The Effects of Surface Runoff on Hart Prairie from Arizona Snow Bowl Facilities, Coconino National Forest

by

Richard Hereford, Research Geologist Emeritus

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Image: West side of San Francisco Mountain—Snow Bowl basin and ski area lie below and to the left of Agassiz Peak on the far right.

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PHOTO FROM VANKAT (2022)

Abstract

HART PRAIRIE, 10 MI NORTH-NORTHWEST OF FLAGSTAFF, ARIZONA, lies on the southwest flank of San Francisco Mountain in Coconino National Forest. The prairie is a debris fan encompassing 1 mi^2 downgradient from the mouth of Snow Bowl drainage basin. Arizona Snow Bowl, a major ski resort, utilizes a stormwater drainage system that directs runoff onto the mid-to-upper prairie, resulting in erosion and spillover of stormwater. This streamflow has not been measured, tested for water quality, related to monsoon rainfall variability, nor attributed to stormwater drainage.

Erosional runoff is ephemeral and dependent on monsoonal rainfall amount. During the summer of 2021 and 2022, the estimated median flow rate on the prairie was 2.5 within a range of < 0.1 to 32.7 cubic feet per second (cfs). These rates are likely one-half of the total basin flow. Erosion of the prairie was previously unknown. Analysis of archival imagery demonstrates that gullies were not on the prairie from 1954 until 1997–2003. The realignment of the catchment's natural drainage channel during 1997–2003 initiated gully erosion. Continued development of Snow Bowl's stormwater drainage caused additional gully erosion and sediment accumulation at multiple sites on public lands. The observed runoff and erosion were caused by rainfall with a return period of 2–7 years. Deforestation for ski trail construction substantially increased seasonal water yield, which amplified erosion and pollution issues.

Surface runoff from the watershed is contaminated by elevated concentrations of suspended solids and excess nutrients (phosphorus and nitrogen). The nutrient concentrations are significantly larger than the estimated regional predevelopment strengths, suggesting a human-made nutrient source related to snow production. Reworking of nutrients in the stable undisturbed soils of the basin is probably insufficient to impose on prairie ecosystems. Instead, we hypothesize that the ski-slope soils store nutrients over time, which results from the repeated application of micronutrients in the reclaimed water used in snowmaking. During relatively large episodic rainfall events, raindrops detach soil and sediment particles. Runoff entrains these particles, transporting them downslope as particulate and dissolved phosphorus (and nitrogen) into the stormwater drainage system that empties onto Hart Prairie.

Introduction

The upper Hart Prairie study area lies in Coconino National Forest south of the drainage divide separating the Verde River and Rio de Flag watersheds (fig. 1). This report evaluates the effects of surface runoff onto the study area from Snow Bowl drainage basin. The investigated topics are discharge flow rates, the magnitude and frequency of rainfall-producing runoff, and water quality. Runoff exiting the basin originates on ski slopes, from other infrastructure, and undisturbed areas. Snow Bowl's stormwater drainage system (fig. 2) distributes this runoff onto the prairie outside of Arizona Snow Bowl's Special Permit Use Area (SPUA).

Previous work assumed that surface runoff onto the prairie was minimal or nonexistent (FEIS, 2005). Instead, new evidence presented here shows that ephemeral streamflow from the watershed is substantial, relatively frequent, and strongly dependent on the amount of monsoon season rainfall. Moreover, water quality analyses indicate that the runoff has elevated concentrations of suspended solids and excess nutrients, specifically phosphorus (P) and nitrogen (N). Indeed, nutrient-rich streamflow was sampled and observed twice (2021–22) running southwest down the fan's hydraulic gradient approaching a developed spring-fed tank (fig. 1).

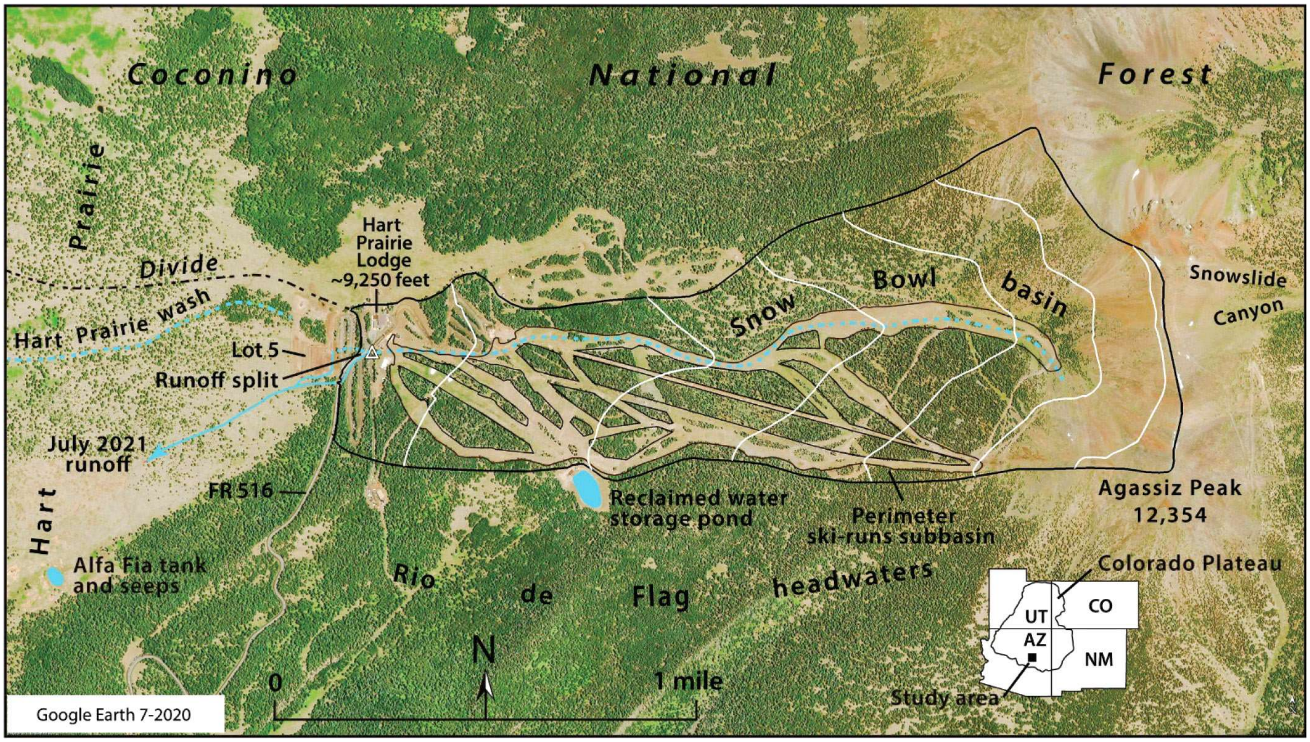

FIGURE 1 West-central side of San Francisco Mountain showing Snow Bowl drainage basin, Hart Prairie, and perimeter of 220-acre 60 percent deforested ski-runs subbasin. Contour interval 500 ft from 9,500 to 12,000 ft. Inset map showing San Francisco Mountain on southwest Colorado Plateau.

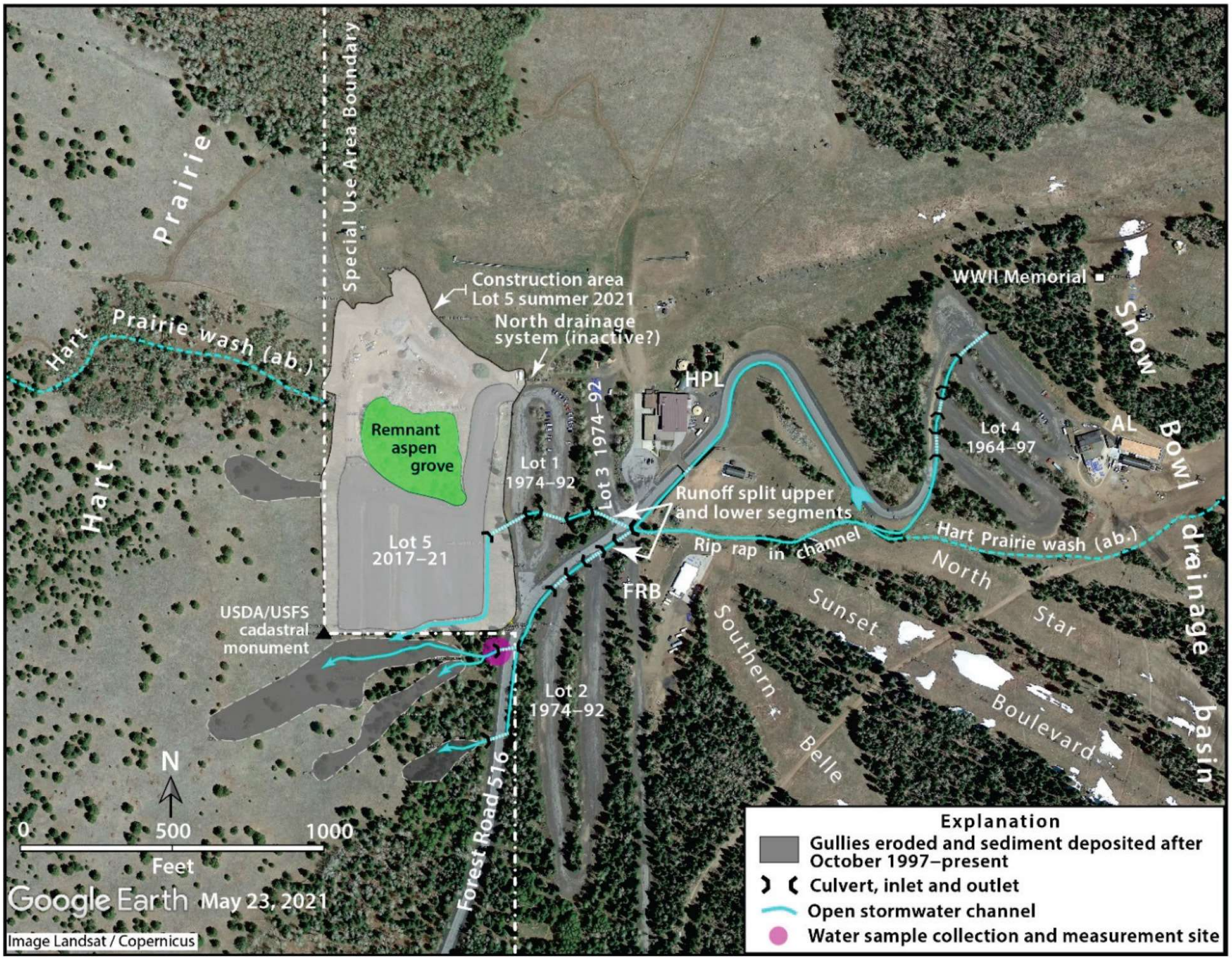

FIGURE 2 Map focused on Snow Bowl facilities showing abandoned Hart Prairie wash (ab.), lower Snow Bowl drainage basin, upper Hart Prairie, and the stormwater drainage system (open channel and culvert symbols). Except for the remnant aspen grove, light-colored pattern is 13.7 acres of fill used in the 2020 construction of Lot 5, including space allotted for future development. Light gray areas outside the boundary (dashed lines) are mapped sedimentary deposits related to stormwater runoff. HPL, FRB, and AL are Hart Prairie Lodge, Fremont Restaurant and Bar, and Agassiz Lodge, respectively.

