Arizona Snow Bowl's new parking lot under construction on Hart Prairie, summer 2020. Realignment of stormwater drainage system has exacerbated existing runoff problems on the prairie. Triangle is cadastral corner monument marking southwestern boundary of Arizona Snow Bowl's Special Permit Use Area.

Documented Stormwater Runoff Beyond Arizona Snow Bowl's Permit Area Causes Erosion and Pollution of Hart Prairie's Ecosystem

by

Richard Hereford*, Tom Brownold, and Gwendolyn Waring Flagstaff, Arizona

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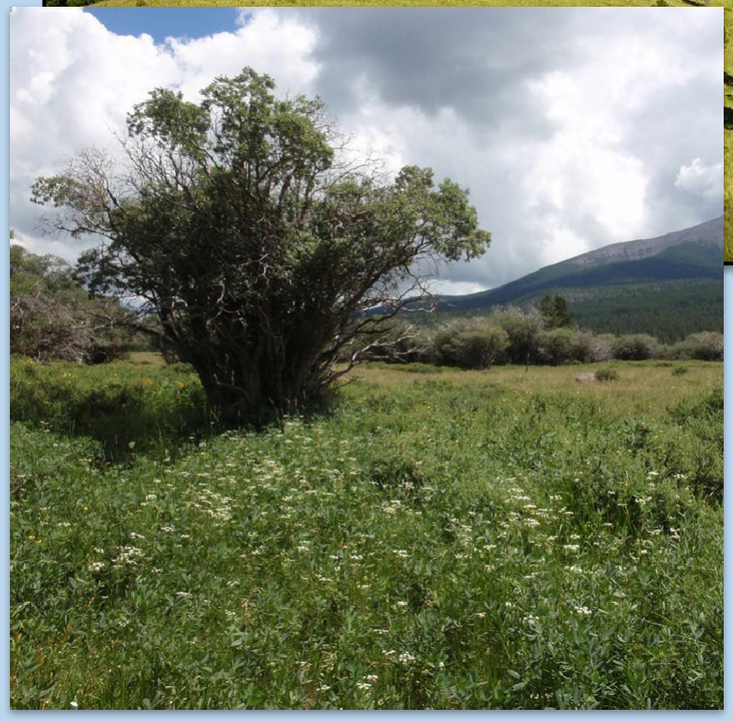
*Corresponding author—This work is not affiliated with nor supported by the U.S. Geological Survey.



Above—*West side of San Francisco Mountain and Hart Prairie. Snow bowl basin is in center of the photograph. Ski runs and lifts above the prairie comprise Arizona Snow Bowl.* ***Below***—*Typical display of vegetation on the prairie; Bebb's willow (Salix Bebbiana) on the middle left and Arizona fescue (Festuca arizonica), a perennial bunch grass lies across mid-ground (Photograph courtesy of Max Licher).*

About Hart Prairie—A Botanist's View

Hart Prairie is an upland riparian prairie on the western slope of San Francisco Mountain. The prairie is an alluvial fan covering more than 250 acres below the mouth of Snow Bowl basin at elevations between 8,400 and 9,000 feet. A diverse assemblage of more than 280 plant species are on the prairie, including all of the conifer species that occur elsewhere on the mountain. Aspen groves, famous for their fall colors, are present at the upper reaches of the prairie. Stands of Bebb's willow on the prairie comprise perhaps the largest population in the United States.

The willows support small communities of plants under their canopies, including delphiniums, roses, bluebells, and geraniums. Forty species of grasses occur on the prairie. On the open prairie and in the shade of trees, 13 species of shrubs are present, including two elderberries, two currants, and nine species of roses. Additionally, milkweeds, sunflowers, bell flowers, honeysuckles, two violets, two geraniums, irises, wild bergamot, two orchids, and nine species of buckwheat are present. All of these plants contribute to the great lushness and diversity of the prairie.

The prairie is a popular scenic area enjoyed by many locals and tourists. But beyond the view of the botanist and the prairie's scenic beauty, the mountain generally and the prairie, in particular, comprise an important sacred landscape and place of worship for over 13 Indigenous Nations and Peoples.

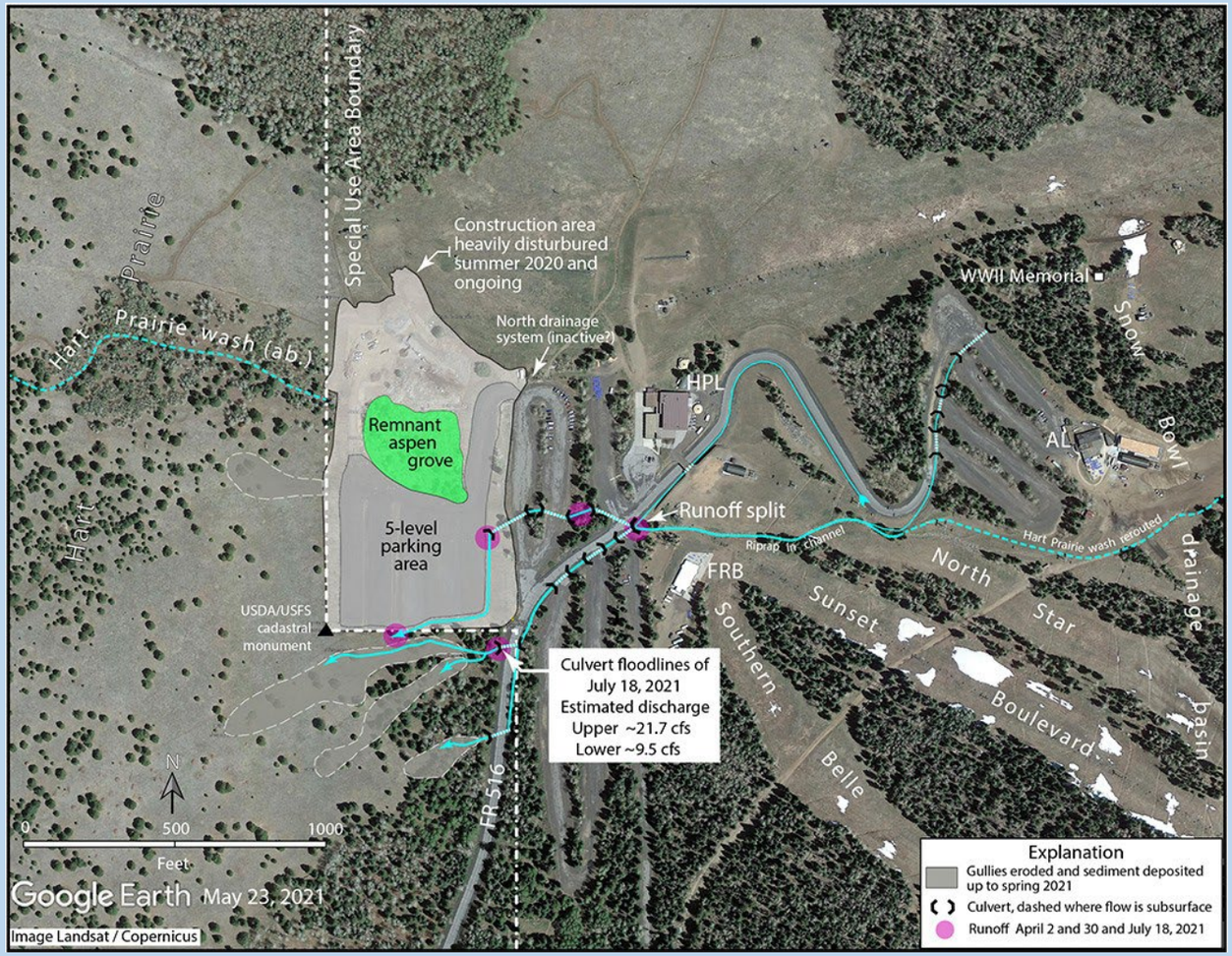
However, the prairie's ecosystem is threatened by uncontrolled, potentially contaminated runoff from Arizona Snow Bowl's stormwater system. Runoff that should be contained at its source.

