OBSERVATIONS OF SALT CRUST CHANGE FROM 1960-2016 AND THE ROLE OF HUMANS AS GEOLOGIC AGENTS AT THE BONNEVILLE SALT FLATS, UTAH

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ABSTRACT

The Bonneville Salt Flats (BSF) is a playa in western Utah valued for its striking landscape, land speed racing, and mineral resources. Concerns about the potential impacts of land use and extraction on the salt flats instigated periodic studies into the thickness and volume of the salt crust. From 1960 to 2016 five studies have measured the thickness and estimated the volume of BSF salt crust, a wedge of halite (NaCl) and gypsum ($CaSO_4 \bullet 2H_2O$) evaporite sediments. This study examines the spatial and temporal patterns of salt crust change at BSF from these studies and compares observations to known human activities with the potential to impact the surface and subsurface sediments and associated brine. A reanalysis of volume calculations from all five studies indicates a ~28% decrease (~25.9 million m^3) in total salt crust volume since 1960 with the majority of the volume changes occurring between 1960 and 1988. This volume is equivalent to a decrease of 28 cm of salt crust thickness for the analyzed area. During this period, human activities including racing, mining, and experimental mining mitigation ("salt laydown") have likely contributed to the observed changes. Drawdown of the shallow brine aquifer, observed from 1960 to 1974, persists through 2016, and may be an important aspect of the observed salt crust changes. Ongoing research aims to clarify the impacts of various natural and anthropogenic factors in influencing the dynamic equilibrium between shallow brine and evaporite sediments at BSF.

INTRODUCTION: MINING, RACING, AND MANAGEMENT AT THE SALT FLATS

A remnant of Pleistocene Lake Bonneville, the Bonneville Salt Flats (BSF) is a saline playa, or salt pan, in the Great Salt Lake Desert of western Utah. Several factors shape the landscape of saline playas including active processes of sediment deposition and erosion linked to pathways of subsurface flow, local to regional climate conditions, tectonics, and topography (Rosen, 1994). Specifically, the formation and maintenance of salt pan environments require: 1) an arid climate where annual rate of evaporation exceeds inflow, 2) a hydrologically closed or restricted basin, and 3) inflow or accumulation of solutes over a long period of time. Salt pans, including BSF, undergo regular seasonal changes that alter the surface landscape with flooding, evaporative concentration, and desiccation (Lowenstein and Hardie, 1985; Bowen and others, 2017). These natural processes lead to deposition and diagenesis (post-depositional alteration) of evaporite sediments on seasonal to millennial time scales.

For many evaporite basins, human production of carbonate, sulfate, and chloride minerals and solutes from brines has led to further alteration of the land surface and subsurface. Reducing the volume of chemical sediments and/or the concentration of solutes in associated brines limits the availability of ions to concentrate over time, which is essential for the formation and preservation of evaporites. Without continued solute input and saturated concentrations, the impact of freshwater additions from meteoric input (precipitation) and mixing with adjacent more dilute groundwater will prohibit evaporite growth and eventually dissolve existing salts. At BSF, natural processes and human activities converge in an environment that is culturally valued for the aesthetics of the salt crust and as a premier location for land speed racing.

BSF is a mixture of public (state and federal) and private lands administered by the Bureau of Land Management (BLM) for multiple uses, which includes issuing permits for filming, racing, research, and mining. An iconic west-

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Figure 1. *Pictures illustrating human activities at BSF. A) International Speedway track unsuitable for racing in July 2015. B) Example of potash mining groundwater drainage canal along the eastern boundary of BSF. C-F) Aerial photos of BSF taken in September 2016 during "Speed Week" showing the impact of cars: highway, access road, and off-road recreational driving footprint. E) Canals on eastern BSF boundary. F) Berm surrounding Salduro Loop, race tracks, cars. G-H) Aerial photos taken in October 2017. G) I-80 and canal where laydown brine is transferred to BSF. H) Evaporation ponds.*

