Stream discharge from rock glaciers fluctuates annually, with warmer years producing more discharge than colder years. Hydrological storage and release is of great interest to communities in semi-arid to arid regions, such as those studied by Corte (1976) in the Mendoza Andes (Gardner and Bajewsky, 1987). Giardino et al. (1992) presented evidence that rock glaciers act as aquifers, and there is a system of inputs and outputs from various processes within alpine drainage basins. Giardino et al. (1992) termed this a "Cascading Model" consisting of four subsystems: the cliff-talus, surface, subsurface, and groundwater. Water moves among these subsystems until it is ultimately removed from the entire system and moved into the channels downslope from the rock glacier, either via surface runoff or groundwater.

Krainer and Mostler (2002) monitored discharge downstream from three rock glaciers (Reichenkar, Gößnitz, and Kaiserburg) in the Austrian Alps during 1998–1999 using pressure transducers and float gages. Water temperature and electrical conductivity (solute concentration) were also measured. Data from gauging stations and local weather stations were combined to develop hydrographs that were analyzed on seasonal and daily timescales. Hydrograph peaks occurred after local storms. High flows during spring and following storms showed low electrical conductivity values, indicating that a majority of the runoff was derived from snowmelt and precipitation. Higher conductivity in late summer derived from the metamorphic bedrock indicated that groundwater is more important than melting of internal ice later in the runoff season.

Williams et al. (2006) examined the geochemistry of rock glacier discharge. During September to October, significantly higher concentrations of Mg^{2+}, Ca^{2+}, and SO_4^{-2} were present in rock glacier discharge in the Green Lakes Valley of Colorado. This supports the assessment by Giardino et al. (1992) that rock glaciers concentrate solutes. Additionally, hydrograph separation identified the percentage of flow derived from different sources. Melted snow represents approximately 30% from the Green Lakes 5 rock glacier, while soil water and base flow represent 32% and 38%, respectively. Melted snow water is dominant in June, while soil water is dominant in July. By September, meltwater from the rock glacier is the dominant source for rock glacier discharge, conforming to the findings of Krainer and Mostler (2002).

Despite substantial work on some aspects of rock glacier hydrology, there have been no comparisons between drainage basins containing rock glaciers and those without. Differences between discharge patterns and baseflow contributions in a paired watershed study may help explain how rock glaciers act as reservoirs, therefore providing insight for future natural resource management. Since baseflows are generally not affected by precipitation, they provide the most promising measure of rock glacier water storage and release. This type of study can also be used to develop a framework on which the overall role of rock glaciers in geomorphology of alpine streams can be based. Until now, there have been assumptions (Krainer and Mostler, 2002) but no data to support comparisons between rock glaciated and non–rock glaciated basins in the same geographic area.

RESEARCH OBJECTIVES

This study examines hydrologic characteristics of two alpine watersheds in the La Sal Mountains of Utah, only one of which contains active rock glaciers. High resolution data are presented for stream discharge, precipitation, runoff temperature, and air temperature with the intent to provide insight to how rock glaciers influence basin hydrology. There are three research hypotheses: (1) Rock glacier discharge declines at a relatively constant rate during the summer with peaks in the hydrograph associated with summer storms. Non–rock glacier basins will exhibit a rapid decrease in flow after the spring melt, and peaks will also occur with summer storms. (2) Rock glacier–influenced streams experience a quicker response in the hydrograph to storms than do non–rock glacier streams. This stems from the fact that most rock glaciers are a matrix of rock with interstitial ice. If rainfall infiltrates through the upper rock layers and reaches the interstitial ice, it will quickly flow off the rock glacier and reach the meltwater streams soon after the onset of precipitation. (3) Warmer temperatures will increase flows from the rock glacier stream through the end of the summer relative to the non–rock glacier stream.

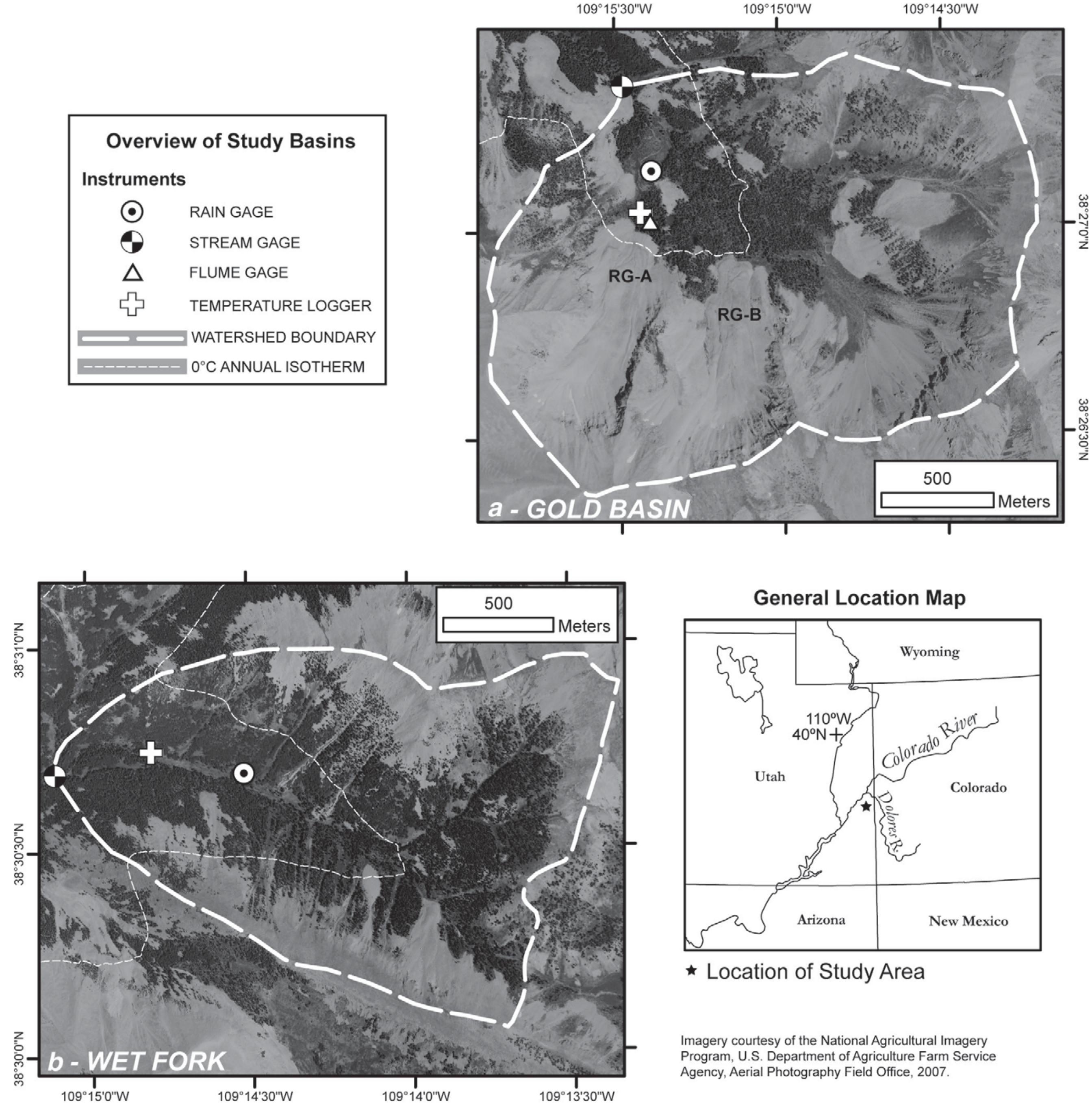
Study Area

The La Sal Mountains of eastern Utah (38°N, 109°W) are an isolated mountain range surrounded on all sides by low, canyon-dissected terrain in southeastern Utah (Fig. 1). Physiographically, the La Sals are part of the Colorado Plateau; they formed during the Oligocene in association with the Laramide orogeny, when intrusive, dioritic magmas uplifted overlying sedimentary rocks several thousand meters (Hunt, 1958; Nelson et al., 1992; Ross, 1992). The laccolithic La Sals are composed of three distinct groups, referred to as the northern, middle, and southern groups. Most peaks in the northern and middle groups exceed 3000 meters. The highest peak, Mount Peale (3877 m), is situated in the middle group, along with Mount Mellenthin (3854 m) and Mount Tukuhnikivatz (3805 m). The southern mountain group has significantly less relief than either the northern or middle mountain groups. The La Sal Mountains form the north end of a drainage divide between the Dolores River to the east and the Colorado River to the west at Moab, Utah (Fig. 1).