A simple solution to the runoff problem is a retention pond placed within Snow Bowl's permitted area. Indeed, the 2005 FEIS recommends the construction of a retention pond, obviously, this did not happen.

Drainage culvert flowing into previously eroded gully on Hart Prairie, July 18, 2021 around 4 pm. Culvert passes under Forest Road 516. Water quality samples were collected here just outside of Snow Bowl's permit area.

SUMMARY

- Documented, uncontrolled runoff onto Hart Prairie occurred beyond Snow Bowl's permit boundary in April, late July, and October of 2021, as well as in July and August of 2022. The runoff emanated from Snow Bowl's stormwater drainage system.
- Preliminary discharge rates of the July 18 2021 runoff are 9.5 and 21.7 cubic feet second (cfs) as estimated from two floodlines in this culvert. The stormwater system drains the one-square-mile Snow Bowl drainage basin, which has 3,040 feet of vertical relief. Given the high relief and small size, basin runoff can be substantial.
- Analysis of monsoon—July, August, and September—climate data suggest rainfall-producing runoff like late July 2021 occurred nine times since 1998.
- The runoff from the stormwater system on the prairie at its widest was 103–180 feet. Runoff extended 2,620 feet past the permit boundary.
- Previous hydrological modeling in the 2005 FEIS indicated runoff from the basin *would be minimal to nonexistent.* We know now that this assessment is incorrect.
- Stormwater runoff polluted with litter consisting of basaltic cinders, plastics, clothing, and gravel spreads onto the prairie where it further erodes preexisting gullies.
- Evidence indicates erosion is coincident with the development of a stormwater system beginning between 1997 to 2003. Gullies did not exist in October 1997. The runoff of July 2021 and its detrimental effects on the prairie is not new. But the concentration of runoff on the south side of the new parking lot is new and results from the realignment of the stormwater system to accommodate the parking lot.
- Runoff contains contaminants most likely from ski slopes that are treated with reclaimed water used in snowmaking, which began in 2012. Initial analysis of the July 18, 2021 runoff indicates it contained a disturbingly high nutrient load of 2,540 and 303 mg/L of phosphorous and nitrogen, respectively. Nutrient loading at these levels is much larger than any permitted in streams, lakes, or reservoirs.
- Rainfall-generated hillslope runoff, such as in July 2021, can entrain accumulated soil contaminates on the heavily treated ski slopes. Our analysis does not necessarily pin-point reclaimed water as the principal nutrient source, but treated ski slopes are the most likely of several possible origins.
- **Regardless of source, runoff with such high nutrient loadings will quite likely disrupt Hart Prairie's ecosystem. Further study is necessary to clarify these nutrient values.**