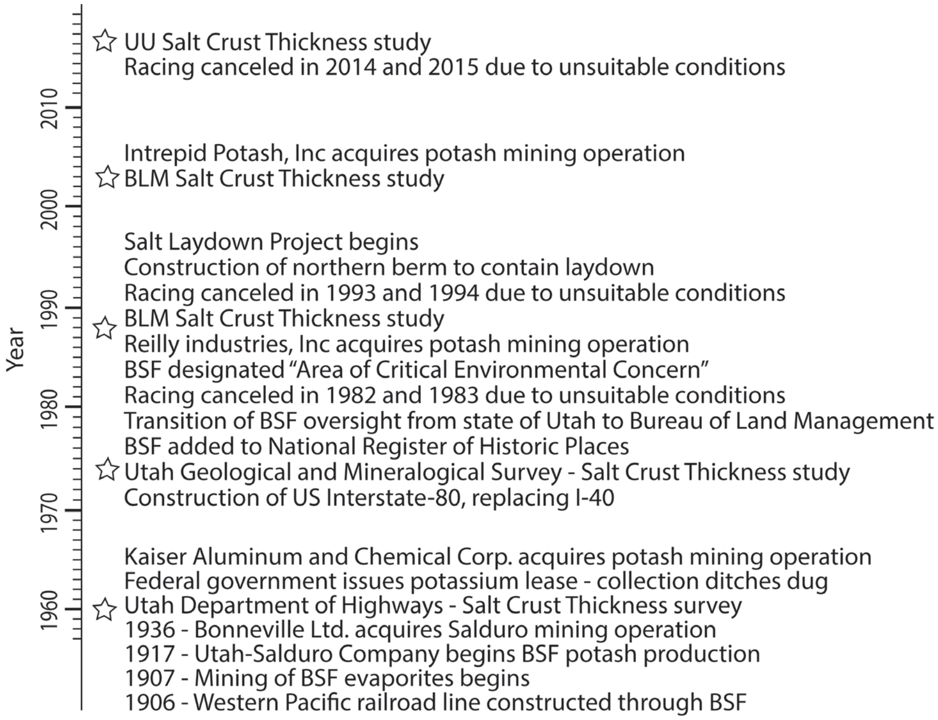

Figure 2. *Timeline from 1960 to 2016 of notable human activities at the Bonneville Salt Flats. Starred events highlight the five measurements of salt crust thickness.*

ern landscape, the salt crust and surrounding mountains are regularly featured in film and photography. From 2003 to 2016, the BLM issued 325 film permits at BSF. Furthermore, it has served as the stage for annual racing events with speeds in excess of 600 miles per hour, these include hundreds of the world's land speed records (Noeth, 2002). Estimates of annual visitation exceed 20,000 persons. The activities of humans on the salt crust and brine are apparent at BSF in the form of tire tracks, prepared race tracks, mining infrastructure including canals and berms, and automobile access roads (figure 1).

For over a century, BSF has been shaped by human interests. The legacy of mining, racing, and land management has led to multiple outcomes for BSF through the 20th century (figure 2). In the 1960s and 70s, Interstate 80 (I-80) was constructed, dividing the surface environment of BSF. In the 1970s, BSF was designated as a national historic site and, in the 1980s, it was listed as an area of critical environmental concern. Preceding an experiment to lay down salt from potash mine waste beginning in 1997, construction of berms altered the surface environment of BSF and limited the possible spatial extent of surface halite on the northeastern boundary of the salt flats (e.g., figure 3). The salt laydown continues seasonally through the present date (White, 2004). Interspersed within these events are government reports and scientific studies characterizing the salt crust, the associated shallow brine aquifer that saturates the salt crust, and the larger Bonneville basin.

THE SALT CRUST AND SHALLOW BRINE

The current BSF salt crust is a lens-shaped surface deposit of up to 1.5 m of interbedded halite (NaCl) and gypsum ($CaSO_4 \cdot 2H_2O$) beds (Bowen and others, 2018) that overlie fine grained laminated carbonate muds and oolitic sands (Turk, 1973). The contact between the BSF evaporites and the underlying fine grained carbonate mud has served as the subsurface boundary of the BSF salt crust (Brooks, 1991; White and Terrazas, 2006). The extent of surface halite varies seasonally and analyses of surface extent from 1986 to 2015 showed that it ranged from 72 km^2 to 156 km^2 in response to seasonal changes in the water budget and winds distributing shallow brine across the surface (Bowen and others, 2017). Along the edges of the salt crust, halite is commonly less than 1 cm in thickness at the surface, with little to no subsurface halite present (Bowen and others, 2018). The morphology and texture of surface halite varies spatially across the salt flats (e.g., Lines, 1979) and takes many forms including thin seasonal crust, organized polygons separated by ridges, puffy efflorescent "popcorn" crust, circular salt-free zones, "bubbles" and "blisters," and smooth surfaces. Subsurface halite and gypsum beds are non-continuous across the salt crust and the presence of subsurface halite correlates with the presence of a dense shallow brine groundwater.