The La Sal Mountains are a prime location to study rock glacier hydrology. They are tectonically young, and the upper parts of many basins are mantled with coarse sediment. The surrounding area is semi-arid, and snowmelt from the mountains is a source of irrigation and municipal water.

HYDROLOGY

Three main streams drain the La Sals: Mill, Brumley, and Pack Creeks all drain to the west from the northern and middle mountain groups. Mill Creek is diverted near Moab to fill Ken's Lake, an off-stream artificial reservoir that provides water to Moab. Smaller diversions on several other creeks supply water to ranches located off the western and eastern flanks of the range. Most creeks are perennial throughout the year, but Pack Creek often runs dry upon reaching Spanish Valley, a collapsed salt anticline. Mill and



Imagery courtesy of the National Agricultural Imagery Program, U.S. Department of Agriculture Farm Service Agency, Aerial Photography Field Office, 2007.

FIGURE 1. study basins in the La Sal Mountains: (a) Gold Basin and (b) Wet Fork. Two rock glaciers were identified in Gold Basin by Shroder (1987), Mount Tukuhnikivatz northeast A (RG-A) and Mount Tukuhnikivatz northeast B (RG-B).

Brumley Creeks both exhibit low discharge in late summer, but rarely run completely dry. Brumley Creek is the only major stream on the west side of the range fed directly by active rock glaciers.

CLIMATE

Climatologically, the La Sals act as a focus for storm systems moving across eastern Utah from the High Plateaus to the west toward the Rocky Mountains to the east. As a result of orographic enhancement, the village of La Sal (elevation 2130 m) receives 325 mm of annual precipitation, while Moab (elevation 1220 m) only receives an average of 208 mm. In the mountains, climate is varied and depends primarily upon altitude and aspect. The months of July and August are generally moist, with 30–40 mm of precipitation each month (Nicholas, 1991). Lapse rates, based on temperature measurements taken at eighteen sites are 8.0 °C per 1000 m, with the 0 °C isotherm of mean annual air temperature placed at 3213 m (Geiger, 2006).

SELECTED SITES

Each of the sites selected for study is located within the U.S. Department of Agriculture's Manti–La Sal National Forest. A basin that lacks rock glaciers is located in the northern mountain group. The Wet Fork of Mill Creek (hereafter Wet Fork) basin (288 ha) has its headwaters on the southwestern flank of Mount Waas (Fig. 1, part B). It is a perennial stream that joins the Dry Fork of Mill Creek at its outlet to form Mill Creek. Wet Fork is also a second-order basin at its outlet (based on U.S. Geological Survey [USGS] quadrangles).

The rock-glaciated Gold Basin occupies the northern slopes of Mount Tukuhnikivatz (Fig. 1, part A). Shroder (1987) identified two rock glaciers as Mount Tukuhnikivatz northeast A and B. Both Mount Tukuhnikivatz rock glaciers are active and contain a steep face at the angle of repose, a sharp angle between the face and upper surface, and longitudinal and transverse furrows and ridges along the upper surface (Wahraftig and Cox, 1959; White, 1976; Shroder, 1987). Gold Basin (352 ha) is drained by Brumley Creek, a tributary of Pack Creek, which joins Mill Creek in Moab. Gold Basin is a second-order basin at its outlet (based on USGS 7.5 minute quadrangles). The Gold Basin gage site is located approximately 700 m down valley from the rock glacier front. It is assumed that the main hydrologic inputs to the stream network in Gold Basin are precipitation, groundwater baseflow, and meltwater from internal rock glacier ice, while losses are mainly through evapotranspiration and deep groundwater storage. Water reaches the channels through a combination of overland flow, infiltration to groundwater, throughflow, and quickflow off the rock glacier ice. The operative hydrologic processes in Wet Fork are largely similar to Gold Basin, but the basin lacks any interaction with a rock glacier.

Both basins share similar physiographic characteristics (Table 1). Each basin has an approximately equivalent area of the watershed below treeline. Wet Fork has approximately twice as much of the land area below the 0°C isotherm than does Gold Basin. With the exception of the rock glaciers, neither basin retains significant snow cover year-round. Rock glaciers appear to be the only source of permafrost present in either basin on a year-round basis. Vegetation is similar in each basin, ranging continuously from aspen (*Populus tremuloides*) in the lower altitudes to Engelmann spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*) in higher elevations.

TABLE 1

Descriptive characteristics of study basins.

Variable	Wet Fork	Gold Basin
Area (ha)	288	352
Area below treeline (ha)	248	237
Area below 0 °C isotherm (ha)	84	43
Average elevation (m)	3316	3421
Basin order[1]	2	2
Basin slope[2]	0.27	0.26
Drainage density (m ha^{-1})[3]	11	6
Relief (m)	802	705

[1] Basin order at the stream outlet using conventions of Strahler.

[2] Calculated using longest flow path.

[3] Drainage density is total length of channels per basin divided by area.

Methods

Instrumentation placed in the field yielded seasonal data for the months of June through September 2007 for three variables: stream discharge, precipitation, and water temperature.

Stream discharge was calculated by establishing a gauging site at the mouth of both Wet Fork and Gold Basin. Each site consists of a surveyed channel cross-section and a HOBO® U20-001-04 Water Level Logger (Onset Computer Corp.). Each logger is a pressure transducer capable of recording pressure to within ±0.075% of actual pressure. Stream gages on Wet Fork and Gold Basin were installed over a two-day period from 10 through 11 June 2007. Each gage sampled water pressure every 10 minutes through 14 September. Depth of flow in meters (resolution: 0.0014 m, accuracy: 0.003 m) was established by barometrically compensating water pressure with ambient barometric pressure, recorded by an additional U20-0001-04 series water level logger secured to a tree located approximately between the two sites in the Geyser Pass area. Compensation was performed using HOBOware software (Onset Computer Corp.) and accounts for changes in water density with changing water temperature.

Manual measurements of discharge were also obtained from the stream channels during visits to the sites throughout the summer. However, discharge variability was not sufficient to produce accurate rating curves of stage and discharge. Instead, velocity measurements were used to calculate Manning's n roughness coefficients for each channel. Mean velocity was calculated using Manning's equation:

$$V = \frac{1}{n} R_h^{2/3} S^{1/2} \tag{1}$$

where V = mean velocity of the stream in the cross section (m s^{-1}); R_h = the hydraulic radius of the stream (m), where $R_h = A/WP$, where A = the cross-sectional area of streamflow (m^2) and WP = the wetted perimeter (m); S = the slope of the stream (m m^{-1}); and n is Manning's roughness coefficient. Due to steep gradients, coarse sediment, and stochastic flow regimes in mountain streams, there exists great difficulty in calculating resistance coefficients (Wohl, 2000). Marcus et al. (1992) stressed that researchers exercise care when interpreting discharges obtained using roughness estimates and field-check estimates using actual velocity measurements where possible. In Wet Fork, a roughness coefficient of 0.11 is used, while in Gold Basin the coefficient is 0.04. These values approximate actual velocity measurements taken in the field for each cross-section to within 0.2 m s^{-1}. Wet Fork has a considerably higher n value due to a high amount of fine, woody debris in the bed of the channel, while the Gold Basin site consists of mostly flattened cobbles and boulders that sit evenly on the channel bottom. Discharge was calculated using the standard equation:

$$Q = VA \tag{2}$$

where Q = stream discharge in (m^3 s^{-1}). Discharge is presented in this article in terms of L s^{-1}. Cross-sectional area for each observed stage height was calculated using the computer program WinXSPRO (USDA Forest Service). Final seasonal data represent the average discharge at each site over 1 hr intervals and are used to determine rates of baseflow and stormflow.