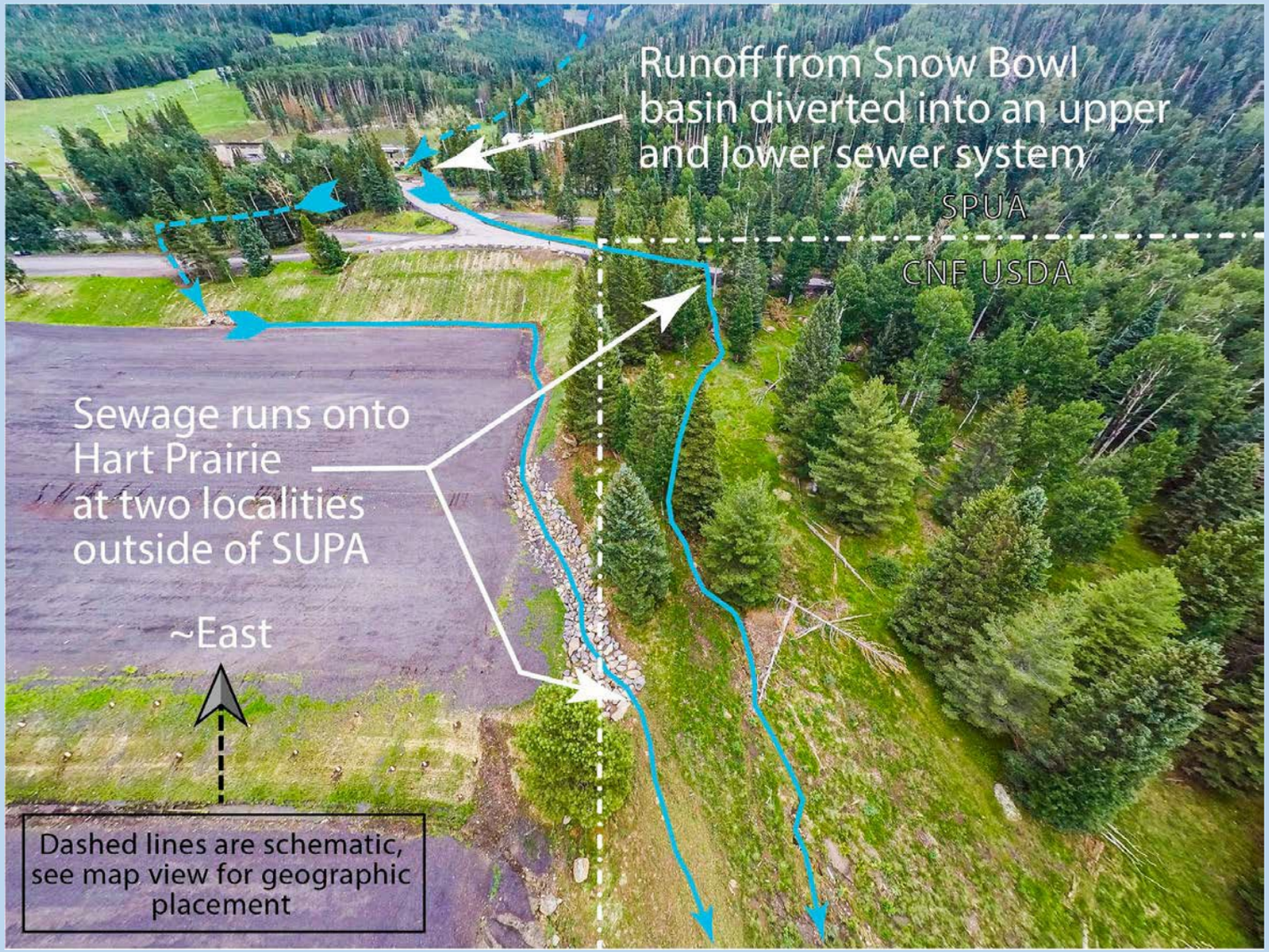


Map of Snow Bowl facilities showing the lower Snow Bowl drainage basin, upper Hart Prairie, the problematic stormwater drainage system (open channel and culvert symbols), and Snow Bowl's parking and visitor facilities.

Mapping Arizona Snow Bowl's Harmful Effects on Hart Prairie

- Development of Snow Bowl's parking lots between 1976–92 blocked the historical course of Hart Prairie wash, which was abandoned and replaced by a stormwater drainage system (see ADDENDUM).
- Runoff from the entire drainage basin enters the stormwater system at the runoff split. A substantial portion of stormwater originates on numerous ski slopes treated with nutrient-rich reclaimed water used in snowmaking since 2012.
- Below the split, runoff is redistributed to the south end of the new parking lot and southwest along FR 516. Where they terminate, only 320 feet separates them, which doubles runoff and concentrates it over a larger area of Hart Prairie.
- The July 18, 2021 runoff was sampled for water quality analysis at the exit of the labeled culvert. It carried an extremely high nutrient load as well as suspended sediment onto Hart Prairie.
- Four light gray patterns map gullies, sediment, and litter from several runoff events mostly after 2011 (if not 2003) and before 2021.

Problematic Drainage System



The stormwater drainage carries snowmelt and stormwater runoff from Snow Bowl basin, which covers about one square mile and has 3,040 feet of vertical relief. Runoff was formerly into Hart Prairie wash before the modern development of the Snow Bowl. Physical evidence indicates that the wash historically carried high-volume floods that the basin produced either from snowmelt, rain on snow, or monsoonal rainfall.

- Wastewater runoff is incising gullies on Hart Prairie where none existed, a process that will severely alter the prairie landscape.
- More importantly, initial water quality analysis of the runoff reveals a heavy suspended sediment load and damagingly high nutrient levels. The reported nutrient levels are preliminary, and further research and study are necessary to comprehend runoff water chemistry fully.

Oblique (distorted) aerial view of the terminal portion of the stormwater drainage system where it debouches onto Hart Prairie.

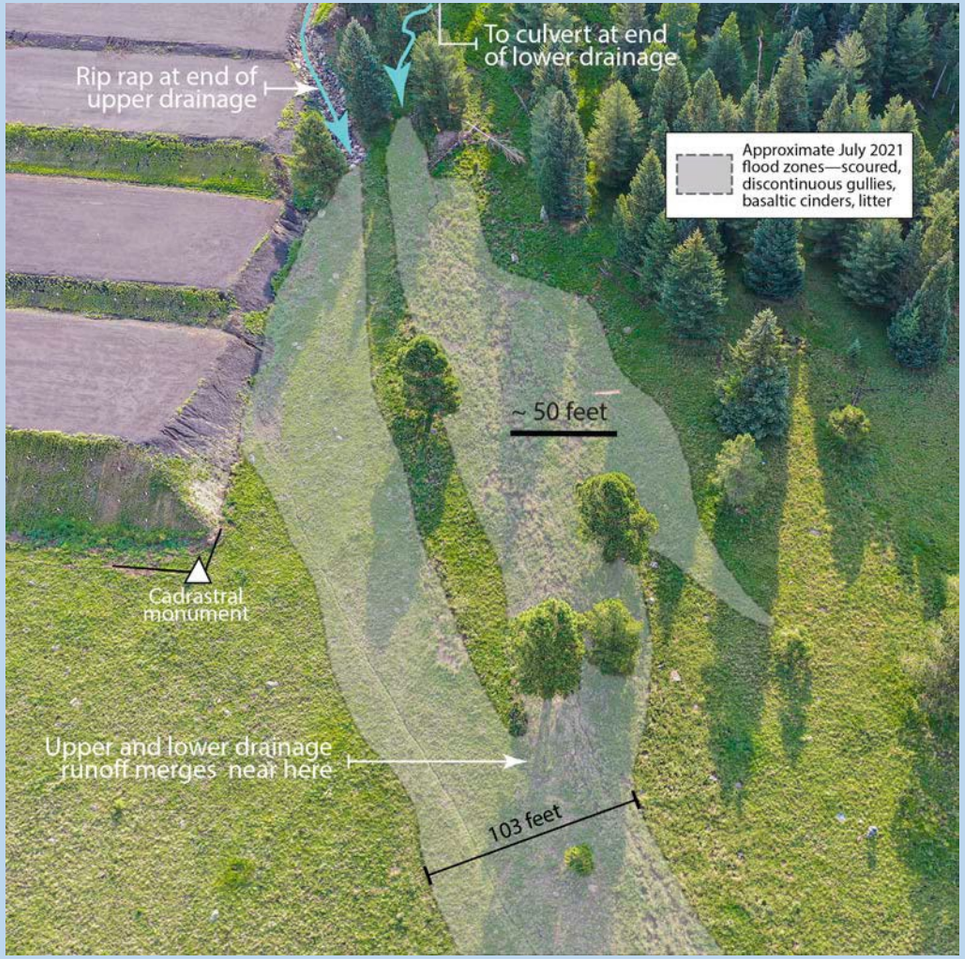
Documentation of Stormwater Runoff Effects on Hart Prairie, late July 2021

Top—Left to right, video clips of lower drainage system. Culvert outflow under FR 516 (far left). Waterline in culvert from peak July flow was substantially deeper than flow in this photograph. Downstream view of eroding gully (middle) and view of runoff across prairie (right). All runoff was south of permit boundary, as seen here by south side of parking lot, July 18, 2021. Videos available on request.