A major concern in the area has been the potential disturbance of natural resources resulting from the application of artificial snow made with reclaimed water on ski slopes. These disturbances can affect the soil, water, vegetation, and wildlife of Snow Bowl basin and the Hart Prairie study area. For the most part, even after the passage of nearly two decades since a call for scientific study, little is known about the environmental effects of reclaimed water on ecosystems in the basin and those of Hart Prairie (Niraula and Tecle, 2006). In the present report, increased surface runoff and the potential chemical pollution of the prairie ecosystem are identified as ongoing disturbances, which are propagated by Arizona Snow Bowl's stormwater drainage system.

Specifically, runoff on the study area has two undesirable effects—erosion of the prairie and the potential of the nutrient-rich runoff to alter the prairie's native vegetation. The vegetation of the Hart Prairie area is abundant and diverse, consisting of more than 280 species (Waring, 2018). Several aspen groves enhance the viewscape of the prairie, which is heavily visited in summer and fall. Beyond aesthetics, 13 Indigenous Nations and Peoples believe that the mountain itself and certain plant species comprise an essential sacred landscape (Jocks, 2022). The environmental problems identified above could be exacerbated by a planned expansion (https//www.azcentral.com > snowbowl expansion) of Snow Bowl operations (Giltin, 2022).

Data and Methods

Surficial geological and geomorphological mapping was done to delineate runoff-produced surface features and deposits on Hart Prairie (figs. 1 and 2). Mapping and analysis were aided by airborne drone photography. Flights were launched and flown outside of the permitted area. A recreational-grade GPS instrument was used to map the extent of surface deposits and locate elements of the stormwater drainage system. More than 80 GPS waypoints were established. Locational accuracy is about 5 ft, which is adequate for the intended purposes and map scale. The boundary of the SPUA was taken from FEIS (2005, fig. 2-2). The southwest corner of Parking Lot 5 is marked by a USDA/USFS1997 cadastral survey monument. The land west and south of the corner monument is outside the permitted area.

Flow rates of Snow Bowl basin stormwater runoff were indirectly measured at an exit culvert at a point where it flows onto upper Hart Prairie (fig. 2). Culverts are a type of hydraulic control structure that permit flow measurement and collection of water quality samples (Ward et al., 2016, p. 324). Culvert discharge calculations were done with readily available engineering software (Anon.1). Lacking design specifications for the culvert, the measured input parameters were water depth in the culvert, diameter, roughness coefficient of the corrugated steel culvert (tabulated), and the culvert's slope. Flow depth was obtained from waterlines preserved in the culvert. Grab samples for chemical analysis were collected by placing a 1-liter container in the pour-over beneath the sample culvert. This sampling method is not ideal for obtaining discharge measurements and water for chemical analysis, although the culvert constrains the streamflow and provides direct access to the runoff.

Rainfall climate data are not available for Snow Bowl watershed. However, this lack of any precipitation measurements is overcome by the presence of a nearby SNOTEL climate sensor *(Snowslide Canyon, Station ID 927; Natural Resources Conservation Service Report Generator; accessed October 8, 2022)*. Rainfall data collected at the sensor is shown to be a good proxy for monsoonal daily, monthly (July, August, and September), and total seasonal rain in the watershed. The sensor is 2-mi east of Hart Prairie Lodge at about the same elevation as the lodge (fig. 1). Specifically, the sensor is near Snowslide Spring at the west end of the Inner Basin of San Francisco Mountain (fig. 1).

The relevance of the SNOTEL data to the monsoonal climate of San Francisco Mountain and particularly Snow Bowl watershed is substantiated by comparison with a data set widely utilized in the absence of local climatological measurements (see FEIS, 2005, p. 3-27). These are the statistically modeled PRISM climate data *(Parameter-elevation Regressions on Independent Slopes Models Oregon State University)*. The PRISM data are available in 4x4 kilometer grids that cover all of San Francisco Mountain. A multiple-comparisons statistical procedure (analysis of variance) of the several grids adjoining Snow Bowl basin, including the Snowslide Canyon sensor, was used to detect differences among the grids. Five of the six grids do not differ significantly[1] from the SNOTEL sensor. The grid that differed was immediately south of the in-basin grid. It lies on the south-facing side of San Francisco Mountain in the headwaters of the Rio de Flag (fig.1). The other grids correlate well with each other and the sensor data, suggesting that rainfall patterns, amounts, and trends are similar. Month-by-month correlations between SNOTEL and the Snow Bowl basin PRISM grid through 2021 are significant. For example, the coefficients of correlation[2] for July through September are 0.97, 0.77, and 0.98. Although monthly and seasonal totals of the two data sources are statistically indistinguishable, caution is needed when using the daily data; the spatial extent of runoff-producing rainfall may vary daily between the sensor and Snow Bowl.

This report uses relatively high-resolution rectified (WGS 84 Datum) Google Earth satellite imagery (https://googlearth.com) covering the Snow Bowl area. The maps (figs. 1 and 2) were mostly compiled on imagery dated May 2021. The sequential development of Snow Bowl's infrastructure from 1954–1997 was

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[1] Statistical procedures such as correlation among one or more variables and regressions are reported as significant if the probability of a Type 1 error is $P < 0.05$. That is, the null hypothesis of no effect is rejected at the $P < 0.05$ level of certainty. For example, there is less than one chance in 20 that runoff discharge rate and suspended sediment concentration are unrelated.

[2] Spearmans correlation coefficient that ranges from -1 to 1. Zero indicates no correlation.

studied using five archival mapping aerial photographic images (https://earthexplorer.usgs.gov). Google Earth images dating from 1997–2021 were used to document the development of Arizona Snow Bowl's stormwater drainage system and interpret its relation to surface runoff and erosion of the prairie.

Description of the Study Area

Snow Bowl drainage basin and Hart Prairie wash

Hart Prairie lies on an alluvial fan, actually a debris fan, at the base of the west flank of San Francisco Mountain (fig.1). The elevation of the fan's head is 9,200 ft; it descends west 1.5 mi to about 8,500 ft. Several springs and wells are present at the toe of the fan. The fan is roughly 1 mi^2, as expressed on the Humphreys Peak 1:24,000 scale topographic map (1983)[3]. Snow Bowl basin lies above the head of the fan. The catchment's drainage area and vertical relief are 1 mi^2 and more than 3,000 ft, respectively. Elevation ranges from 9,000 to 12,354 ft atop Agassiz Peak. Timberline lies at 11,640–11,820 ft at the head of the watershed where alpine tundra is dominant. Vegetation below the timberline is mainly a dense spruce-fir forest that occupies about two-thirds of the drainage.

Snow Bowl basin opens to the west, joining the fan's head. The basin is bounded on the south and north by steep forested hillslopes; to the east, it terminates at a steep, largely unforested face that exposes volcanic bedrock at and below Agassiz Peak. This eastern boundary is a prominent north-tending ridge separating Snow Bowl basin from the Interior Valley of San Francisco Mountain (fig.1). For practical purposes, the watershed is equivalent to most of the Snowbowl Subarea of the FEIS (2005). Consequently, this area is directly affected by Snow Bowl's snowmaking activities (FEIS, 2005, fig. 3H-1, p. 3-160).

Snow Bowl watershed, before ski development, was drained by an unnamed wash, herein referred to as Hart Prairie wash, which flowed west down the fan somewhat south of the fan's axis. On the fan, the channel is narrow, well-formed, and incised 5–15 ft below the fan's surface, and the channel contains evidence of historical streamflow that predates the completion of Snow Bowl's stormwater drainage system. The wash now extends as a groomed piste approximately 1.5 mi east into the headwaters near timberline (fig. 1). The wash has no natural tributaries, although ski runs drain the south side of the basin by overland flow into the modified Hart Prairie wash.

Soils in Snow Bowl basin consist of gravelly fine sandy loam, loam is a mixture of sand, silt, and clay; this soil was assigned a severe erosion hazard (FEIS, 2005; soils map unit 740, p. 3-238). The soils are formed on the colluvium of the parent andesite bedrock and are of the type typically found in cold, mountainous regions. Bedrock underlying the soils is one or more andesite flows that date at ca. 600 ka; they are related to the younger volcanic eruptions of San Francisco Mountain (Holm, 2019; Youberg and Ben-Horin, 2021). The rock contains small amounts of the accessory phosphatic mineral apatite (P_20_5), totaling 0.5 percent by weight in rock with 60 percent quartz ($Si0_2$; Holm, 1988; younger andesites of Holm 2021). Weathering of andesite is a natural source of P in surface runoff (Porder and Ramachandran, 2013; Olson and Hawkins, 2013). However, the amount of weathered P and N in the catchment available for runoff is probably limited by the low erosional potential of the undisturbed mostly forested hillslopes on the north and south sides of the basin, excluding the ski slopes.