Additionally, a 7.6 cm Parshall flume was installed on a meltwater stream on the north side of northeast Mount Tukuhnikivatz rock glacier A, approximately 45 m from the rock glacier front. This stream is one of three small streams draining the rock glacier. Water depth was monitored using a HOBO® U20-001-04 series water level logger, and water pressure was barometrically compensated to give depth of water in the stilling well accurate to 0.001 m. Discharge was established using the factory-calibrated rating curve for the flume:

$$Q = 0.2108d^{1.579} \qquad (3)$$

where d is the water depth (m). The flume is rated for flows ranging from 0.00002 $m^3 s^{-1}$ (0.02 L s^{-1}) to 0.01407 $m^3 s^{-1}$ (14.07 L s^{-1}). Discharge data from the Parshall flume, collected every 30 minutes, were filtered to give only the discharge occurring on the hour.

Precipitation in each basin was recorded using a single HOBO® RG3-M tipping bucket rain gage. Gages were installed over a two-day period from 10 through 11 June 2007. Each gage was placed in an open area sufficient to allow precipitation to reach the funnel without interference from trees or terrain. The data logging rain gage stores each tip of the 0.2 mm bucket with a time stamp indicating the date and time (accurate to seconds) of the tip. Seasonal data were aggregated into hourly precipitation values. For the purposes of this study, we assumed spatial uniformity of precipitation, although we acknowledge that orographic effects may increase precipitation amounts at higher elevations. To mitigate these effects, the rain gages were placed in localities of intermediate elevation within each watershed to derive a representative value. In Wet Fork, the gage was placed at an elevation of approximately 3080 m, and in Gold Basin at approximately 3140 m.

Water temperature at each of the three stream gage sites, including the Parshall flume, was collected using the U20-001-04 series water level logger. The logger's built-in thermometer is accurate to within 0.4 °C at a water temperature of 0 °C.

Daily air temperature is available for 19 sites throughout the La Sal Mountains. Temperature data loggers were installed in 2002 and 2004 by J. W. Nicholas. The loggers are HOBO® H8 Pro Series temperature loggers (Onset Computer Corp.).The capability of this model ranges from a maximum recordable temperature of 50.0 °C to a minimum of –30.0 °C, with an accuracy of ±0.5 °C in standard resolution mode. Each logger was installed 1–2 m above the ground surface on a tree out of direct sunlight. No solar shields were used, and there is no evidence of solar loading. Temperature was recorded every 10 minutes at each of the sites. Additionally, temperature data from the Natural Resource Conservation Service's (NRCS's) La Sal Mountain SNOTEL site was appended to the data retrieved in the field.

Results

SUMMER PRECIPITATION PATTERNS

Precipitation in the La Sal Mountains tends to occur mostly during the late afternoon and early evening in conjunction with convective storms. A notable spike in precipitation occurs in Wet Fork during 19:00 hours; however, this spike is attributed to a single storm that produced 24.4 mm of rain in a single hour on 23 July. Another storm on 6 August produced 19.2 mm of rain in a single hour, with the balance of the 65.6 mm falling during the 19:00 hour time period from several smaller storms.

Daily precipitation in the La Sal Mountains over the period of 11 June through 14 September 2007 is varied, with occasional spikes in precipitation exceeding 15 mm per day. Daily precipitation in one basin generally correlates with that in the other; however, the amount of precipitation is usually greater in Wet Fork than Gold Basin during the study period. Most precipitation occurred between mid-July and late-August. A notable dry period occurred throughout most of June.

SUMMER RUNOFF PATTERNS

Discharge from Wet Fork (Fig. 2) is approximately constant throughout summer, ranging between 57 L s^{-1} and 106 L s^{-1}, with small peaks caused by storms, implying that the hydrologic regime in Wet Fork is controlled by baseflow. Wet Fork shows an approximately diurnal pattern of discharge throughout the summer season. The diurnal variation is not consistent, ranging from 22 L s^{-1} in mid to late June, to 30 L s^{-1} in mid to late July. The variation then declines to approximately 8 L s^{-1} by mid September. The hydrograph does not present a pattern that indicates the end of snowmelt within the basin, as is evident in the rock-glaciated Gold Basin. This suggests snowmelt in the higher elevations of Wet Fork is reaching the stream by subsurface throughflow or is being transferred to deep storage in the coarse glacial substrate.

Four runoff events were identified in Wet Fork (Table 2). Each peak discharge was recorded in the evening between 19:00 and 20:00 hours MDT. The rising limb of each hydrograph is short, with a maximum time to peak of 3 hr. Additionally, a very small portion of each storm actually leaves the basin as stormflow, signaling that overland flow and subsurface throughflow are not enough to move precipitation to the channel. The only remaining source of precipitation is thus rain falling directly in the channel. To test this finding, the area occupied by channels in Wet Fork was calculated using the following criteria: the downstream 50% of the second order channel is 2.3 m wide, the upstream 50% of the second order channel is 1.6 m wide, and the two first order channels are approximately 0.91 m wide. Based on the criteria, total channel area in Wet Fork is approximately 4445 m^2, 0.15% of the total watershed area. The ratio of precipitation falling in the channel to total basin precipitation is used as a baseline for comparing the differences in the ratio of stormflow to basin precipitation (Table 3).

The ratio of stormflow to basin precipitation is remarkably similar to the ratio of channel precipitation to basin precipitation. This similarity indicates that most stormflow generated in Wet Fork is derived from precipitation falling directly in the channel. Overland flow and throughflow must not, therefore, be important hydrologic processes in Wet Fork. This is likely due to the character of its soil, a gravelly, sandy loam with high infiltration capacity.

Gold Basin on the other hand, exhibits a much greater range of discharge, from zero L s^{-1} to 108 L s^{-1} on 15 June (Fig. 3). The basin exhibits a marked early season diurnal pattern that gradually decreases to zero by 21 July. During the time between maximum seasonal runoff and the onset of zero surface runoff around 20 July, the diurnal variation gradually decreases to zero from a maximum of 97 L s^{-1}. Throughout the remainder of summer, discharge is characterized by flood peaks that coincide with storms. Field

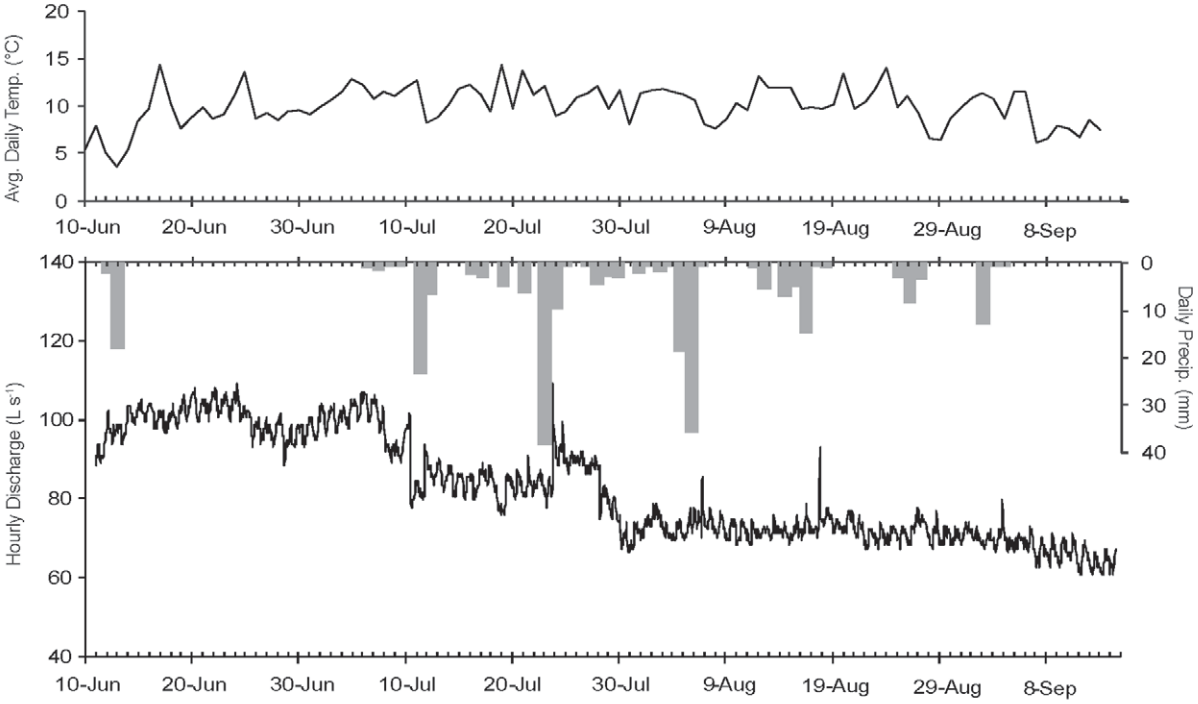


FIGURE 2. Recorded hourly discharge, daily precipitation, and average daily temperature in Wet Fork.