Bottom—Left to right, upstream view of wastewater from lower drainage culvert onto meadow; downstream view of runoff over riprap at end of upper drainage system onto the prairie; downstream view of runoff near junction of the two drainage segments. Total width of two segments near this point was 180 feet.

Flood Zones, Flood Path, and Example of Litter Carried in Floods

Below—Oblique aerial view of flood scour zone (gray pattern) showing combined runoff of upper and lower drainage segments. Diagnostic features are litter from parking lots and other Snow Bowl facilities: dark basaltic cinders, granular asphaltic debris, and discontinuous gullies. Boundary of permit follows south side of parking lot. Flood zone above split at lone tree is 180 feet wide with 25 feet of separation.



Top—Path of combined wastewater down southwest side of Hart Prairie alluvial fan. Flow ended 2,620 feet southwest of lower system culvert (see ADDENDUM*).* ***Runoff along preexisting tracks, trails (such as here), and roads is a widely recognized precursor of gully incision and arroyo development in the Southwest.***

Middle—Flow terminated northeast of Alfa Fia tank. A single plastic water bottle is near scale.

Bottom—Example of litter in runoff consisting of aluminum cans, face mask(s), miscellaneous colored plastic fragments, and various clothing items (circled). Face masks are diagnostic of 2021 runoff. Inset, cobble-size asphaltic clast in gravel.

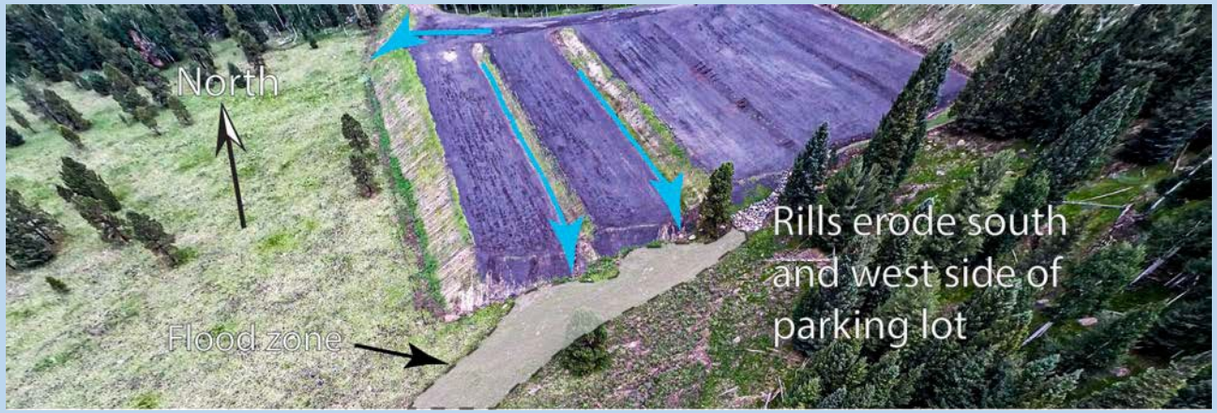
Repeat Photographs Document Sediment Movement and Widening and Deepening of Gullies Since 2020

Upstream views of lower drainage system at and downstream of culvert. Upper left 9/20/2020 upper right 7/27/2021, scale 50 cm long with 10 cm (~4 inches) divisions. Common features are circled. Gully is deeper and substantially wider (rectangles).

Lower left and right dates same as above; left–configuration on gravel bar of pebble-size clasts and basaltic cinders (at scale); right–in this wide-angle view of meadow clasts were moved while others moved downstream; gully is wider and deeper particularly at distant scale where gully is more than two feet deep reaching four feet deep at plunge pool farther upstream.

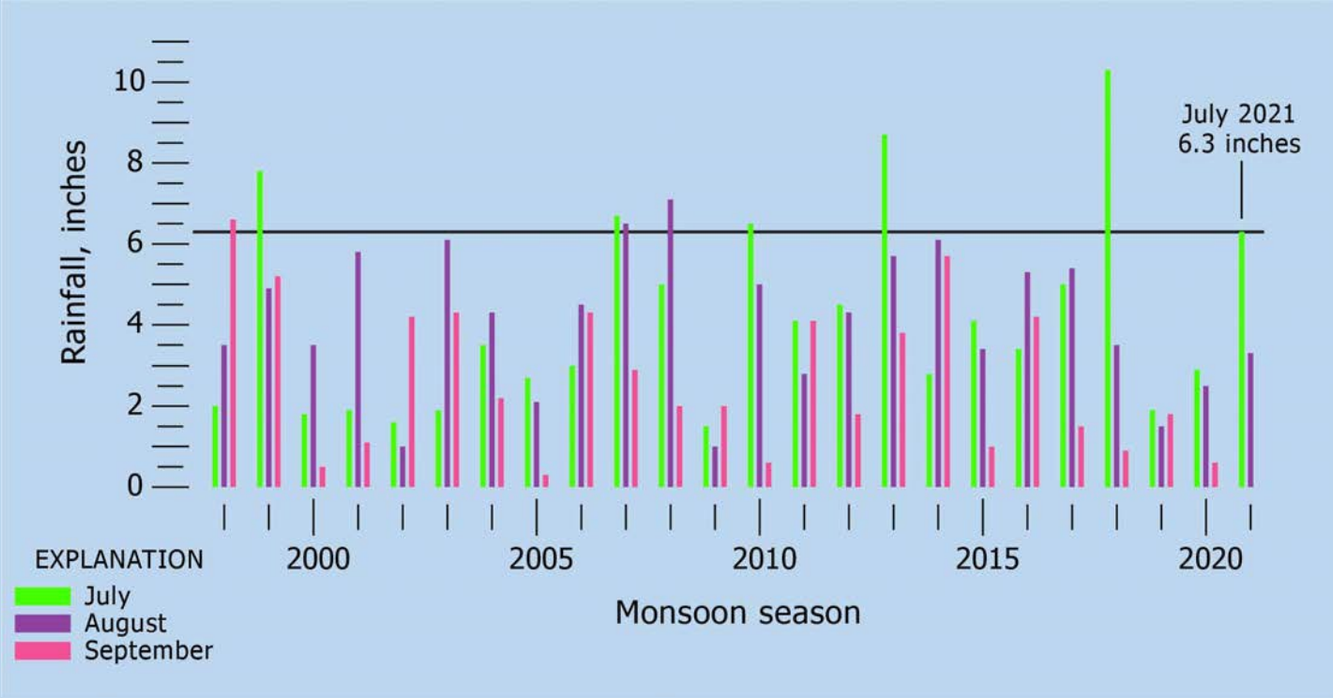
Upstream view of lower drainage gully—left 9/20/2020, right 7/27/2021. Gully substantially deeper and wider.