The depth and chemistry of this shallow unconfined brine aquifer are important factors that impact the presence and changes in the salt crust. Past research on the

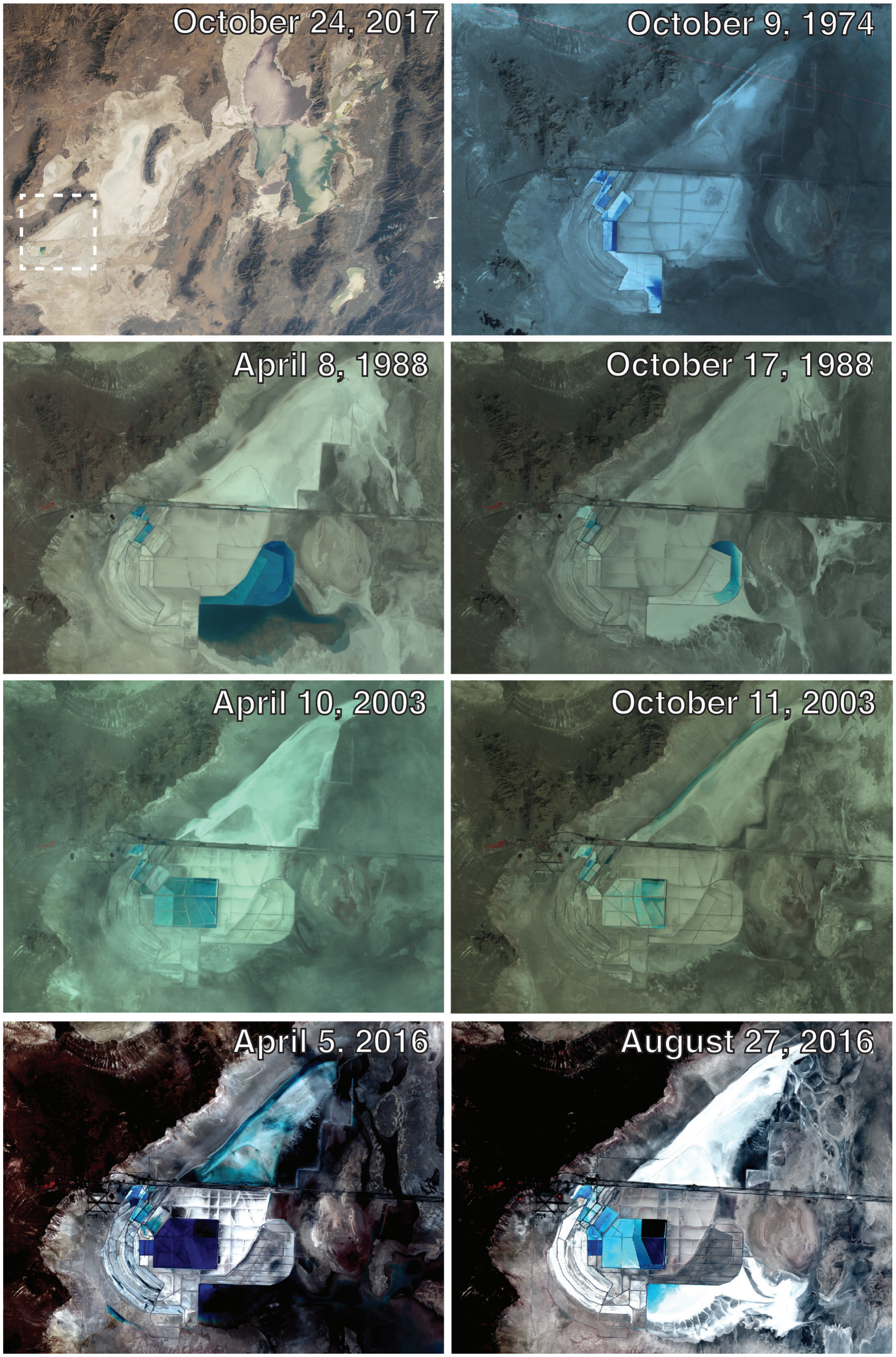

Figure 3. *Photograph (ISS053-E-134166) of the Great Salt Lake and Great Salt Desert in context of the larger Bonneville basin from the international space station on October 24, 2017 (top left). North is up on all images. Satellite imagery from Landsat 1, 5, and 8 was obtained through USGS Earth Explorer portal for path 39, row 32, which captured the Bonneville Salt Flats under variable conditions of halite extent and surface ponding from 1974 to 2016. These satellite images show that the extent of surface halite varied both across years of study and seasonally between each spring (left) and the period of thickness measurements (right).*

shallow brine aquifer suggested it was between ~4.5 and ~7.5 meters thick and was generally disconnected from the underlying, confined regional sediment-fill aquifers with the possibility of leakage between the two (Turk, 1973; Lines, 1979). In the shallow aquifer, hydraulic conductivities are highest in the upper three meters of clay and salt (Turk, 1973). Past observations of vertical cracks > 2 cm in width exposed in canal excavations have contributed to the idea that vertical fractures may provide preferential flow paths through clay layers contributing to high values of hydraulic conductivity (Turk, 1973).

The salt flats are characterized by a seasonal winter pond that varies in depth and spatial extent as flooding of the playa occurs in wetter and cooler months, and desiccation occurs during the warmer and drier times of the year when evaporation peaks (figure 3). Evaporation is estimated as the largest pathway of hydrologic discharge at BSF (Mason and Kipp, 1998). Recharge to the shallow brine occurs through infiltration of precipitated waters on the playa surface and/or from lateral flow through adjacent alluvial fans into the BSF playa margin. In addition, the salt laydown project has contributed