TABLE 2

Characteristics of recorded runoff events in study basins.

Event	Date	Time of peak	T_p	Q_p	P	Percent of precipitation as stormflow
Wet Fork						
1	2007-07-11	20:00	2	95	25.2	0.26%
2	2007-07-23	19:00	2	106	38.0	0.31%
3	2007-08-06	19:00	0	84	19.4	0.13%
4	2007-08-17	19:00	3	95	13.8	0.19%
Gold Basin						
1	2007-07-12	6:00	7	64	21	3.31%
2	2007-07-25	14:00	8	5	7.2	2.17%
3	2007-08-06	2:00	9	97	37.6	7.94%
4	2007-08-14	13:00	8	5	9.6	1.57%
5	2007-09-05	2:00	7	37	23.4	3.65%
Gold Basin Flume						
1	2007-07-12	0:00	4	21	21	14.51%
2	2007-07-24	20:00	3	8	7.2	10.64%
3	2007-08-05	17:00	4	25	37.6	19.95%
4	2007-08-13	16:00	2	21	9.6	15.26%
5	2007-08-27	10:00	9	11	13.6	8.70%
6	2007-09-04	20:00	23	25	23.4	14.51%

Notes: T_p = time to peak in hours; Q_p = peak discharge in L s^{-1}; P = precipitation in millimeters. Dates given as yyyy-mm-dd.

TABLE 3

Comparison of precipitation falling in channels to total basin stormflow.

Event	P_{wf}	S_f	$P_{channel}$	$P_{channel}/P_{wf}$	S_f/P_{wf}
1	72,478.8	190.2	112.3	0.0015	0.0026
2	109,293.5	342.4	169.3	0.0015	0.0031
3	55,797.2	72.5	86.4	0.0015	0.0012
4	39,690.8	74.30	61.5	0.0015	0.0018

Notes: P_{wf} =area depth of precipitation falling in Wet Fork in m^3; S_f = stormflow at Wet Fork outlet in m^3; and $P_{channel}$ = area depth of precipitation falling in Wet Fork channels in m^3.

observations on 15 September reveal that the stream is still flowing approximately 150 m upstream of the gauging site before being lost into the channel substrate.

Five runoff events were recorded at the outlet of Gold Basin (Table 2). Timing of peaks are more varied than those in Wet Fork, with three peaks occurring in the early morning hours (2:00 to 6:00), and two peaks occurring in the early afternoon (13:00 to 14:00). Time to peak of each hydrograph is greater in Gold Basin than Wet Fork. This may indicate that precipitation takes longer to infiltrate through the rock glaciers and talus present in Gold Basin before reaching the channel. The amount of precipitation leaving the basin as stormflow is also greater than in Wet Fork, so less precipitation is being lost to deep storage, although some precipitation may reach the stream as throughflow.

Discharge measurements from the Parshall flume located in Gold Basin (Fig. 4) range from 0.07 L s^{-1} on 15 September to 25.18 L s^{-1} on September 4; however, the area drained by this channel is approximately 2.02 ha, approximately 5.98% of the total watershed area of Gold Basin. The same marked diurnal pattern during the early summer snowmelt season that occurs in the Gold Basin outlet hydrograph is also evident at the Parshall flume, and the pattern ceases by early July. The diurnal variation attributable to melting of the snowpack ranges from a maximum of 16.18 L s^{-1} on 14 June to 1.36 L s^{-1} by 5 July. Throughout the remainder of the summer, discharge is characterized as a relatively constant flow, with an average daily diurnal variation of 0.76 L s^{-1} excluding storms. In fact, diurnal variation gradually declines throughout the summer following the cessation of variation due to snowmelt (linear regression, $m = -0.0084$, $r^2 = 0.59$).

Six runoff events were recorded by the Gold Basin flume (Table 2). Peaks generally occurred in the late afternoon to early evening hours, and peak discharge was usually reached 2–4 hr after the onset of stormflow. Event 6 has an abnormally long time to peak; however, this is attributed to a dual peak hydrograph, where two distinct storms resulted in two different peak discharges on the same hydrograph. This runoff event is treated as a single event here due to the inability to accurately separate the stormflow associated with the first peak from the secondary peak. The percentage of

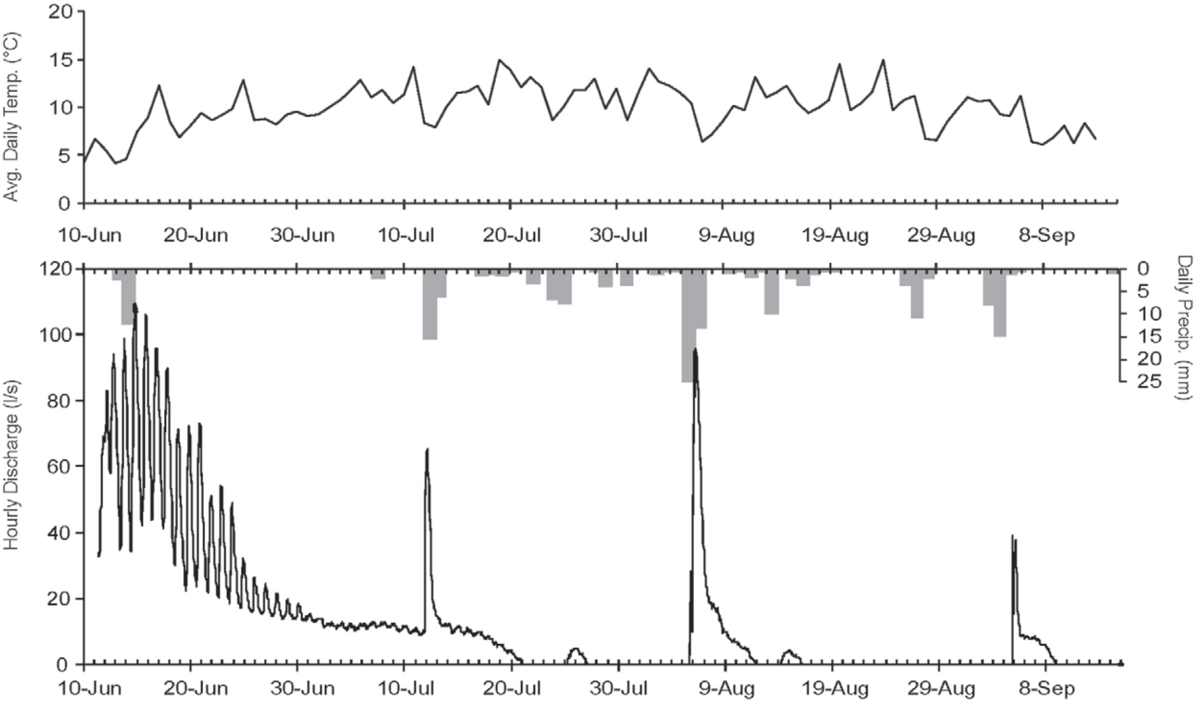


FIGURE 3. **Recorded hourly discharge, daily precipitation, and average daily temperature in Gold Basin.**