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[3] Two watersheds divide the Hart Prairie area, although the physical divide is subdued. The smaller southern watershed (ca. 2 mi^2) includes Snow Bowl drainage basin (1 mi^2), Hart Prairie wash, and Hart Prairie debris fan (1 mi^2), the three named topics of this report *(fig. 1)*. Its headwaters are on Agassiz Peak, the second highest of San Francisco Mountain. The wash and debris fan occasionally drain to the Rio de Flag, a tributary of the Little Colorado River. The northern portion of the prairie is the larger watershed (ca. 4.6 mi^2); its headwaters are on Humphreys Peak, the highest point in Arizona. The watershed drains to the Verde River through several intermittent streams. The approximate boundary between watersheds is shown in FEIS (2005, fig. 3H-1; Little Colorado/Verde River Divide). The northern area has been the topic of numerous studies on the restoration and preservation of the Bebbs willow community within the privately held Hart Prairie Preserve (The Nature Conservancy) and public lands (Kurska and Tecle, 2015).

Ski runs

Arizona Snow Bowl's service facilities and ski runs occupy about one-third of the forested Snow Bowl watershed (fig. 1). Advertised ski runs, the most challenging of which are mainly on the north-facing slopes of the basin, include eight lifts, 16 named runs (55 altogether), and 777 skiable acres (Snow Bowl Trail Map 2020-2021; FEIS, 2005 p. 2-5; 2-7). Mapping of Snow Bowl basin using Google Earth satellite imagery outlines a forested area of 220 acres apparently dedicated to ski slope development. Deforested ski slopes within this area occupy 147 acres including the upper portion of Hart Prairie wash.

Snowmaking on the ski runs began in 2012. Since then, the ski slopes have been treated with human-made snow using reclaimed water provided by the City of Flagstaff. Depending on seasonal weather conditions, up to 1.5 million gal/day of reclaimed water is applied to the ski slopes. This amounts to about 178 million gal/per season from mid-November through the end of April. Reclaimed water is the only aqueous source of artificial snow. The reclaimed water contains the nutrients P and N, whose concentrations are maintained at <5 mg/L and <8 mg/L, respectively (J.L. Huchell, written commun., 2022). At these concentration levels, the water is substantially enriched with nutrients by one or more orders of magnitude relative to domestic water and U.S. Environmental Protection Agency (EPA) guidelines for small streams and rivers.

Autumn at Hart Prairie, looking southeast towards the San Francisco Peaks with ski runs visible at Arizona Snowbowl.

Stormwater Drainage System and the Erosion of Hart Prairie

Satellite and aerial photographic imagery reveal the history of runoff onto upper Hart Prairie from 1954 to May 2021. Briefly, results indicate that initial and ongoing erosion and sediment deposition on Hart Prairie coincides with the development and location of parking lots and the installation of Snow Bowl's stormwater drainage system (Table 1).

Dates	Comments
Aerial Photography (low resolution)	
February 25, 1954	Alfa Fia tank present, access road crosses Hart Prairie wash, south side basin forested
August 31, 1964	Ski-lift, Agassiz lodge, and parking lot northwest of lodge; access road crosses wash unobstructed, channel apparent and continuous east of lodge, basin forested
September 29, 1974	Another NW trending parking area present northwest of Agassiz Lodge at base of wide ski run, Hart Prairie wash appears unobstructed possibly widened and active, access road apparently crosses wash
September 25, 1992	Several ski runs added, wash east of Agassiz Lodge possibly used as a ski run, parking Lots 1 and 2 added, Hart Prairie Lodge present, Lot 3 present west of lodge, wash flows west through open channels and culverts into original channel southwest side of Lot 1, access road crosses wash near present runoff split
October 17, 1997	Hart Prairie appears active below Lot 1, channel widened and deforested east of Agassiz Lodge
Satellite Imagery (high resolution)	
October, 1997	Wash apparently directed under Lot 1, as above, channels and runoff on prairie not evident, dirt access road crosses wash
December 2003	Gully present southwest side of Lot 1 probably from rerouting wash out of channel onto prairie, runoff possible from heavy rainfall September 1998, July 1999, and August 2003, access road to Hart Prairie Lodge crosses wash
June 2007	Poor image resolution
September 2010	
June 2011	Upper segment of drainage system present at runoff split, passes northwest under FR 516 then turns west to pass under Lot 1 where it turns west to empty onto prairie in gully of December 2003, evidence of runoff south of Lot 1 and west of FR 516, heavy rain July–August 2007, August 2008, July 2010
May 2012	Two culverts of lower segment of drainage present under FR 516, northernmost culvert used in this study for water samples and runoff measurements, no change from June 2011, narrow strip of red material (cinders) on west shoulder FR 516
April 2013	Sediment plume and gully now extend 870 ft west of Lot 1, incipient gully present in culverts mentioned above
April 2015	Gully well formed on prairie below sample collection culvert, sediment deposited 900 ft west of culvert, gully west of Lot 1 appears active, gully developed northwest end, Lot 1, large rainfall August 2013 and August 2014
April 2017	Gullies and sediment from both FR 516 culverts present up to 900 ft length and 340 ft wide, construction Lot 5 began
June 2017	Former wash upstream of FR 516 incised and appears recently active
October 2017	Construction Lot 5 underway, construction and excavation east of Hart Prairie Lodge completes upper drainage segment draining Lot 4 and ski slopes south and southeast of lodge
May 2021	13.7 acre five-level Lot 5 mostly complete, former channel of wash armored with rip-rap, upper segment of drainage system rerouted to south end of new lot, termini of segments separated by 320 ft concentrating catchment runoff on southwest side of Hart Prairie alluvial fan

TABLE 1 Development of Snow Bowl's stormwater drainage system as related to erosion of upper Hart Prairie and selected Arizona Snow Bowl facilities, based on aerial photography and satellite imagery, 1954-2021.

The ancient course of Hart Prairie wash on the prairie was blocked and rerouted by the development of Snow Bowl's parking lots and other facilities after 1997, particularly in 2020–21. Over time, a stormwater drainage system has evolved, completely replacing the wash above the head of the fan. The present drainage is a two-segment system. Each segment, referred to as an upper and lower segment, is a series of open channels with connecting culverts that originate at the runoff split *(fig. 2)*. In July 2021, following the completion of Lot 5, both segments of the present system carried stormwater for the first time. Stormwater from each component empties onto Hart Prairie at two closely spaced exit points at the SPUA boundary. The recent erosion observed on Hart Prairie during the summers of 2021 and 2022 was the direct result of stormwater runoff at these two exit points.

Evidence of earlier surface runoff and the related erosion of upper Hart Prairie is the presence of "soils" or sedimentary deposits from runoff events that post-date October 1997. These consist of four mapped occurrences of silty to small pebble-sized gravel eroded from the basin, dark basaltic cinders applied to roads and parking lots, cobble-size asphaltic clasts, and a variety of litter (fig. 2). Litter in the stormwater is deposited on the prairie along with the sediment; it consists of aluminum cans, face masks, miscellaneous colored plastic fragments, and various clothing items. Face masks are diagnostic of the July 2021 runoff. The various occurrences extend up to 900 ft beyond the SPUA boundary. Three of them originated from exit culverts of the drainage system. The fourth and northernmost deposit and 630 ft of its related channel were removed or covered by the fill used to construct Lot 5.

The deposits and related shallow gullies mapped in Figure 2 are absent in imagery dated February 1954 to October 1997. Although features in these early high-altitude aerial photographs are not well resolved, Hart Prairie wash appears confined within its incised channel on the fan until at least 1997. In the Snow Bowl catchment, the wash was narrow and bounded by forest. Elements of the present stormwater drainage system were not evident in 1997. Between 1997 and 2003, however, the wash was evidently diverted from its original channel south of Hart Prairie Lodge, which formerly ran northwest from the lodge through what is now the remnant aspen grove *(fig. 2)*. Rerouting directed runoff onto the prairie at the west side of Lot 1. By 2003, the first erosion anywhere on the prairie was evident in this area; erosion consisted of a well-developed gully and a dark band of alluvium south of the remnant aspen grove. As previously noted, the gully is covered by the construction fill used in Lot 5. The elements of the present two-component drainage system were apparently in place by 2012. Three years later, in 2015, although probably beginning in 2013, a well-developed gully with a related sediment stream extended 900 ft west of both the sample culvert and the culvert 290 ft to the south *(fig. 2)*.

The initial erosion of the southwest side of upper Hart Prairie fan, mentioned above, is related to the final installation of the two-component drainage system in 2012. Incision of the gully is documented by a stratigraphic section of alluvium deposited by stormwater (fig. 3). The alluvium is exposed in the gully 55 ft downstream of the sample and measurement culvert (fig. 2). The section consists of four units (or beds) that overlie the bouldery deposits of the much older Hart Prairie debris fan, which is probably mid- to latest Pleistocene (Youberg and Ben-Horin, 2021). The lowest bed in the sequence is a dark-colored clay-rich soil, probably an A-horizon (unit 1), formed on the bouldery fan deposits. A distinctive light red bed of basaltic cinders (unit 2) overlies the eroded surface of unit 1. Deposition of this bed, as explained below, resulted from the first runoff onto the southwest side of the prairie. The cinder bed, in turn, is overlain by a bed of silt-to-sand-size sediment containing scattered red cinders (unit 3). The surface of the stratigraphic section is formed on clayey sand with small pebbles of andesite bedrock (unit 4). The cinders were eroded from the west shoulder of FR 516. Based on the satellite imagery, a narrow band of red material was placed on the road's shoulder sometime after June 2011 and before May 2012. The gully was not present when units 1 to 4 were deposited. Thus, the present gully (fig. 4) was probably incised during the summer of 2013 and certainly before April 2015 (Table 1). From 2012 to the present, modifications, and additions to the drainage system expanded deposition and gullying on the prairie to the three sites south of Lot 5.