Rills, Another Style of Runoff-Related Erosion



Left, rills were eroded into south and west-facing sides of parking lot during late July runoff. Right, rill of farthest west of two channels.

How Unusual was the Rainfall of July 2021?

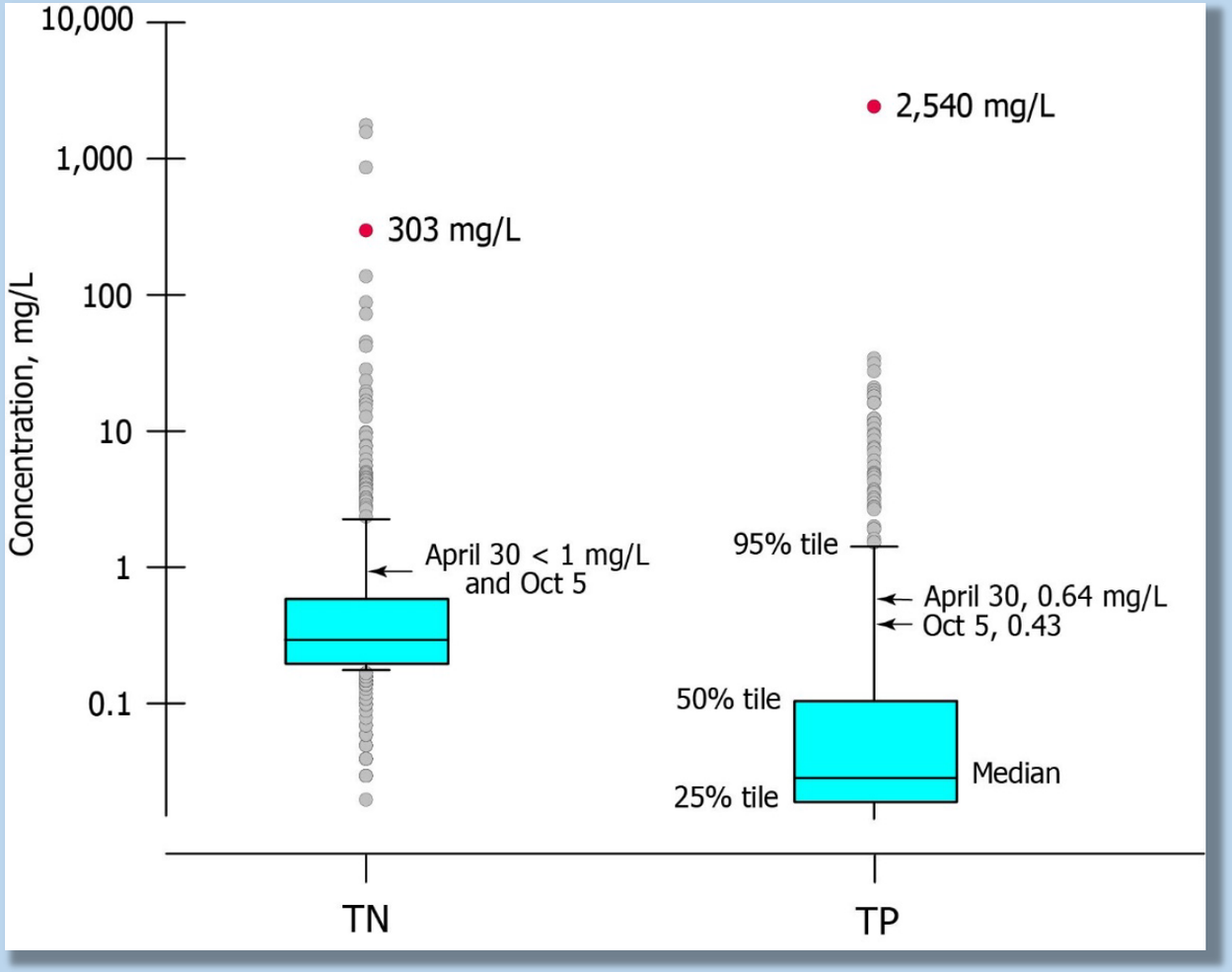


Bar chart of seasonal monsoon rainfal, 1998–2021. The seasonal total rainfall of the monsoon months, July, August, and September, are color coded.

We hypothesize that the July 2021 rainfall, although not unusual, is important because it is a fair representation of the amount of rain necessary to produce high-volume runoff. All things being equal, the July runoff-producing rainfall of 6.3 inches is a meaningful threshold.

- Damaging runoff is evidently possible near or above this rainfall amount. July is typically the wettest month of the monsoon season. July rainfall was close to or above the threshold six times between 1998 and 2021. But August and September rain were also close to or above the July threshold twice and once, respectively.
- So, since 1998, runoff-producing rainfall within 10 percent of the threshold occurred nine times, if not more often.
- The average recurrence interval of monsoon rainfall close to and above 6.3 inches is only two to three years. This does not consider winter snowmelt runoff. We know little about how often it occurs nor the size of such runoff.
- The nine runoff events, by analogy with July 2021, were capable of eroding Hart Prairie and transporting sediment and other contaminants. Although we cannot identify the effects of all nine runoff events, four large mapped areas show evidence of runoff activity.
- The three monsoonal runoff events since 2012 are particularly interesting as they post-date snowmaking on ski slopes with reclaimed water.
- Water-quality sampling of surface runoff from ski slopes at the termini of the stormwater system in both winter and summer can help resolve the extent of prairie contamination by reclaimed water. Although plastics and asphaltic litter in the runoff constitute severe pollution by themselves; the alarmingly high nutrient levels of runoff are ecologically unacceptable.

Preliminary Water Quality Assessment



Box plots showing the statistical distribution of total nitrogen (TN) and total phosphorus (TP) compared with flowing surface waters of the Coconino Plateau region (data from Bills and Flynn, 2002).

Samples of the April 30, July 18, and October 5, 2021 runoff events were collected for standard water quality analysis. Red circles are the total nitrogen and phosphorus concentrations, respectively, of the high runoff event of July 18, which had a flow rate of approximately 10 cubic feet per second.