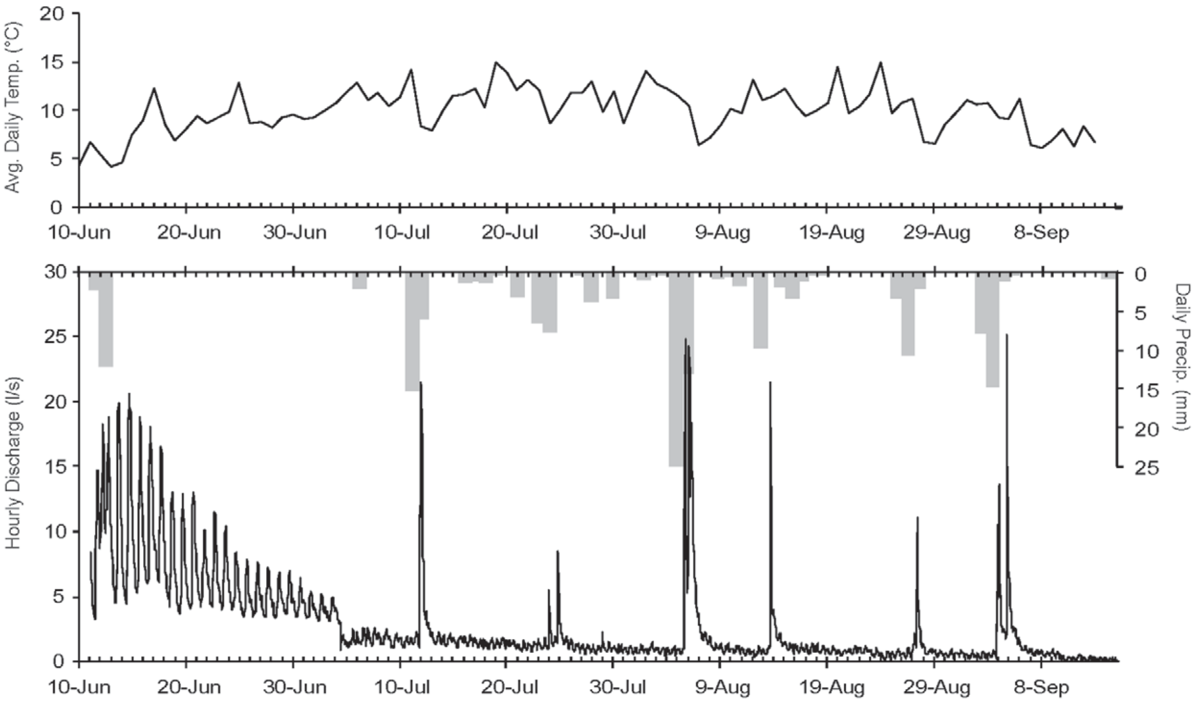


FIGURE 4. **Recorded hourly discharge, daily precipitation, and average daily temperature at the Gold Basin flume.**

precipitation falling on the rock glacier and cirque walls that leaves the basin as stormflow is considerably greater than values obtained from the Gold Basin outlet gage, with approximately 9%–20% of precipitation reaching the channel during each storm.

Stormflow from the Gold Basin flume provides a significant percentage of total basin runoff (Fig. 5). A storm on 25 July, although producing only 7.2 mm of rain, drove a rock glacier response that generated a nearly 30% contribution to total basin stormflow. This is attributed to high rainfall intensity (2.4 mm hr^{-1}) associated with the 25 July storm. However, a storm on 6 August that produced 37.6 mm of precipitation resulted in a 15% contribution of total basin stormflow. The percent of flume contribution to total basin stormflow exhibits a negative trend with increasing precipitation, signaling that the importance of other hydrological processes on a basin scale increases during heavy storms. These processes may include overland flow, subsurface throughflow, or loss to deep storage. The net effect, however, is that stormflow from Mount Tukuhnikivatz rock glacier A appears to influence the hydrology of Gold Basin on the whole by driving higher amounts of surface runoff during smaller storms.

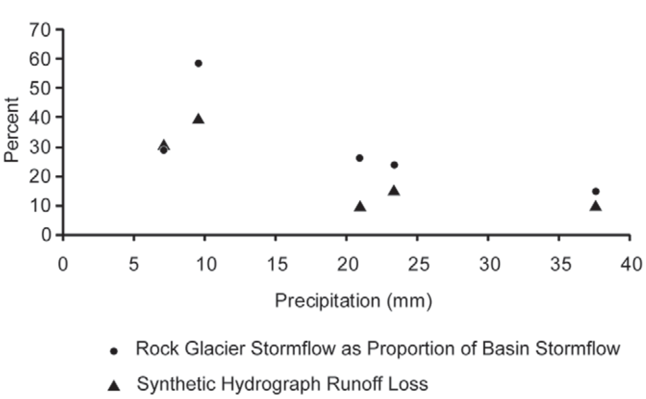


FIGURE 5. Relationship of increasing precipitation to proportion of rock glacier outflow from flume at base of Mount Tukuhnikivatz rock glacier A as total basin stormflow.

When flume hydrographs are compared with hydrographs from the outlet at Gold Basin, individual flume hydrographs are similar to the shape of total basin hydrographs. It is useful to analyze how the basin hydrograph would be shaped if the influence of rock glacier was removed. Two parameters to consider are peak discharge and total surface runoff volume. To examine the influence of the rock glacier drained by the flume, the flume hydrograph was subtracted from the basin hydrograph to produce a hydrograph representing contributions of the remaining area in the watershed. This hydrograph was multiplied by the rock glacier area to create a synthetic hydrograph describing runoff from the basin if the rock glaciated area drained by the flume was removed. This assumes an equal distribution of substrate and vegetation as well as similar hydrologic processes across that distribution (Fig. 6). Synthetic hydrographs generally have lower peaks. Total runoff loss represented by the removal of rock glacier hydrographs is approximately 10%–40% of the total basin outlet hydrograph (Fig. 5). As precipitation increases, the percentage of total runoff loss attributed to removal of the rock glaciers decreases, indicating that heavy storms are more likely to diminish rock glacier hydrologic response during storms as a result of other watershed processes such as overland flow, throughflow, and loss to deep groundwater storage.

As of this writing, no other study has attempted to determine a unit hydrograph (UHG) for a rock glacier. The Gold Basin flume provides the best approximation of runoff response for application to other rock glaciers worldwide (Fig. 7). UHGs were calculated