a significant volume of water to the surface of the salt flats over the last 20 years (White, 2004). The dissolved solutes in the shallow brine aquifer are essential for the persistence of surface halite at BSF. The shallow brine is also valued for potash production by mine operators and the consumers of their products.

SYNTHESIS OF SALT CRUST THICKNESS STUDIES

Five studies from 1960 to 2016 measured the total salt crust thickness at BSF (figures 2 and 4). In 1960, thickness measurements were collected as part of a transportation engineering study conducted by the Utah Department of Highways (now Utah Department of Transportation; Christiansen and others, 1962). With public concern that mining operations may adversely affect the salt crust, a follow-up study was conducted by the Utah Geological and Mineral Survey (now Utah Geological Survey) in 1974 (McMillan, 1974). The survey reported ~15% decrease in total “hard salt” volume and 9% decrease in salt crust area over 14 years. Given these results, a continuation of studies was conducted by the Bureau of Land Management in 1988, 2003, and by University of Utah researchers in 2016 (Brooks, 1991; White and Terrazas, 2006; Bowen and others, 2018). In 1988, recalculated salt crust volumes from 1960 and 1974 measurements reported progressive 16% and 14% declines, respectively, during this period. White and Terrazas (2006) recalculated the salt crust volume from 1988 and showed ~2% decline from 1988 - 2003 with respect to Brooks’ (1991) calculation for 1960 volume.

For this study, data and results were synthesized from all known salt crust thickness reports and publications of salt crust thickness change in order to address three questions:

1. Are volume calculations comparable across salt crust studies?
2. How has the total volume and spatial morphology of the salt crust changed from 1960 to 2016?
3. What role might human activities have in the observed changes to the salt crust?

Methods of salt crust observation have varied through time resulting in a range of thickness measurements