- These sampled values are outliers in the regional data set. However, this is not an ideal comparison, we use it only to place the extreme values TN and TP in a numeric context.
- The remaining two samples had relatively high nutrient concentrations that are above the 50th percentile of the regional data. Flow rates were less than or equal to 0.4 cubic feet per second.
- The ratio of nitrogen to hydrogen in the July 18 sample indicates excessive phosphorus compared with nitrogen. In a natural system, the ratio is typically nitrogen greater than phosphorus.
- The pathways of nitrogen in the environment are complex and many. Phosphorus in contrast is relatively straightforward.
- **Excess phosphorus in the runoff is larger than what occurs in the natural environment, which indicates the surplus is man-made.**

What is the Source of Suspended Sediment in Surface Runoff?

Left—Turbid, reddish brown runoff of August 14, 2022. The degree of turbidity is partly related to sediment concentration. Right—Continuation of the runoff as it flows in the open channel around the new parking lot and onto Hart Prairie.

Suspended sediment load or total suspended solids (TSS) was high in the large July 18, 2021 runoff event. Sediment includes all solid particles in suspension that are greater than 0.4 microns, that is clay, silt, and sand.

- Sediment concentration of the July 18 runoff was 94,900 mg/L, which is near the lower limit of hyperconcentrated streamflow. This flow was 10 percent suspended sediment by volume.
- High sediment load is a well-known and reliable indicator of channel and hillslope erosion in a drainage basin, which in this case means erosional activity in Snow Bowl drainage basin.
- Ski slopes are the likely source of the suspended sediment as they are easily eroded. The slopes are steep, deforested, and mechanically disturbed.
- Soils on the slopes are eroded during intense rainfall events, shedding sediment-laden runoff downslope into the stormwater drainage system for delivery to Hart Prairie.

The $64,000 Question—How does Excess Phosphorus get Into Surface Runoff?
A Model for Phosphorus Accumulation on Ski Slopes and Transport by Hillslope Runoff

Snow blowing and snowmaking on an unknown ski slope in the West (Credit: snowmakers.com).

A Large Volume of Reclaimed Water is Used in Snowmaking

- ❑ The City of Flagstaff is authorized to supply Arizona Snow Bowl up to 164 million gallons of water per season, which varies according to seasonal climate.
- ❑ Typical reclaimed water contains 5 mg/L of phosphorus. The concentration of phosphorus does not vary much and is strictly regulated.
- ❑ 164 million gallons of reclaimed water contains 3.4 tons of phosphorus (as phosphates).
- ❑ The total area of ski runs, as we mapped them, is 92 acres.
- ❑ The phosphorus applied to ski slopes averages 74 pounds per acre, which is about the same amount used to fertilize one acre of corn.
- ❑ Reclaimed water for snowmaking began in 2012.

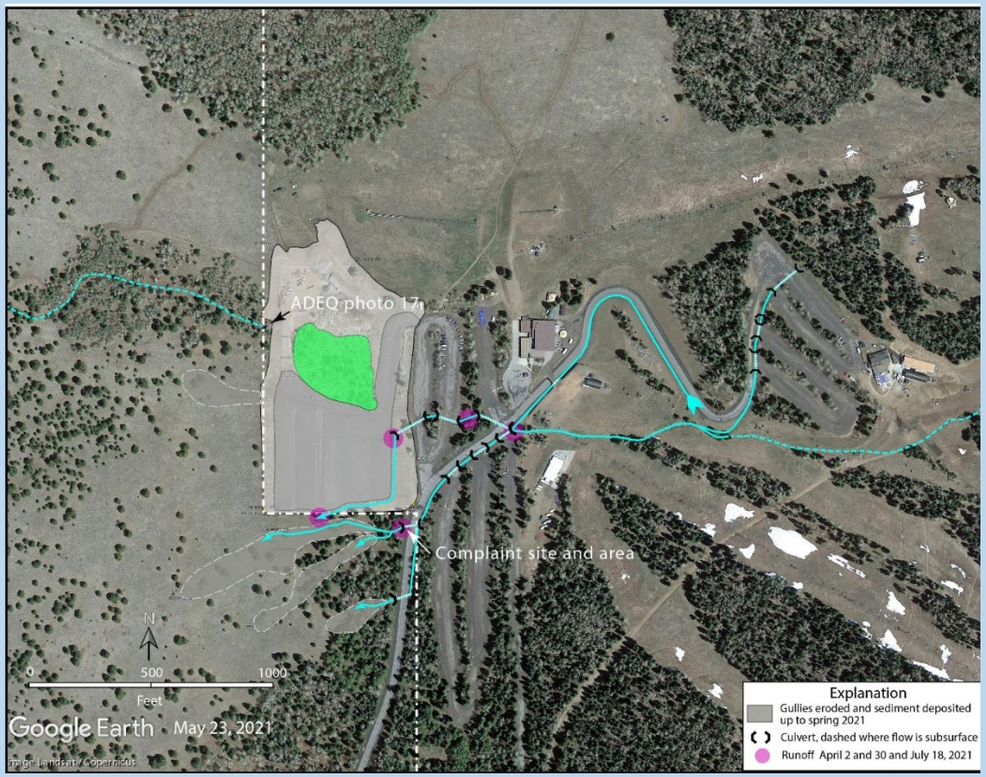
- ❑ Phosphorus is everywhere in Snow Bowl basin and the World, for that matter. It is essential for all life forms.
- ❑ In Snow Bowl basin, natural sources of phosphorus (and nitrogen) include atmospheric deposition and the andesitic rocks of the basin, which contain small amounts of the phosphatic mineral apatite.
- ❑ A mass balance calculation by A.E. Stewart (2022) found that phosphorus and nitrogen concentrations on basin hillslopes are increased by 1,095 and 297 percent, respectively, over their natural or inherent concentrations.
- ❑ Stewart's analysis also shows that additional man-made nutrient contributions from septic-tank leakage, parking lots, and other non-point source are negligible.
- ❑ **Ski slopes treated repeatedly with massive amounts of reclaimed water are the likely source of phosphorus in surface runoff, even though the reclaimed water contains permissible amounts of phosphorus.**

A Model of Excess Phosphorus in Snow Bowl's Surface Runoff?

- ❖ The snowpack, applied or natural, is an essential source of nutrients and water that are held in storage.
- ❖ The soil and snowpack form a continuum, so what's in the snowpack can enter the soil during seasonal melting.
- ❖ Accumulated nutrients, phosphorus, in this case, attach to soil and sediment particles.
- ❖ These particles can be mobilized by erosional hillslope runoff, which entrains the particles and directs them downslope to the wastewater drainage system that ultimately leads to Hart Prairie.