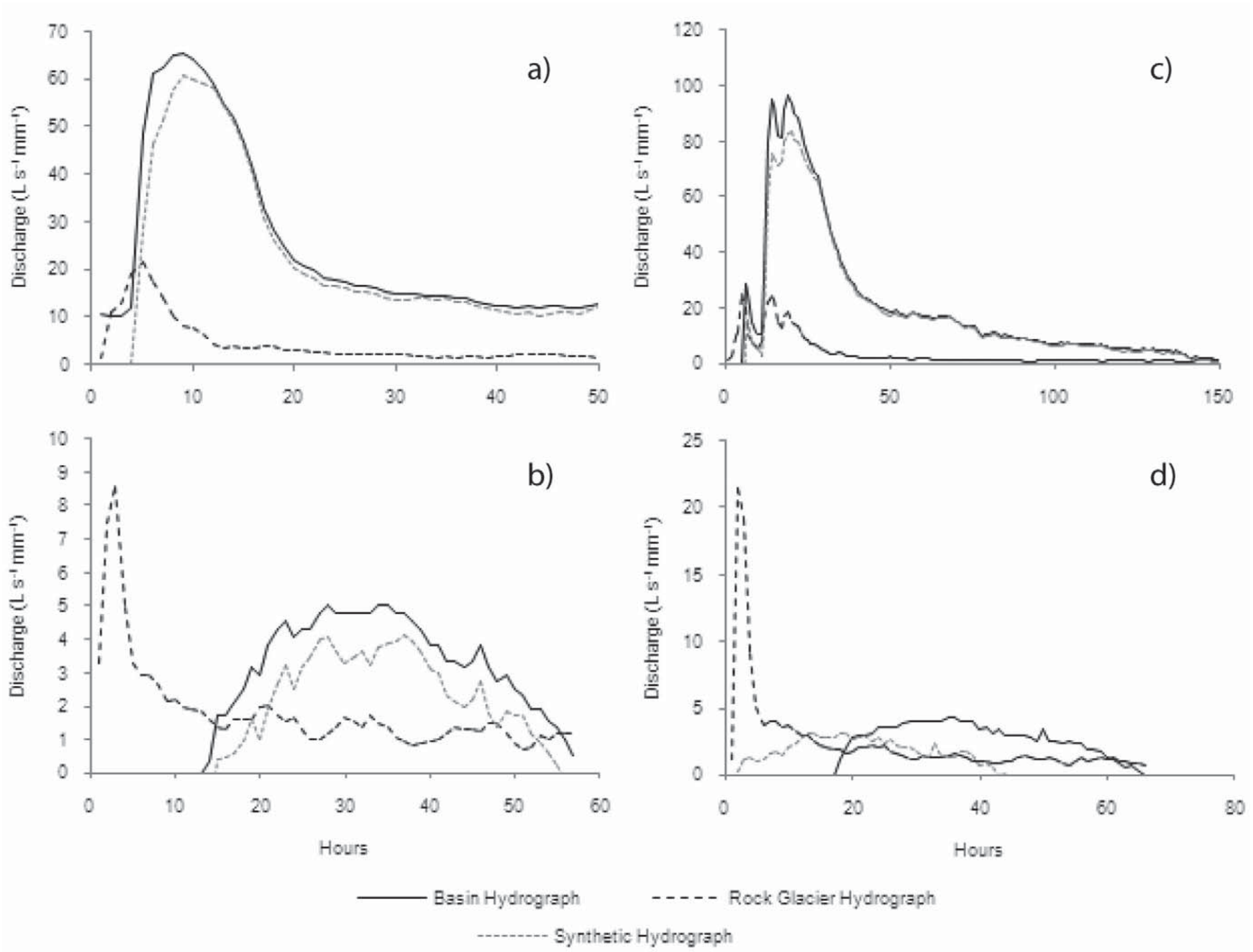


FIGURE 6. Influence of rock glacier runoff on basin runoff hydrographs, Gold Basin. Time is hours after onset of precipitation. Hydrograph (a) corresponds with Event 1 (12 July); hydrograph (b) corresponds with Event 2 (24–25 July); hydrograph (c) corresponds with Event 3 (5–6 August); and hydrograph (d) corresponds with Event 4 (13–14 August). See Table 2 for description of runoff events.

using the method presented in Brooks et al. (2003). This method involves separating the stormflow from baseflow for each ordinate of the hydrograph (by hour) and converting stormflow to direct runoff from the basin in terms of volume for each ordinate. Direct runoff is then divided by watershed area for each ordinate to determine runoff in terms of length. The UHG is then expressed in terms of discharge per unit length of runoff by dividing stormflow for each ordinate by the total amount of runoff expressed in terms of length. The final UHG is expressed in terms of length only, by subtracting ordinate x_1 from x_2, dividing the UHG (discharge per unit length) by the watershed area, and then multiplying by proper conversions to render the final units in terms of length. The sum of the UHG for all ordinates is 1. Detailed calculations can be found in Geiger (2008). Events 1, 2, and 4 have similar shapes, and each runoff event ends between 15 and 40 hr after the onset of the storm. Event 3 has a unique shape compared with events 1, 2, and 4. The dual peaks are lower, at approximately 3 L s^{-1} mm^{-1} and stormflow takes place over a prolonged period that approaches 20 hr in duration. The storm produced 37.6 mm of rain over a 21 hr period during the evening hours on 5 August and 6 August. Thus, it appears that precipitation of modest intensity (1.21 mm hr^{-1}) over a longer duration will result in a shallow, extended UHG. This is in contrast with events 1, 2, and 4, which have rainfall durations of 18, 3, and 9 hr, respectively. A similar situation is evident during event 6, which is characterized by two separate peaks. The initial peak is lower than the second, which is the result of two different storms during a single period of stormflow. Precipitation during this storm takes place over a 23 hr period during the early morning hours of 4 September. Event 5, in which approximately 13.6 mm of rain fell, takes an abnormally long time to reach its peak, approximately 17 hr after the onset of precipitation. This is attributed to the storm intensity (0.65 mm hr^{-1}), which is comparatively less than other storms in Gold Basin (mean = 1.24 mm hr^{-1}). Rock glacier UHG response in the La Sal Mountains appears to be controlled by rainfall duration and intensity.

TEMPERATURE OF SURFACE RUNOFF

Daily surface runoff temperatures recorded at each of the three gage sites have distinct patterns (Fig. 8). Mean daily temperatures for Wet Fork remain consistent throughout the summer around 3.5 °C. Gold Basin outlet temperatures gradually increase from 2 °C

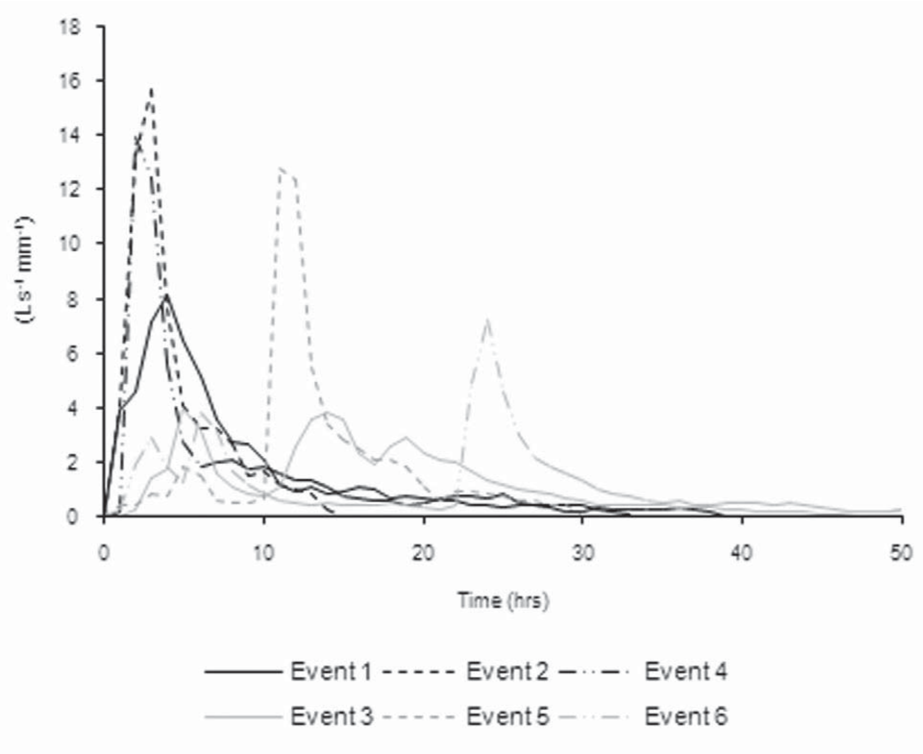


FIGURE 7. Selected unit hydrographs for the Gold Basin flume. Note that rainfall events 1, 2, and 4 are symbolized in black due to their similar shape. For a complete description of rainfall events, please see Table 2.

on 12 June to 3.2 °C by the onset of zero runoff around 26 July. Throughout the remainder of the summer, any runoff from Gold Basin consistently remained above 3 °C, with the exception of a single day on 6 August; however, this is attributed to a storm in which 37.6 mm of precipitation fell. Runoff from the Gold Basin flume remains below 1 °C throughout the summer.

In addition to mean daily runoff temperature, diurnal change in runoff temperature was also determined (Fig. 9). As Wet Fork