Unit	Thickness (cm)
4	16–30
3	15–20
2	15
1	43

Explanation

Unit 4. Very fine to coarse sand, silty, clayey, grayish brown (5YR 3/2), grades upstream (right) to light gray (N8) coarse sand with granule to small pebbles of andesite and dark basaltic cinders, possibly related to fallen aspen trunk blocking stream flow

Unit 3. Fine to medium sand, clayey, scattered red cinders, grayish brown (5YR 3/2)

Unit 2. Granule to small pebble size cinders, distinctive light red (5R 6/6), upper part truncated downstream

Unit 1. Very fine sand, silty, clayey, medium dark gray (N3), overlies large debris fan boulders, possible A horizon

FIGURE 3 Stratigraphic section of alluvium deposited by stormwater runoff (units 2–4). Exposure in gully about 55 ft downstream of sample culvert (fig. 2). Red cinder bed (unit 2) was derived from red cinders applied to west shoulder of FR 516 before June 2011 and by May 2012. Scale 50 cm (1.6 ft).

(A) (B)

FIGURE 4 Upstream views of gully related to runoff at the sampling and measurement locality (fig. 2). (A) Gully at culvert incised since 2011 (Table 1). (B) Gully 220 ft downstream from culvert; knickpoint (abrupt channel steepening) in foreground. These migrate upstream and downstream widening and deepening the channel. Scale 50 centimeters (1.6 ft).

Hydrology of Surface Runoff and Monsoon Climate

Surface water hydrology

The surface water hydrology of Snow Bowl watershed is unknown. In contrast, the hydrology of the south side of San Francisco Mountain, which adjoins the basin, was addressed in several studies (Hill et al., 1998; Leao and Tecle, 2005; Schenk et al., 2021). These studies were undertaken to understand flooding issues in and around Flagstaff. The studied drainages are not readily comparable to Snow Bowl. Most of them are larger, below timberline, south facing, lack the steep slopes and absolute relief of Snow Bowl, and in most cases, their periods of record are too short for the purposes of this evaluation.

Runoff data, if any exists, for streamflow at the head of Hart Prairie fan is unavailable. Runoff has evidently not been previously measured nor sampled for water quality in that area. Anecdotal information mentions runoff on the prairie, but flow rates were unknown, and the runoff was not linked to the stormwater drainage system. A total of seven runoff events occurred in the summers of 2021 and 2022, although the largest of these likely predates 2021 (Table 2).

LOCATION OF CULVERT OUTLET:
Lat 35.328809° Long –111.712112° WGS 84; bearing ~58 ft at 222° from USDA 1997 S B P corner 2

Date	Discharge, cfs	Lab Sample Number[3, 4]	Total Suspended Solids, mg/L	Total Phosphorus, mg/L	Total Nitrogen, mg/L
April 30, 2021	<0.1 observed[1]	2110747-01	—	0.64	>1.0
July 14–18, 2021	21.7 waterline[2]	—	—	—	—
July 18, 2021	9.5 observed[1]	2110747-02	94,900	2,540	303
October 5, 2021	<0.4 observed[1]	21J1474-01	1,660	0.43	<1.00
July 29, 2022	0.8 observed[1]	22H2668-01	3,980	17.4	11.6
August 14, 2022	2.5 observed[1]	22H2668-02	5,340	28.9	12.7
Before summer 2021?	32.7 waterline[2]	—	—	—	—

1 Flow observed and rate estimated from waterline
2 Flow not observed, flow rate estimated from waterline
3 Nortest Analytical–Legend Technical Services of Arizona
4 Grab samples, typically frozen within one hour and analyzed from 1–3 days after collection

TABLE 2 Coordinates of outlet culvert at sample and measurement locality (fig. 2); estimated discharge rates onto Hart Prairie determined from waterline of observed runoff or waterline only, and abbreviated water quality analyses of spring and fall 2021 and summers 2021 and 2022. Complete reports and chain of custody documentation available from author.

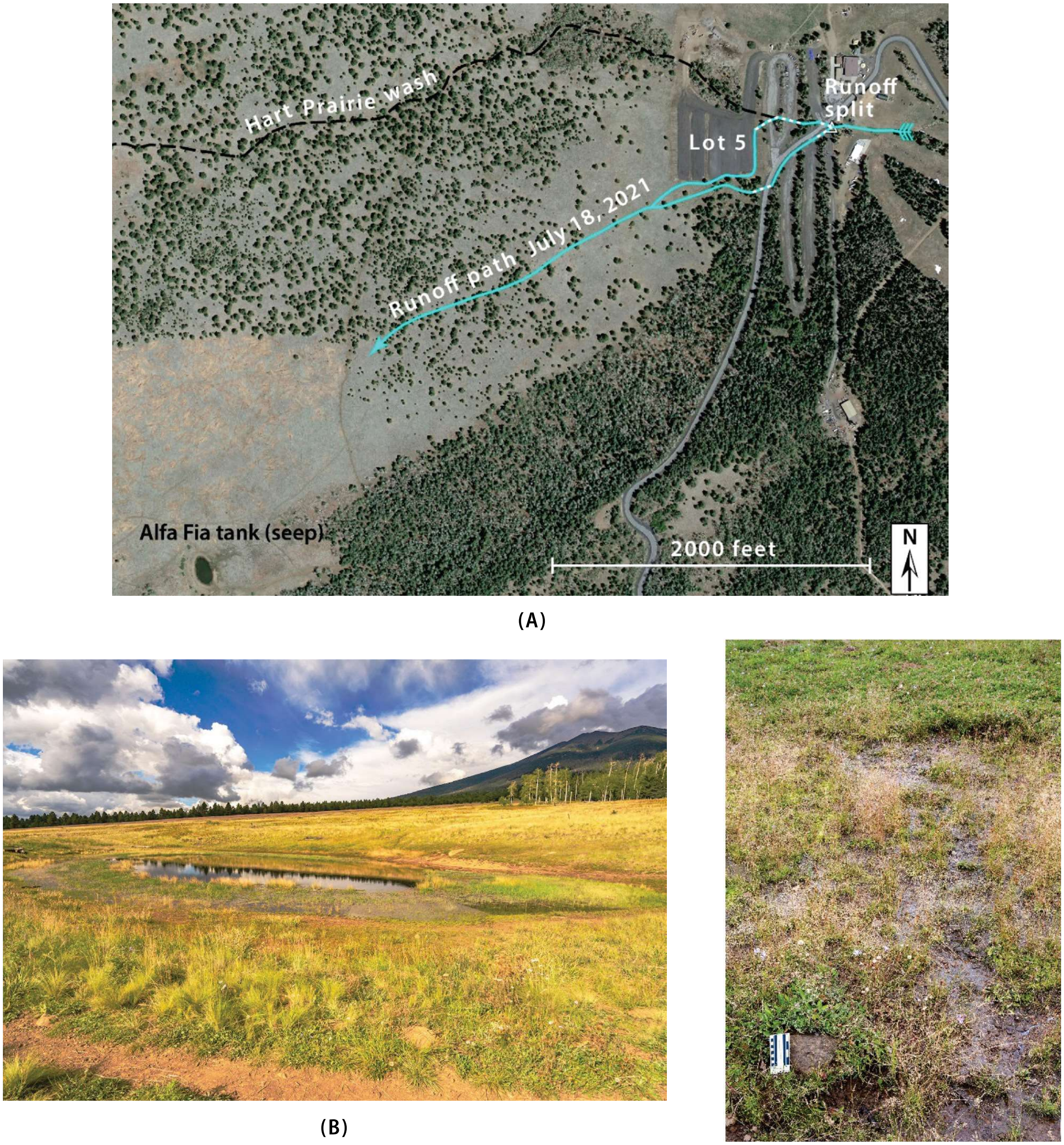
Discharge flow depth was measured indirectly using recent waterlines preserved in the measurement culvert (fig. 2). Estimated discharge rates ranged from < 0.1 to 32.7 cfs. The lowest flow rate on April 30, 2021, was too shallow (slightly above the culvert's corrugated surface) to adequately measure depth, so its discharge was assigned to the lowest possible in the culvert. The water appeared clear and was not noticeably turbid like the other flows; its likely source was snow melting in the open channels of the drainage system. The turbidity of the other flows varied from translucid to mostly opaque, with a distinctive light red coloration depending on discharge rate and total suspended solids (TSS; fig. 5). The highest observed flow on July 18, 2021, was 9.5 cfs. The flow extended southwest of Lot 5 for almost one-half mile down the southwest side of Hart Prairie fan following a preexisting linear feature. This flow path is new and far removed from the natural course of Hart Prairie wash. Evidence of earlier runoff on the southwest side of the fan was not found. The trajectory of this runoff was directed toward Alfa Fia tank, a perennial constructed earthen stock tank fed by two seeps. Larger flows, such as the 21.7 cfs of summer 2021 and the earlier 32.7 cfs would likely reach the tank (fig. 6).

(A)

(B)

(C)

FIGURE 5 Stormwater runoff, afternoon Aug. 14, 2022. (A) Upper segment flowing under Lot 1. (B) Flow from (A) passes around the south side of Lot 5 to exit on Hart Prairie (upper left). (C) Lower segment stormwater flowing onto Hart Prairie at sample and measurement culvert; pavement of FR 516 at top.