—A Final Note and Caution About—

Arizona Department of Environmental Quality (ADEQ) Site Investigation of Snow Bowl Facilities Investigation Number 395741 Dated April 22, 2022



Map focused on Snow Bowl facilities showing the location of ADEQ photo 17, the locus of ADEQ's investigation, and the distant complaint site area. ADEQ team investigated an area approximately north and east of photo 17, which has no hydrological connection to the grievance locality. The complaint site area was not in ADEQ's field of view.

ADEQ's field investigation guides were J. R. Murray and other senior executives in Snow Bowl management. They led the ADEQ team to an area 950 feet northwest of the complaint site. The site they viewed lies entirely within Snow Bowl's permit area. In contrast, the complaint site is unquestionably outside of the western Snow Bowl boundary on Coconino National Forest land. They were not shown this much larger, principal stormwater drainage system that is responsible for essentially all runoff onto Hart Prairie. Evidence of runoff at the complaint site, which was made available to ADEQ, is abundant; it reflects a large drainage basin with extreme relief and steep, erodible ski slopes.

In contrast, the area shown to ADEQ staff by Arizona Snow Bowl management lacks any evidence of surface runoff. Significantly, the grievance site and the investigated site have no surface hydrological connection. These are two completely different surface hydrological situations. Moreover, ADEQ was looking for contaminated snowmelt runoff, whereas runoff in the complaint area is wastewater from monsoon rain falling on the Snow Bowl drainage basin.

ADEQ's inspection results are: "***No deficiencies were noted during the course of the inspection. No ADEQ action will result from this inspection.***"

We caution all concerned that this conclusion does not apply to the complaint site, which ADEQ did not visit. Proof that ADEQ's location was not the grievance site is in their written field descriptions and Photo Log.

The investigative situation is egregious for two reasons: the examination and resulting conclusions have nothing to do with the runoff problem at the grievance area, and the complainants were not asked to participate in the investigation. Thus, the determination is wrongly biased in favor of Arizona Snow Bowl's interests.

This unfortunate situation needs to be corrected. A proper field investigation of the specific complaint site is essential to understand the actual offsite wastewater problem at the Arizona Snow Bowl. **Otherwise, the results of Complaint Inspection #395741 are meaningless.**

NOTES

A second drainage system at the north end of the new lot captures runoff from the parking lot adjoining the new lot's east side. This system is evidently not functioning. It is apparently designed to direct runoff through dual culverts across the remnant aspen grove into abandoned Hart Prairie wash outside the permit area.

A recreational grade GPS instrument was used to map the area disturbed by summer 2020 construction and other features shown on the map (page 4). Locational accuracy is about 5 feet, which is adequate for the intended purposes and map scale. The perimeter of the disturbed area surrounding the lot was surveyed by following the base of the parking-lot fill or the top of the cut above the fill. The boundary of the Special Use Permit Area is from Figure 2-2 of the 2005 EIS. The southwest corner of the parking lot is marked by a USDA/USFS 1997 cadastral survey monument. Land west and south of the corner monument is *outside* the permitted area.

Relatively high resolution, rectified (WGS 84 datum) Google Earth satellite imagery (https://google.com) covering the Snow Bowl area is used in this report. GPS points were originally plotted on June 12, 2017 imagery. The present map (page 4) was compiled on recent imagery of May 23, 2021. The disturbed area was remapped guided by this image. Sequential development of Snow Bowl since 1954 was studied using archival mapping aerial photography flown between 1954–2005 (https://earthexplorer.usgs.gov). This photography documents blockage of Hart Prairie wash by construction of Snow Bowl facilities. Development of gullies and contamination of upper Hart Prairie related to the main or southern storm drainage system was documented using sequential Google Earth imagery (see ADDENDUM following p. 12).

Culvert discharge calculations were done using standard engineering software incorporating Manning's roughness coefficient. Slope of the culvert, which is relativley steep, was obtained by instrumental leveling over the culvert's length.

Monsoon season (July, August, and September) monthly rainfall totals from two sources were evaluated. The Natural Resources Conservation Service SNOTEL climate sensor that measures rainfall in Snowslide Canyon within the Inner Basin of San Francisco Mountain. Rainfall data covering Snow Bowl drainage basin is modeled and gridded PRISM* data. The modeled data are statistically indistinguishable from SNOTEL measurements. The SNOTEL data were used to estimate rainfall in Snow Bowl basin from 1998 to July 2021.

*Parameter-elevation Regressions on Independent Slopes Models, Oregon State University

About the Authors

Richard Hereford, Research Geologist (Emeritus), Environmental Consultant.**

Tom Brownold, owner, Tom Brownold Photography, FAA Part 107 Certified Drone Pilot.

Gwendolyn Waring, PhD, author of *The Natural History of the San Francisco Peaks, A sky Island of the American Southwest* (2018), 205 pages.

**herefordrichard@gmail.com

DEFINITIONS*

sewage (p. 183)—The waste and *wastewater* [emphasis theirs] produced by residential and commercial sources and discharged into sewers (USEPA, 1994).

wastewater (p. 225)—(a) *return flow*. (b) *Seepage* of water from a ditch or reservoir. (c) The spent or used water of a community or industry that contains dissolved and suspended matter. Cf: *effluent* (b); *industrial waste*; *reclaimed water; municipal waste*. See also: *gray water*; *sanitary wastewater*; *septic wastewater*; *sewage*.

storm water (p. 199*) direct runoff.*

storm sewer (p. 199) A *sewer* that carries direct runoff from rain or snow (USEPA, 1994). Cf: sanitary sewer; combined sewer.

***** Glossary of Hydrology, 1998, Wilson, W.E., and Moore, J.E., eds., Alexandria, Virginia, American Geological Institute, 248 p.

ADDENDUM
Development of Drainage System and Gullies Using Google Earth Imagery, 1997–2021

Interpretation of 13 sequential images reveals gully erosion of Hart Prairie is linked to Snow Bowl's stormwater drainage system. Erosion began between 1997 and 2003 and accelerated after installation of the present drainage system between September 2010 and June 2011

Refer to map on page 4 of presentation for locations named on images, images are arranged chronologically by month and year. Main elements of evolving drainage system shown with trianglular symbols. Outline of disturbed area related to new parking lot and remnant aspen grove shown with thin white lines. Full track of July 2021 runoff is on last page of addendum.