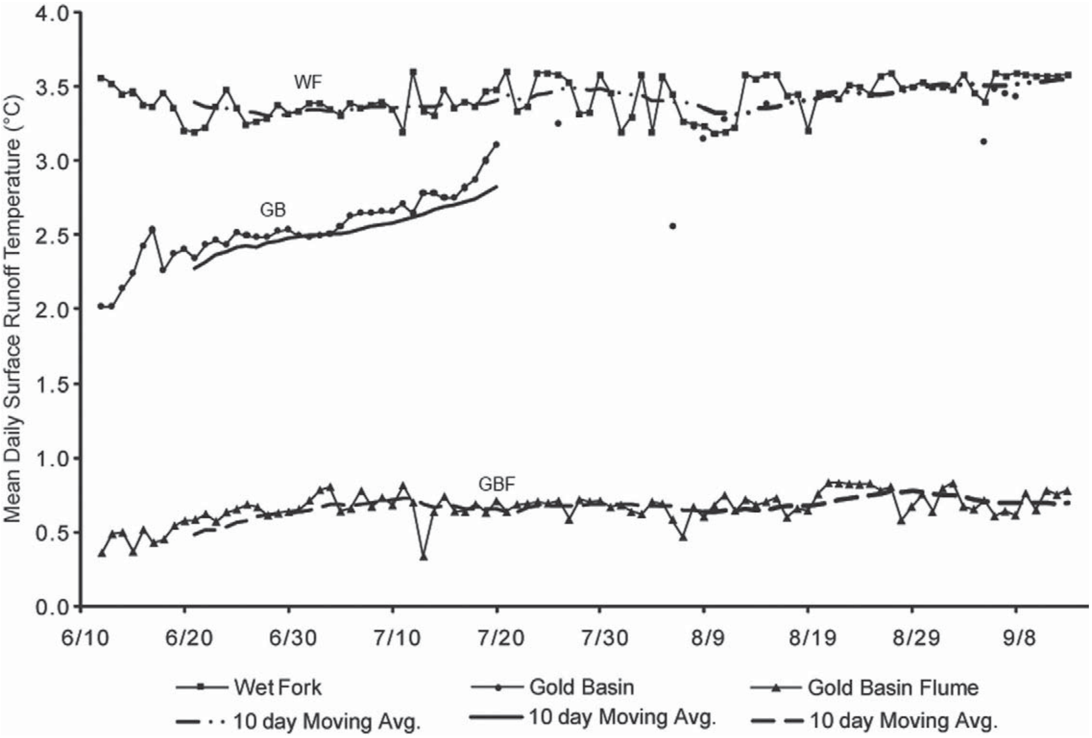


FIGURE 8. Comparison of daily surface runoff temperature at gage sites. The Gold Basin flume shows temperature of runoff to be less than 1 °C throughout the study period. The Gold Basin gage ran dry for several periods in the mid to late summer resulting in lack of data for those periods.

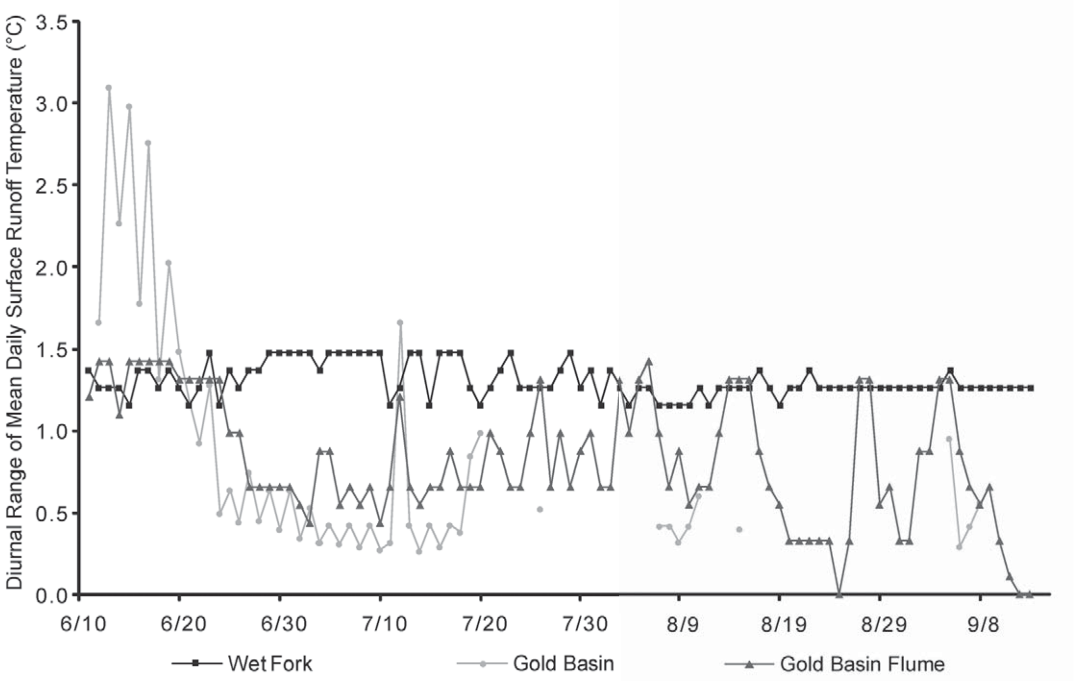


FIGURE 9. Plot of the diurnal variation in mean daily surface runoff temperature at each gage site.

displays a diurnal pattern of runoff throughout the summer, the temperature of daily runoff shows a similar pattern, with ranges constantly between 1.1 °C and 1.5 °C per day; however, a seasonal pattern of water temperature decline is not apparent (linear regression, $m = -0.0013$, $r^2 = 0.12$). In Gold Basin, daily runoff temperature ranges generally decrease in magnitude through early July. The Gold Basin flume has daily ranges with a maximum of approximately 1.4 °C and a minimum of 0 °C throughout the summer; however, variability throughout the summer is much more significant than in Wet Fork.

Discussion

In interpreting the results, it is important to note the short time scale of this study. Patterns in small catchments are extremely volatile from year to year and can make prediction of long-term conditions difficult. The main emphasis of this study is the comparison of basin hydrographs influenced by rock glaciers to hydrographs that are not influenced by rock glaciers. The patterns of rock glacier response to rainfall should be similar from year to year. Furthermore, the summer of 2007 was similar to average conditions at the NRCS's La Sal Mountain SNOTEL site over a 19-yr temperature record and 26-yr precipitation record. In 2007, the average temperature from May through September was 12.2 °C, while the 19-yr average was slightly cooler at 11.5 °C, with a standard deviation of 0.8 °C. In terms of precipitation, 2007 was slightly moister with 338 mm of precipitation compared to an average of 288 mm (standard deviation 82 mm).

Hydrographs from the non–rock glaciated Wet Fork and rock glaciated Gold Basin in the La Sal Mountains are distinctly different. The summer season hydrograph of Wet Fork is characterized by continuous baseflow, with minimal peaks associated with storms. There is a slight daily diurnal variation in flow that gradually decreases throughout the summer. This could result from evapotranspiration or snowmelt. At the time of instrumentation, there was little snow present in the low to mid-elevations of the basin, but snow may have persisted in the upper elevations. The range of recorded stage throughout the summer was about 0.07 m. For this gage location, approximately 0.01 m of water depth translates to an approximately 9.75 L s^{-1} variation in discharge across the observed range. We acknowledge that there are several sources of uncertainty in determining the runoff values at this and other sites, including channel survey, Manning's *n* selection, instrument error, and pressure changes between the stream gage and atmospheric logger. We assume that these sources of uncertainty are present across the range of all specific discharge values, not specific stages (i.e., overbank flow vs. in-channel flow).

Daily variation in runoff temperature in Wet Fork is also fairly constant, suggesting that daily flow patterns are being driven by deep flow paths rather than shallow. Clow et al. (2003) attributed much larger diurnal runoff temperature variations (~3 °C) to be the result of shallow flow paths where daily variations in solar heating can affect runoff temperatures.

Conversely, Gold Basin displays a marked period of spring snowmelt, with large diurnal variations that gradually cease by mid-July when baseflow declines to zero. Thereafter, all discharge at the gage can be attributed to storms driving flood peaks. This is contrary to rock glacier hydrologic response reported by Krainer and Mostler (2002), where peak discharges occurred following rain on snow events early in the season, then slowly decreased throughout summer. In Gold Basin, peak discharge for the summer was achieved following a storm on 6 August when the basin was largely devoid of snow cover. In addition, there is not enough runoff from the rock glacier to keep the stream flowing at the basin outlet in late summer, but there remains some runoff at the Gold

Basin flume. Mean daily temperature of runoff in Gold Basin also gradually increased throughout the spring snowmelt, becoming stable toward the end of summer. There is no relationship between mean daily air temperature and surface runoff.

The flume located on the north face of Mount Tukuhnikivatz rock glacier A provides an intrabasin comparison for the outlet of Gold Basin. Rather than a dry channel in mid to late summer, discharge from the rock glacier remained constant, between 0.5 and 5 L s^{-1}, and gradually declined throughout the summer except during storms. Similar results were reported by Krainer and Mostler (2002) for the Kaiserberg rock glacier in the Austrian Alps, the total flow from which also decreased throughout the summer season. The rising limb of flood hydrographs are also quite steep, with most hydrographs requiring only about 2–4 hr to reach peak discharge, indicating that water moves at high velocities through the rock glacier matrix. It also appears that the proportion of rock glacier stormflow to basin stormflow is controlled to an extent by precipitation intensity. Additional investigation is needed to refine this observation, but it may indicate that rock glaciers act as impermeable surfaces during high intensity events, increasing the amount of water leaving the basin as surface runoff. In Wet Fork, which has comparatively smaller areas of talus and bedrock, time to peak is similar, ranging from 0 to 3 hr. In Wet Fork, however, a low amount of precipitation actually leaves the basin as surface runoff, most of which is attributed to precipitation that falls immediately on either side of the channel (Table 3); other precipitation is likely lost to groundwater.