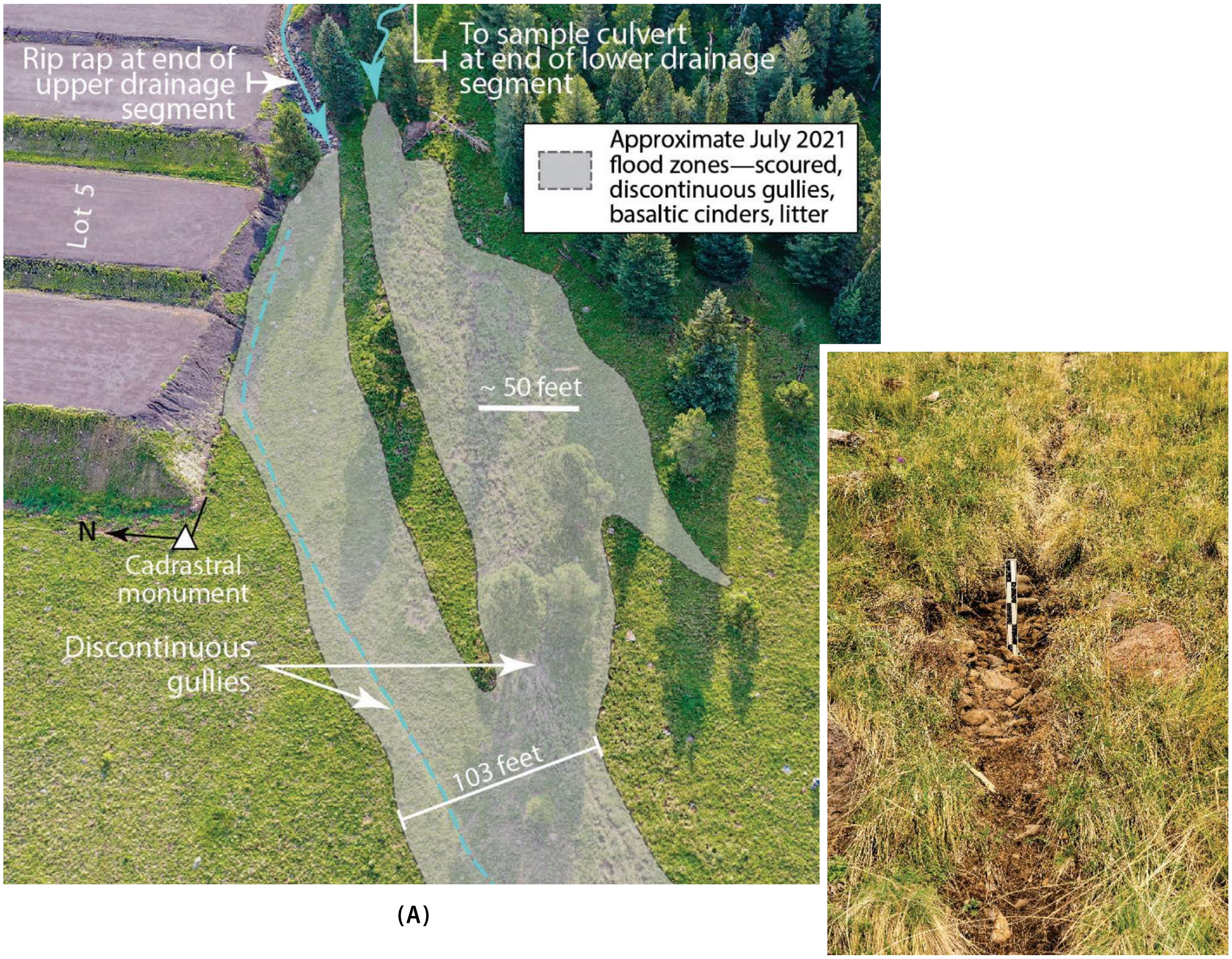
(A)

(B)

(C)

FIGURE 6 Alfa Fia tank and seeps southwest of Snow Bowl. (A) Mapped path of runoff on Hart Prairie, July 18, 2021. (B) Alfa Fia tank with Snow Bowl basin upper right skyline, and (C) one of two seeps feeding tank on distant shore of earthen tank, September 9, 2022 (scale 10 cm).

The estimated flow rates do not represent the discharge of the watershed. Instead, they are likely less than one-half the estimated flow of any runoff event. Basin runoff is split into two streams by the drainage system (fig. 2). The culvert of the upper drainage segment has a larger diameter than the lower component, and the slope of the upper culvert and open channel is steeper. Thus, disregarding any blockages, the upper segment will carry more water than the lower segment. In any case, the two flows combine at the south end of Lot 5, where erosional effects are concentrated (fig. 7). The first combined flow in the new system occurred in late July 2021. The flood zone just downstream of Lot 5 reached a maximum width of 180 ft, narrowing to 103 ft southwest of the cadastral monument. The flow followed a preexisting trail on the prairie, which is likely the precursor of a lengthy incised gully.



(A)

(B)

FIGURE 7 Flood zone and gullying on Hart Prairie related to runoff in late July 2021 and July 29 and August 14 of 2022, respectively. (A) Aerial view of late July 2021 runoff zone flowing from upper and lower segments of drainage system merging downstream into a single flow that extended nearly one-half mile southwest down the prairie. (B) Discontinuous gully in 2022 developing in a former foot or horse trail (scale 50 cm). Gully is two ft deep.

Earlier workers used water balance techniques to estimate runoff onto Hart Prairie from Snow Bowl FEIS (2005). It was predicted that Hart Prairie would be essentially unaffected by runoff. The modelers assumed that the permeable, highly infiltrative bedrock and the soil substrate of the basin would readily absorb runoff. Thus, the watershed can yield zero or minimal net-surface runoff. Although minimal runoff is not quantified, it was concluded that any runoff on the prairie would be inconsequential FEIS (2005, p. 3-230). By design, therefore, any excess moisture in the water balance is presumably consumed by groundwater recharge and is not available for surface runoff (FEIS, 2005, p. 3-233).

The observed and measured runoff events (Table 2 and fig. 5) do not support the hypothesis of no surface runoff. Furthermore, the satellite imagery documents runoff from multiple sites related to the stormwater drainage system. These observed events, moreover, are not abnormalities as shown by the previously described soil mapping. Significantly, deposits of active and inactive alluvial channels, bars, and low terraces in several drainages of southern San Francisco Mountain were mapped by Youberg and Ben-Horin (2021); these features are evidence of recurring and recent runoff. Their results demonstrate that substantial runoff from drainages on the mountain has occurred throughout the Holocene (the past 11,000 years) or at least the past several thousand years. The key runoff indigents are substantial rainfall, snowmelt, or rain-on-snow events, although little is known about the latter two. However, snowmelt runoff in April 2023 produced enough runoff to reach the Rio de Flag in Fort Valley 8.2 miles south of the prairie.

Sources of runoff and sediment in Snow Bowl drainage basin

The basin, as defined in this evaluation, encompasses 640 acres (fig. 1). In this area, four potential sources of water and sediment runoff are apparent in topographic maps and satellite imagery. These are (1) the forested hillslopes on the south and north sides of the basin (excluding ski runs); (2) the headwaters area at the east end of the basin, mostly above timberline below and north of Agassiz Peak; (3) the ski runs on the south side of the basin; and (4) Snow Bowl service facilities such as parking lots, the lodges, and other infrastructure.

The forested slopes of the north side of the watershed and those between ski runs on the south side are an unlikely source of surface runoff, although throughflow is possible. The forests are relatively dense, and the forest floors have several areas with numerous downed randomly orientated tree trunks that can block surface runoff. In the forests, physical evidence of runoff, such as gullies and shallow channels, is mostly absent in satellite imagery. Lacking surface runoff and little throughflow, the north and south side undisturbed forested slopes probably drain into subsurface bedrock and enter groundwater.

The most likely sources of natural runoff are the steep talus slopes and the near-vertical bedrock present above the timberline. Ninety-seven acres are above timberline, including 14 acres of active talus with evidence of runoff. Recent sediment movement in this area is blocky debris flow material with linear downslope extensions of sediment below the cliffs of the uppermost headwaters. Runoff from these mostly unforested areas flows into the former Hart Prairie wash. This area is not treated with reclaimed water. Thus, snowmaking activity and ski-slope construction have not affected runoff from these areas, and nutrient concentrations of any runoff should reflect predisturbance levels.

The ski slopes, various snow bowl facilities, and three of the five parking lots (Lots 2–4) are primary sources of runoff and sediment in the watershed. The ski slopes occupy 120 acres, including Hart Prairie wash, which has been deforested, widened, and developed into a ski run. The parking lots and other facilities occupy 27 acres. So, 147 acres of forest have been removed for ski slope construction and infrastructure development. The south side of the catchment is densely forested in early aerial photography (Table 1); the forested area is 247 acres. Thus, 60 percent of the south side of the watershed has been deforested. The approximate seasonal increase of this subbasin's water yield is close to eight inches within a confidence interval of four to 14 inches. This result is based on studies of the variability between the percentage of basin deforestation and increased water yield (Ward et al., 2016, p. 442).

Generally, studies show that deforestation, construction of ski runs, removing soil and vegetation, and reconfiguring hillslope topography strongly influence the chemical and physical properties of hillslope soils while increasing surface runoff and erosion (Pintaldi et al., 2017; Freppaz et al., 2013). This type of development combined with snowmaking utilizing reclaimed water can affect the ecosystems of the area (Niraula and Tecle, 2006).

Monsoonal climate and runoff

Monsoon rainfall characteristics are undetermined in the watershed as recording precipitation weather stations are absent as previously mentioned. However, it is generally understood that summer rain is a regular occurrence and constitutes the source of warm-season moisture and potential runoff. However, the magnitude and frequency of runoff-producing rain have yet to be studied. The temporal variation of monthly and seasonal monsoon rain was analyzed for the SNOTEL sensor's period of record, 1998 through September 2022 (fig. 8). July rainfall is typically the largest of the season, followed by August and September. Unusually heavy rain in July occurred in 1999, 2013, 2018 (the largest July amount), and 2022. August amounts are typically less than July, although August exceeded July in eight cases. The dry seasons usually have below-normal rainfall for each month.