WW II Memorial
Lot 1, drains north
Drainage system not detected, Lot 1 in place by 1992 blocking Hart Prairie wash; gullies absent; note faint track crossing southwest corner of new parking lot that was utilized by July 2021 runoff
Google Earth
Image U.S. Geological Survey
Oct 1997
N
1000 ft


WW II Memorial
Gully present west of Lot 1 probably results from rerouting of former Hart Prairie wash, which is incised south of Hart Prairie Lodge; possibly eroded by heavy rainfall in September 1998, July 1999, and August 2003
Google Earth
Image © 2021 Maxar Technologies
Dec 2003
N
1000 ft


WW II Memorial
Little change from 2003; low monsoon rainfall
2004 to 2006
Google Earth
Feb 2006
Image © 2021 Maxar Technologies
1000 ft
N


WW II Memorial
Elements of present drainage system not detected,
image resolution low
Google Earth
Image USDA Farm Service Agency
Sept 2010
1000 ft
N


WW II Memorial
Upper segment of drainage system in place at runoff split, sewer passes northwest under road then turns west to pass under Lot 1 where it empties onto prairie in gully; former Hart Prairie wash incised; evidence of runoff west of FR 516, possibly related to heavy rain July 2010
Google Earth
June 2011
N
1000 ft


WW II Memorial
Lower segment of system present with two culverts under FR 516
May 2012
Google Earth
1000 ft
N


Drainage ditch probably directs sheetwash north of remnant aspen grove and elsewhere into small retention pond (above left)
WW II Memorial
Sediment plume and gully now clearly extend 870 feet west of Lot 1 onto prairie
Incipient gully below upper culvert
April 2013
Google Earth
1000 ft
N

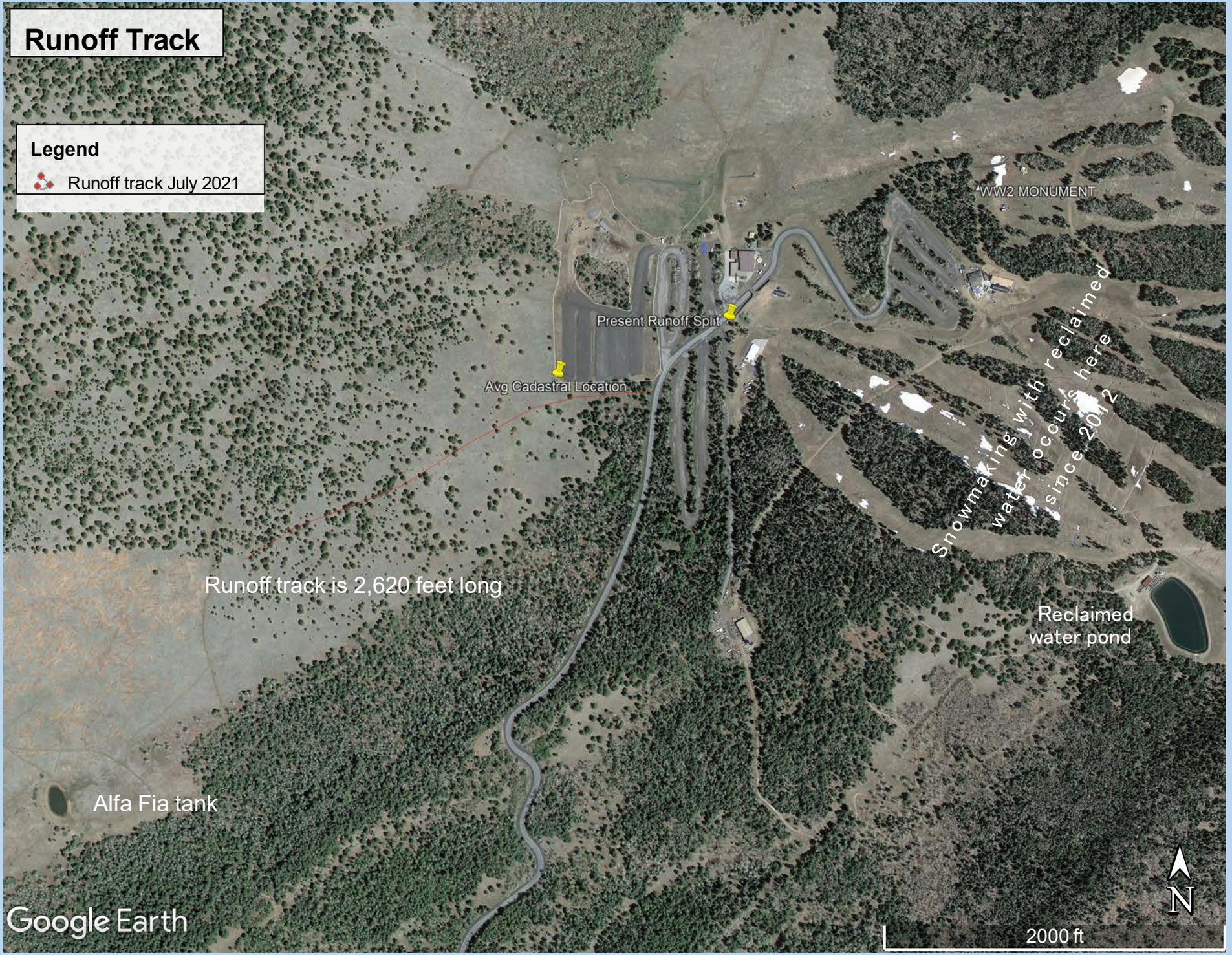

WW II Memorial
Gully west of lot 1 appears active; gullies here probably related to large rainfall of July 2013 and August 2014
Gully well formed, sediment deposited 900 feet southwest of culvert
April 2015
Google Earth
1000 ft
N


WW II Memorial
Gullies and sediment from both culverts present, up to 900 feet long and 340 feet wide
Google Earth
April 2017
1000 ft
N


WW II Memorial
Former Hart Prairie wash incised and appears recently active
June 2017
Google Earth
1000 ft
N


WW II Memorial
Construction of new parking lot underway; construction east of Hart Prairie Lodge completes upper drainage segment that drains four parking lots at Agassiz Lodge and treated ski slopes south and southeast of lodge
Google Earth
Image © 2021 Maxar Technologies
Oct 2017
N
1000 ft


New five-level parking lot mostly complete, paved with granular reclaimed asphalt,drains south; future development and construction continue north of remnant aspen grove
WW II Memorial
Former channel of Hart Prairie wash armored with riprap
Upper segment of drainage system rerouted to south end of new parking lot, first active July 2021; termini of segments separated by only 320 feet
May 2021
Google Earth
1000 ft
N


Runoff Track
Legend
Runoff track July 2021
WW2 MONUMENT
Present Runoff Split
Avg Cadastral Location
Snowmaking with reclaimed water occurs here since 2012
Runoff track is 2,620 feet long
Reclaimed water pond
Alfa Fia tank
Google Earth
N
2000 ft