It was expected in this study that warmer mean daily temperatures through late summer would increase rock glacier runoff. However, it appears that the active debris layer of the rock glacier acts as many previous workers have reported (Potter, 1972; Gardner and Bajewsky, 1987) to insulate the internal ice and minimize total melting on a seasonal basis. The insulative effect is only moderate; there remains a diurnal variation in surface runoff and mean daily runoff temperatures throughout the summer. While surface runoff is often colder following storms, temperatures generally rebound to pre-storm levels soon after rainfall, suggesting precipitation does not play a significant role in the melting of internal ice. Daily mean surface runoff temperatures from the rock glacier remain at or below 0 °C throughout the summer, supporting similar findings by Krainer and Mostler (2002).

UHGs from the Gold Basin flume also provide insight into how rock glaciers respond to storms. Peak flows are generally reached approximately 5 hr after the onset of precipitation, and flows gradually reduce back to normal baseflow over a period of 15 to 40 hr. Some UHGs have significantly different shapes than others and can be attributed to differences in rainfall duration and intensity. A primary research goal in rock glacier hydrology should be the continued creation of UHGs worldwide so comparisons can be drawn between rock glaciers in different geographic areas.

In agreement with results of Krainer and Mostler (2002), rock glaciers in the La Sal Mountains mimic the discharge patterns by ice glaciers, including the high rate of discharge during spring snowmelt, diurnal discharge variations during periods of fair weather, and flood peaks associated with storms. The magnitude of these events is significantly lower and much of the cause of this phenomenon must be attributed to the insulative effect of the rock glacier debris matrix.

Krainer and Mostler (2002) also made some basic assumptions regarding other alpine basins that do not contain alpine glaciers or rock glaciers, including the absence of pronounced diurnal variations in discharge, absence of extreme flood events, and higher water temperature based on local weather conditions. These assumptions are confirmed by the results from Wet Fork. There is a small diurnal range in discharge; however, this was largely attributed to local groundwater flow into the channel. Flood peaks associated with runoff are of low magnitude compared to normal baseflow, and stormflow lasts 9 hr at a maximum. Higher water temperatures are also present throughout the summer, usually at or just below 3 °C. A drainage basin dominated by baseflow, such as Wet Fork, is different from a drainage basin with rock glaciers in terms of hydrology. Wet Fork is a gaining stream, continually fed by baseflow throughout its entire length. Gold Basin is a losing stream at the outlet and only flows following storms. Comparing the hydrology of the two basins shows that indicated hydrologic processes such as infiltration, overland flow, baseflow, and soil water largely control overall hydrologic response to storms.

A central finding of the study is the prominent effect rock glaciers have on basin hydrographs. Figure 6 demonstrates that removing the area occupied by the Mount Tukuhnikivatz rock glacier A and assuming concurrent hydrologic processes replace the removed area will decrease flood peaks and total flow. Rock glacier meltwater in Gold Basin cannot be totally accounted for by a single stream gage, so synthetic hydrographs do not represent the total removal of all Gold Basin rock glacier areas from the outlet hydrograph. However, if removing the approximately 6% of Gold Basin occupied by Mount Tukuhnikivatz rock glacier A decreases flood peaks and total flow, it can be assumed removing the area occupied by Mount Tukuhnikivatz rock glacier B will have a similar effect. Complete instrumentation of all meltwater streams would be required to determine the total effect of removing the rock glaciers from the hydrograph.

There are still several unknowns to be explored in rock glacier hydrology. While stable isotope analysis has shown that groundwater is linked to surface runoff down-valley from rock glaciers, little is known about the spatial pattern of subsurface throughflow (Williams et al., 2006). Soil moisture probes and piezometers could be a useful addition to fully instrument and monitor the hydrologic regime of alpine drainage basins. Piezometers in Wet Fork could be especially useful to analyze impact of precipitation on baseflow contributions to channels, especially since a small proportion of precipitation leaves the basin in the form of stormflow. Increased understanding of the subsurface hydrologic processes operating in small alpine drainage basins will continue to be important, especially since residence time can affect biotic uptake of nitrogen and rate of acid neutralization (Clow et al., 2003). Additionally, Earth's changing climate may affect the role of rock glaciers as mechanisms for alpine water storage. Clow et al. (2003) report mean monthly air temperature increases of 0.12 to 0.15 °C from 1992 to 2000 in the Loch Vale area of Colorado, results that are consistent with other parts of the Front Range of the Rocky Mountains. Caine (2010) reported increased late-season streamflow in the Green Lakes Valley, Colorado, that is attributable to melting permafrost. As mean annual air temperatures slowly rise, the continued existence of forms of alpine permafrost such as rock glaciers will be threatened (Williams et al., 2002; Baron et al, 2009). It is important that the effect of rock glaciers be considered. Glaciers across the world have been widely considered for their roles in future warming scenarios. In western North America, Moore et al. (2009) described potential implications of melting glaciers in terms of streamflow, water quality, and geomorphic hazards as they relate to socio-economic and ecological considerations. In the Hindu Kush region of Pakistan, Akhtar et al. (2008) found that hydrologic forecast models that completely removed the effect of valley glaciers reduced future runoff by 94%. While rock glaciers do not necessarily contain as much water per unit volume as glaciers, they may in fact be more important at a regional scale. Azócar and Brenning (2010) demonstrated that rock glaciers in the Chilean Andes contain 12% more water than glaciers in the region. It is important that rock glaciers receive continued attention and investigation for their role in water resources.

Conclusions

Discharge from an alpine drainage basin occupied by rock glaciers in the La Sal Mountains of Utah was dramatically different from a similar drainage basin without rock glaciers. Rock glacier hydrographs are dominated by spring snowmelt until the onset of only rock glacier baseflow due to internal melting by mid-July. Throughout the remainder of summer, flood peaks are consistent with summer storms. Discharge immediately below the toe of the rock glacier gradually decreases through the summer, even with the onset of warmer temperatures, confirming the importance of the coarse debris layer in insulating rock glaciers from atmospheric temperatures.

Discharge from a drainage basin lacking rock glaciers remained nearly constant throughout the summer, with slight diurnal variations derived from baseflow. Flood peaks were generally short in duration and stormflow associated with flood peaks lasted 9 hr at a maximum. Additionally, the proportion of precipitation that reached the basin outlet as stormflow was generally small, indicating significant losses to deep groundwater storage.

The rock glaciated Gold Basin showed a constant decline in discharge throughout the summer following the complete melting of the previous winter's snowpack. Discharge from Wet Fork, on the other hand, did not rapidly decline following the end of spring snowmelt. Spring snowmelt was not evident in Wet Fork, and discharge remained constant throughout the summer as a result of groundwater baseflow. However, snowmelt may not have been observed due to either (1) late installation of gauging equipment, or (2) slow infiltration of meltwater into the subsurface, as there were some small snowfields present at high elevations. Rock glacier streams also experienced a longer time to peak than did streams in Wet Fork. Finally, there appears to be no correlation between summer air temperature and rock glacier discharge, as discharge declines throughout the summer and warmer air temperatures do not increase rock glacier discharge.

In conclusion, rock glaciers have a pronounced influence on hydrology of an alpine catchment in the La Sal Mountains of Utah. Flood peaks occur later after the onset of precipitation, peaks are higher, total surface runoff is greater than a non–rock glaciated basin. In a non–rock glaciated basin, peaks occur much faster and the total amount of precipitation leaving the basin as stormflow is significantly less than a rock glaciated basin. Rock glaciers have the net effect of increasing total surface runoff from alpine drainage basins. As climate change threatens alpine permafrost worldwide, drainage basins containing rock glaciers could experience a shift in hydrologic regimes. Initially, increased surface runoff could be expected as rock glacier ice melted during the summer runoff season. Once all internal ice is lost, water from snowmelt that formerly ran off on the surface of the internal ice may instead infiltrate through the rock glacier matrix and exit the basin in the form of groundwater. Such a shift could dramatically affect downstream water users who rely on in-stream diversions, especially in semi-arid regions.

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