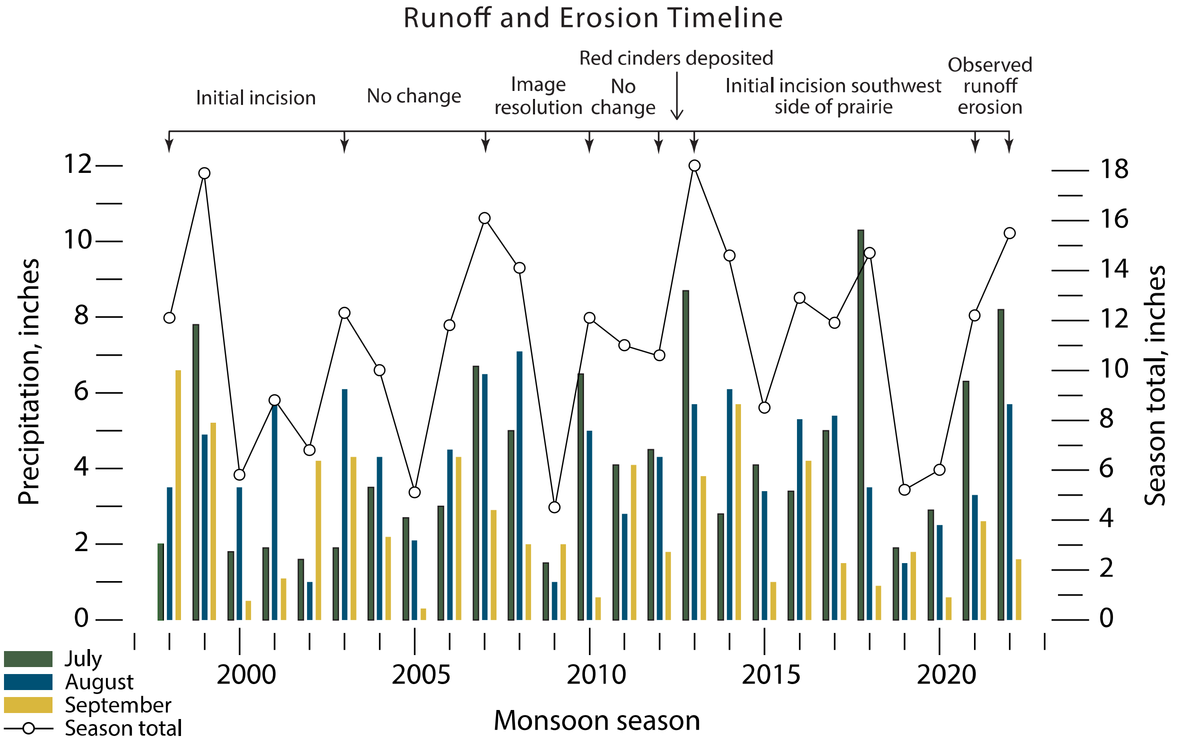


FIGURE 8 Monsoon monthly rainfall (bars) and total season rainfall (line with symbols), 1998–2022. Timeline relates runoff and erosion to variation of seasonal rainfall based on time-sequential analysis of erosional features in satellite imagery (Table 1).

Total monsoon season (July through September) rainfall varies from 3.5 to 18.2 inches. The largest was in 2013, when rain was relatively large each month. The second largest (1999) had a similar pattern. The driest year was 2009, followed by 2019, both of which had little moisture each month of the season. This seasonal rainfall variation is loosely linked with evidence of erosion and runoff episodes (fig. 8, "Runoff and Erosion Timeline"). The runoff and erosional events are inferred from the analysis of satellite imagery (Table 1).

The daily seasonal rain recorded at the sensor is significantly correlated with the rainfall patterns of the season. The strongest correlation is the inverse relation of total rain with the number of days with no rainfall during the season; the coefficient of correlation is -0.80. Another correlation is the direct relationship between the total and maximum daily rainfall of the season; the coefficient is 0.60. Finally, an essential connection between rainfall and runoff is the daily precipitation amount ≥ 1 inch; this correlation is 0.76. This is a measure of seasonal rainfall intensity and seems inherently related to runoff and erosion in the Southwest (Leopold, 1951).

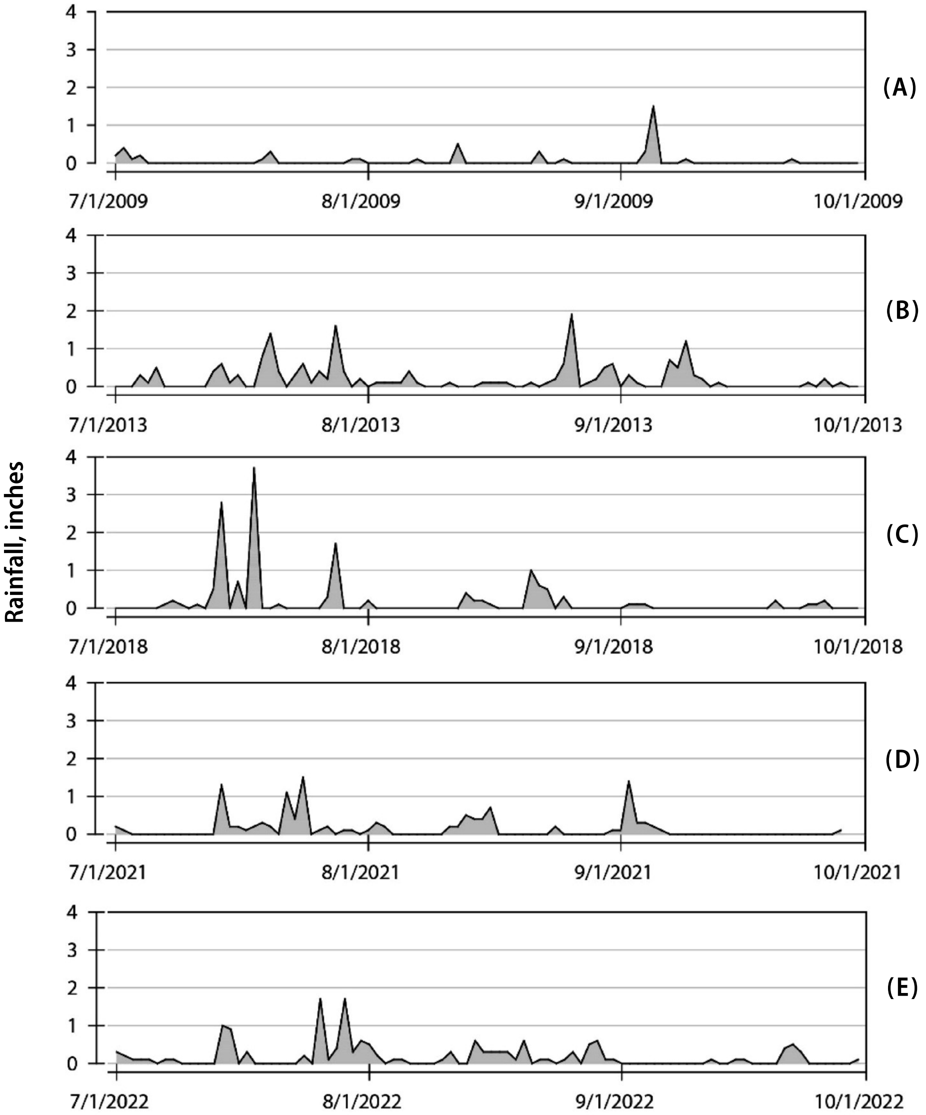


FIGURE 9 Daily rainfall of selected seasons. (A) driest season; (B) wettest season; (C) unusually wet July; (D) and (E) seasons with measured and sampled runoff.

These relationships are displayed in selected plots of seasonal daily rainfall (fig. 9). The daily amounts are shown for the driest (2009), wettest (2013), exceptional single-month rain (July 2018), and the two seasons of measured and sampled runoff (2021 and 2022). The driest season (fig. 9A) had 76 days without rain and a maximum rainfall of 1.5 inches in early September. Substantial erosional runoff, if any, was probably unlikely in 2009. In contrast, the wettest year (fig. 9B) had 43 days of no rain, a maximum rainfall day of 1.9 inches, and a total of 6.1 inches of rain ≥ 1 inch. The initial runoff and erosion on the southwest side of the fan are reasonably attributed to the 2013 season (figs. 3, 4). The largest daily rainfall of any month was 3.7 inches in July 2018 (fig. 9C). The season had 65 days without rain and recorded 9.2 inches in four days. Most of the moisture fell during mid-July. The high-intensity rainfall of mid-July 2018 could produce substantial runoff, although the visual record of runoff in 2018 is inconclusive (Table 1). But the highest waterline in the measurement culvert is estimated at 32.7 cfs. As a first approximation, it seems reasonable to relate the waterline to the unusual rainfall of July 2018.

The observed and measured 2021–22 runoff seasons provide insight into the rain amounts and frequency needed to produce runoff (fig. 9D and 9E). Seasonal totals were above to well above average (11.2 inches) in both cases (12.3 and 15.5 inches). Mean days with zero rain were 56 and 47, respectively, which is somewhat less than the average number of 60 days. Rainfall ≥1 inch was 5.3 and 4.4 inches, substantially above the 3.3-inch average.
The rainfall intensity of the ≥ 1-inch category for 2021–22 is 1.7 and 1.3 inches/day.

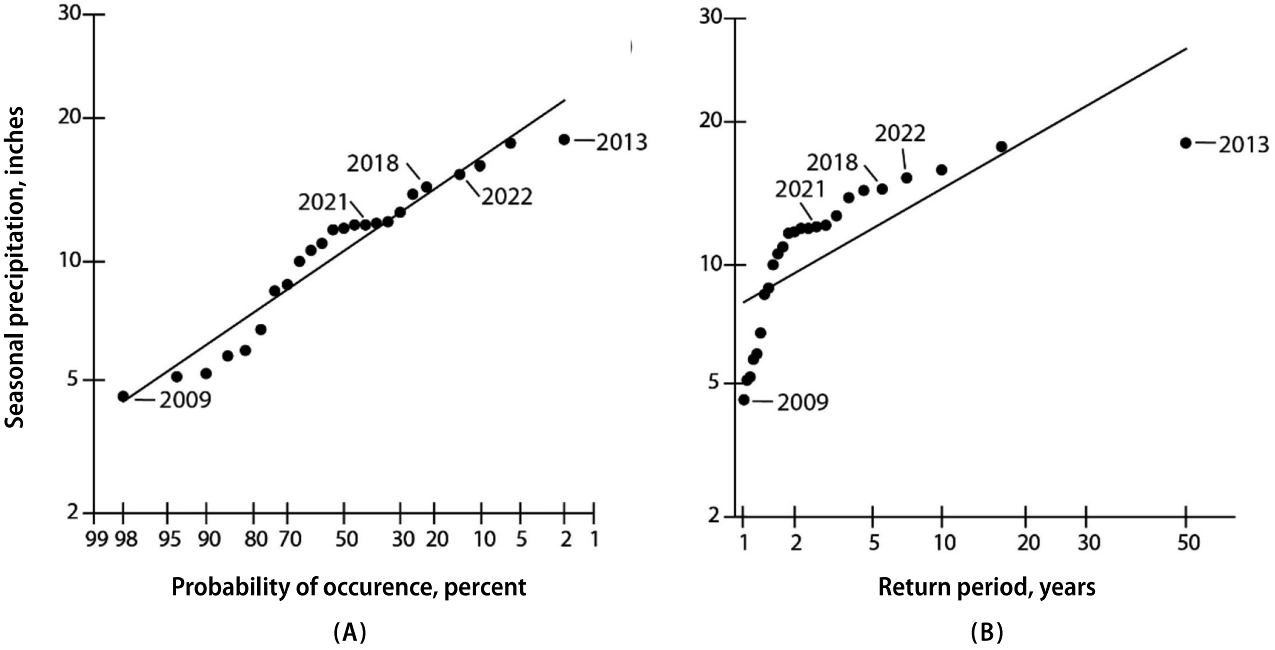


FIGURE 10 (A) Probability of rainfall occurrence and (B) return period for a given amount. Labels are wettest (2013), driest (2009), wettest July (2018 season), and 2021 and 2022 study period.

The probability of occurrence and the associated recurrence intervals of seasonal rainfall are in Figure 10. The former analysis (fig. 10A) indicates variation above and below the theoretical probability (log-log regression line). This results from the clustering of rainfall amounts of 10–12 inches. The return periods also deviate from the theoretical, particularly in the 2–5 return period (fig. 10B). Rainfall amounts of the 2021 and 2022 runoff events (12.2 and 15.5 inches, respectively; fig. 8) have a theoretical probability of occurrence of about 38 and 14 percent, respectively. The corresponding return periods are 2.6 and 7.1 years. Seasonal runoff-producing rainfall amounts such as 2021 and 2022 have a 90 and 28 percent probability of at least one occurrence in five years. Generally, this analysis indicates that substantial runoff from Snow Bowl basin is not unusual.

Water Quality Analyses

Relationship of nutrient concentrations to suspended solids and discharge rate

Water quality analyses of the five observed and sampled runoff events are in Table 2. Collected near the apex of the Hart Prairie debris fan (fig. 2), these analyses are the only known chemical studies of Snow Bowl basin runoff. Notably, these were grab samples and do not reflect flow-weighted first-flush composite samples that typically carry the bulk of nutrient pollutants associated with a rainfall-induced runoff event. Nonetheless, the TSS, total phosphorus (TP), and total nitrogen (TN) concentrations are high. P and N are nutrients that enhance plant growth, but excess nutrients degrade water quality. The nutrient levels of the sampled runoff are elevated above certain fertilized agricultural lands (Dubrovsky et al., 2010). Excess nutrients in Hart Prairie runoff are problematic as they can enter and degrade groundwater affecting downgradient springs and wells.

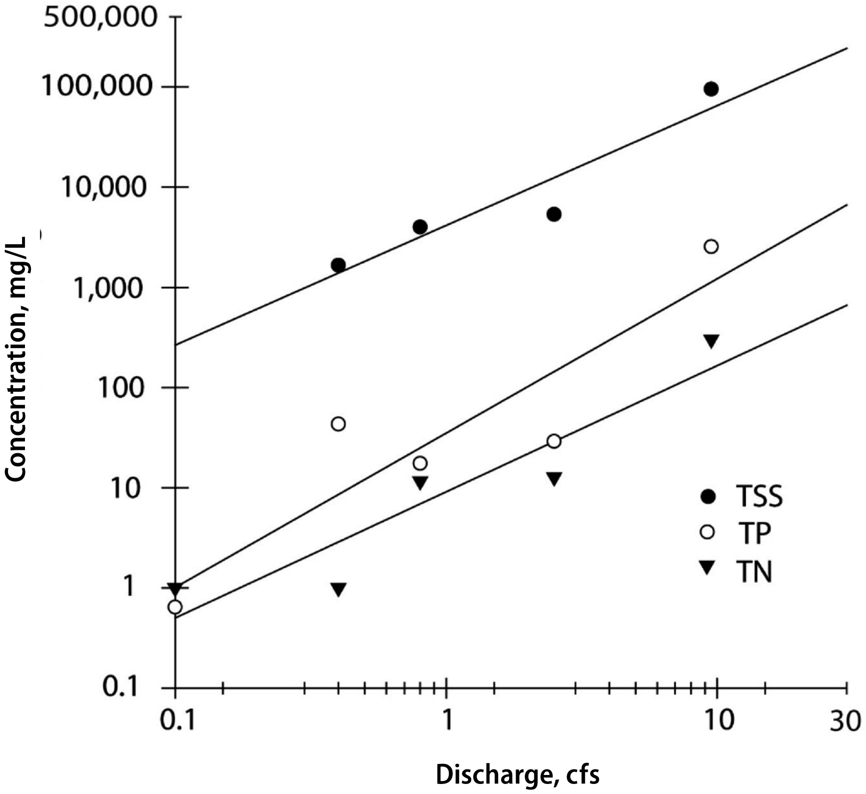


FIGURE 11 TSS, TP, and TN concentrations as a function of discharge. Trend lines are statistically significant ($P < 0.05$), meaning TSS, TP, and TN concentrations are largely a log-log function of discharge.

The degree of concentration of TSS, TP, and TN is significantly correlated with the discharge flow rate, although the data are sparse and scattered (fig. 11). As discharge rises erosion increases along with suspended solids and nutrients. Suspended solids are ubiquitous in streamflow. The solids in the samples were filtered for particle sizes greater than 0.4 microns, which includes size categories of clay, silt, and sand. When sampled, the TSS concentration of the July 18 runoff was 94,900 mg/L, corresponding to 10 percent suspended solids by weight, which seems anonymously large. Indeed, the flow is in the lower range of hyperconcentrated streamflow (Pierson, et al., 1970). But much larger concentrations are typical of many streams and rivers of the degradational Colorado Plateau region (Beveridge and Culbertson, 1964).

The clay and silt are essential components of the sediment load (TSS) because nutrients are bound in the fine-grained sediment. The P in the suspended sediment is particulate P, in which P anions are sorbed in the structure of clays (primarily kaolinite) and fine silt, soil particles, and in particles of primary phosphatic minerals (Sims and Pierzynski, 2005). The suspended solids indicate active surface erosion by runoff in Snow Bowl watershed. This runoff carries sediment along with P and N into surface waters as the output phase of the P biogeochemical cycle. This results in the observed and generally expected (Sandström, et al., 2019) significant relationship between suspended solids that is controlled by flow rate and total P (fig. 11). The finer part of the suspended sediment load is enriched in P (and also N) due to the preferential erosion of fine-grained particles on hillslopes, such as Snow Bowl's ski slopes. Sorption/desorption happens rapidly during streamflow, with soil material in stormwater acting as a P sink or source (River and Richardson, 2017).

Erosion of the ski slope soils, or any erodible slope, is a well-known three-step process beginning with relatively large episodic rainfall events (Berhe et al., 2018). The kinetic energy of raindrops detaches soil particles and aggregates of the soil matrix. In the case of Snow Bowl's ski slopes, surface runoff can transport the detached particles and dissolved solids downslope into the stormwater drainage system and onto Hart Prairie.

Nutrient runoff compared with estimated predevelopment standards

The U.S. Clean Water Act requires that nutrient standards be established to prevent changes in biological or ecological conditions that promote the degradation of local water bodies. Any such changes should logically apply to Snow Bowl basin runoff on Hart Prairie. A voluminous literature addresses the issue of standard nutrient concentrations to aid the management, restoration, and protection of the Nation's water bodies (Smith, et al., 2003; Evans-White et al., 2014). The standard can be in numeric or narrative form. The latter procedure relies on field examination and biological evidence of excess nutrients. In the case of Hart Prairie, this approach seems risky because years to decades may pass before the biological evidence of polluted runoff on the prairie is recognized. The narrative standard seems to favor under-protection of the ecosystem, particularly in watersheds such as Snow Bowl with recent, ongoing development.

The EPA recommends using numeric standards to identify nutrient pollution levels, set remediation goals, and control pollution sources. Arizona's site-specific nutrient standard for TP and TN is 0.05–0.20 and 0.50–1.00 mg/L, respectively (Evans-White, et al., 2017, Table 7). As Table 2 shows, nutrient concentrations of sampled basin runoff are significantly larger than the state's nutrient standards. Across the nation, officials of tribal, federal, and state entities are in an ongoing process of developing criteria for TP and TN. The challenge of establishing numeric standards is identifying naturally occurring nutrient levels (i.e., background, presettlement, or reference levels) for a given water body or aqueous feature (Olson and Hawkins, 2013). Many papers address nationwide and global nutrient contents of relatively large rivers and water bodies, which are ubiquitously nutrient rich due to human activity, primarily agricultural fertilization (Longzhu, et al., 2020). However, few papers consider presettlement nutrient amounts of small, undeveloped catchments like Snow Bowl.

Evaluating whether the present nutrient levels of Snow Bowl basin runoff (Table 2) are ecologically harmful raises a critical question—what were nutrient levels before the development of the basin for recreational activity, particularly snowmaking? This question is informed by knowledge of background nutrient levels in small undisturbed headwater streams. The predevelopment levels are those under which Hart Prairie's ecosystem evolved. If present strengths are roughly similar to background levels, then remedial action is probably unnecessary. A frequently cited paper by Smith et al. (2003) used water quality data from 63 essentially undeveloped headwater basins to estimate or model concentrations in the 14 Level-one nutrient Ecoregions of the United States (https://www.epa.gov/eco-research/ecoregions-north-america). San Francisco Mountain lies in Ecoregion 2, the forested mountains of the western U.S.A, and two of the reference stations used in (Smith et al., 2003) are on the southern Colorado Plateau portion of the ecoregion.

The statistical models developed by Smith et al. (2003) to predict presettlement nutrient levels were criticized by Hawkins and Osborn (2013, and others cited therein). The authors (O and H) used new data, including 823 reference stations, from which they developed two models to better estimate reference site-specific nutrient quantities. Olson and Hawkins' (2013, fig. 1) analysis used data from the Gila Mountains ecoregion, which is the southeastern portion of Ecoregion 2 of Smith et al. (2013, figs. 1 and 7). The Gila Mountain region is noted for its abundant relatively young volcanic rocks; it is geologically like the San Francisco Mountain volcanic field. The former region was apparently chosen to illustrate the effect of bedrock geology and other factors on nutrient concentrations, specifically P, which is a minor constituent of the volcanic bedrock. It is noteworthy that the difference in background nutrient levels between these two published studies is slight, significantly less than, and does not overlap with the sampled runoff concentrations of Snow Bowl watershed (Smith et al., figs. 4B and 4C; Olson and Hawkins, 2013, figs 6A and 6C). The minor differences between the two studies further support Smith et al. (2003) findings for Ecoregion 2 and its application to the interpretation of Snow Bowl's predevelopment nutrient levels.

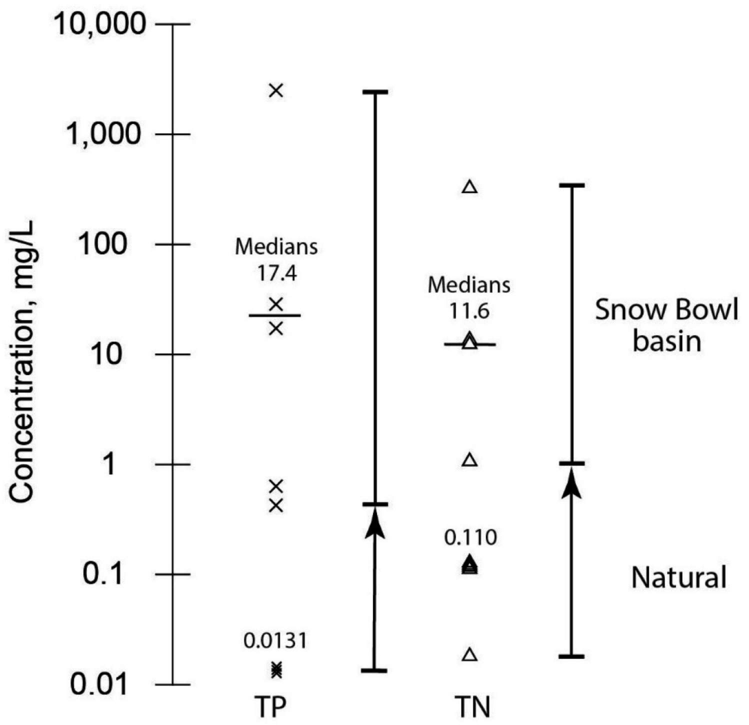


FIGURE 12 TP and TN concentrations of Snow Bowl basin sampled runoff (Table 2) and natural or presettlement concentrations of USEPA Ecoregion 2 (after Smith et al., 2003, fig. 4); and Upper Gila Mountains ecoregion of Olson and Hawkins 2013 (figs. 2, 3, and 5 predicted highest probable model concentrations).

The sampled nutrient concentrations of Snow Bowl basin runoff (fig. 12) are significantly larger than the modeled presettlement strengths of Smith et al. (2003) and Olson and Hawkins (2013). Indeed, median TP and TN concentrations are several orders of magnitude larger than the natural levels of Ecoregion 2 and the equivalent Gila Mountain ecoregion. Moreover, the EPA 25th percentile guidelines for Ecoregion 2 are 0.01 and 0.12 mg/L for TP and TN, respectively. The median sample concentrations are also substantially larger than EPA guidelines, as well as the median nutrient content of streams, rivers, and washes of the Coconino Plateau on which San Francisco Mountain lies (Bills and Flynn, 2002). However, these water bodies drain relatively large areas, suggesting the concentrates are diluted.

The large disparity, nonetheless, between the estimated concentrations, EPA guidelines, and measured concentrations may stem partly from downstream dilution. Dilution is not accounted for in the EPA guidelines, nor in the nutrient modeling of Smith et al. (2003) who assumed that dilution was minor owing to the small area of the reference watersheds. Olson and Hawkins (2013) used annual precipitation amounts to measure dilution in their models; the effect was evidently minor. The available information supports the notion that the median sampled nutrient strengths of catchment runoff are well above those of the estimated and modeled presettlement levels of Ecoregion 2 as well as those of the Gila Mountains ecoregion.

Finally, a mass balance analysis of nutrients in Snow Bowl basin demonstrated that the concentrates exceed expected natural levels (Stewart, 2022, pers. commun.). In his study, Stewart also found that typical sources of excess nutrients, such as atmospheric deposition of P and N, runoff from parking lots, and leaking septic systems are relatively unimportant and do not alter the mass balance calculation results. The largest in-basin source of excess nutrients probably resides on the ski slopes. Thus, some portion of the excess is human-made, although how much is not well known. The excess likely derives from the repeated, seasonal application on Snow Bowl's ski slopes of the relatively nutrient-rich reclaimed water used in snowmaking. It is reasonably well known that applied nutrients are stored in the snowpack and enter soils during seasonal melting (Freppaz et al, 2018); nutrients are then released during soil erosion initiated by monsoonal runoff.

Discussion

Runoff and the resulting erosion of the upper prairie are products of the stormwater drainage system and seasonal variation of monsoon rainfall amounts. Natural runoff from the watershed, formerly contained in Hart Prairie wash (fig. 1), was rerouted into a two-component, two-exit stormwater drainage system (fig. 2). The close spacing of the exits (320 ft) concentrates runoff on the southwest side of the fan. This results in active erosion of gullies where none were present as late as 1997–2003 (figs. 3, 4, and 7). Runoff presently follows a footpath or trail leading to a constructed earthen tank fed by two seeps (fig. 6). Incision occurs along the footpath downstream of the culvert exit points. These are the first indications of an erosional process, generally called arroyo cutting or gullying, that will accelerate over time. Gullies will likely form discontinuously in accordance with a long-recognized erosional process—they widen, deepen, and extend down and up the slope of the fan connecting into a continuous erosional feature (Cooke and Reeves, 1976).

The estimated runoff at the mouth of Snow Bowl catchment is much larger than anticipated by previous hydrological modeling studies. Runoff onto Hart Prairie was inaccurately thought to be minimal to nonexistent. The notion of no or little runoff from the watershed is not supported. Furthermore, the flow rates, which seem substantial, are likely less than one-half of the total catchment runoff (Table 2). The importance of surface runoff on the erosion of Hart Prairie was not previously recognized.

According to FEIS (2005, p. 2-52; fig. 3H-1), four small springs on Hart Prairie downgradient of Arizona Snowbowl, two of which are used for domestic water, would not be affected by changes in groundwater solute concentrations related to snowmaking. But this conclusion was based on the assumptions of little to no surface runoff and nutrient concentrations that were not appreciably elevated. However, the substantial surface runoff can infiltrate into groundwater, and the nutrient concentrations of the runoff are elevated.

The sampled Snow Bowl basin runoff has excessive nutrients, P and N. This conclusion is supported by the median nutrient strengths of the sampled runoff, which are significantly larger than the estimated predevelopment nutrient concentrations of Ecoregion 2 (fig. 12; Smith et al., 2003) and the volcanic Gila Mountain region of Olson and Hawkins (2013). Generally, nutrients enter the aqueous system through the erosion of hillslopes in a watershed. Indeed, soil erosion of sloping landscapes is a fundamental step of biogeochemical nutrient cycling. Although the water quality data are limited, the results presented herein suggest that catchment runoff is nutrient rich by most accepted standards, including predevelopment criteria.

What then is the source of excess nutrients in the runoff? That hillslopes in the catchment are eroding is apparent from the relatively high TSS of the sampled runoff. However, the contribution of TSS from the undisturbed, forested hillslopes is probably minimal compared with the heavily disturbed ski slopes. Thus, the 147 deforested acres of ski slopes are a likely source of excess nutrients. As TSS concentration rises with increasing flow rate, so will nutrient strengths (fig. 11). The nutrients are in the suspended sediment load attached to finer-grained sediment and soil particles. Reclaimed water used in snowmaking contains dissolved P anions ($H_2PO_4^-$ and HPO_4^{-2} and probably other species). The ski slopes are treated with this relatively nutrient-rich water. In a typical season, based on an average TP concentration of 5 mg/L, 72 lbs/acre of P are applied to the slopes, not including Hart Prairie wash ski run. The resulting snowpack stores (accumulates) these applied chemicals, releasing them into the soil during periodic melting, as described by Freppaz, et al. (2018). As P anions move deeper in the soil solution, substantial nutrient retention occurs on soil particles and fine-grained sediment; subsurface leaching of this P is fairly small (Smil, 2000; Sims and Pierzynski, 2005). In this manner, P can accumulate on and in the ski slope soils. N also accumulates, but its pathways through the soil are complicated due to its many forms and gaseous phase.

Recommendations

The erosion-runoff issue is addressable in one of two ways. Appropriately sized retention ponds placed upstream of the runoff split would control runoff and eliminate chemical contamination of the prairie (fig. 2). Another possibility is returning Hart Prairie wash to its original pre-1997–2003 course (Table 1, figs. 1 and 2). The stormwater drainage could be modified at the split so that all runoff is directed around the east side of Lot 1 into the unused north drainage system, where it would connect with the natural channel in the remnant aspen grove. But this alternative does not address the possible pollution caused by groundwater moving downgradient.

Although the association of excess nutrients with snowmaking on ski runs is plausible, the explanation of the high nutrient levels in Snow Bowl catchment runoff is somewhat unsettled pending further study. Geochemical studies of the ski slope and forest soils are needed to test for P and N concentrations; this can help resolve the excess nutrient issue as the forest soils and soils above timberline should yield predevelopment runoff concentrations. In addition, soils and deposits on Hart Prairie (figs. 2 and 3) should be analyzed for nutrient levels. Finally, a testing program for contamination of Alfa Fia tank and water sources in lower Hart Prairie is needed to search for down-gradient groundwater contamination.

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