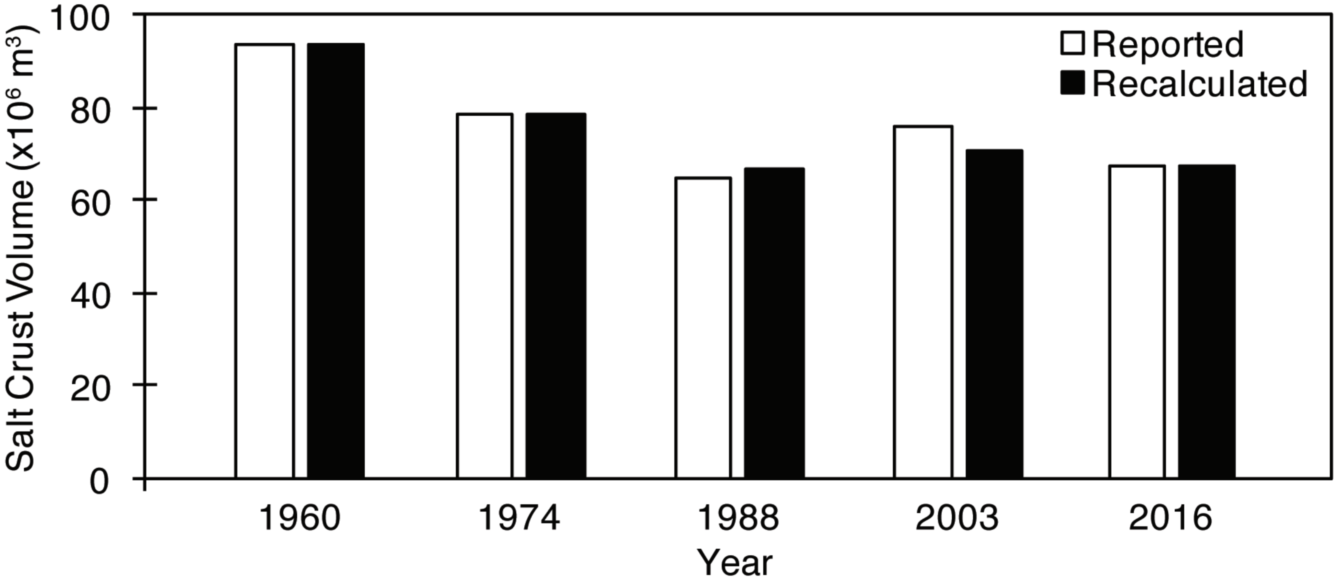

Figure 4. *Difference between reported salt crust volume and recalculated comparable volumes for studies from 1960 to 2016.*

and volume calculations, and the comparability across studies has been questioned. In 1960, 1974, and 1988 similar methods of motorized auguring and a pole-hook were used for stratigraphic measurements (UDOT pole method) of salt crust thickness (Brooks, 1991; McMillan, 1974). In 1960 and 1974, these measurements were overseen by the same individual making for, potentially, the most consistent values of thickness recorded across studies. However, this measurement method has been discussed as both difficult to replicate and inaccurate in later studies (Brooks, 1991; White and Terrazas, 2006). In 2003, mud auguring was used to make measurements with increased precision and the internal sedimentological character of the salt crust was described (White and Terrazas, 2006). In 2016 both sonic coring and mud auguring were used and internal sedimentological characteristics (e.g., gypsum vs. halite) were described and compared to 2003 (Bowen and others, 2018).

METHODS OF ANALYSIS

Although changes in methods and technology have been demonstrated to impact the precision and accuracy of salt crust thickness measurements through time, and different studies have included differing detail in salt crust stratigraphy and composition, this collection of repeat analyses over time allows for a unique analysis of temporal changes in the salt crust on decadal timescales at BSF. For this work, all field-based measurements are assumed comparable for evaluating changes in total salt crust volume over time. Salt crust thickness measurement data from past studies were used to recalculate total salt crust volume to reduce errors introduced by varying methods of calculation of volume over time (figure 4). Ordinary kriging with variogram modeling using an exponential function was applied to spatially distributed thickness measurements from 1960, 1974, 1988, 2003, and 2016 to recalculate total salt crust volumes and to map spatial patterns of salt crust change (figures 5 and 6). The area included in these volume calculations was based on the areal extent of analysis in 2003 and 2016. The detailed methods for this process were described in full by Bowen and others (2018), appendix E. These re-analyses do not change the interpreted volume significantly.

United States potash production and consumption estimates are reported annually by the USGS and Utah potash production is reported annually by the Utah Geological Survey, and were synthesized for evaluation of the contribution of Utah potash mining to overall U.S. production and consumption (Boden, Berg, Krahulec, and Rupke, 2014; Boden, Berg, Krahulec, and Tabet, 2013; Boden, Berg, and Rupke, unpublished; Boden, Krahulec, Tabet, Rupke, and Berg, 2015; Bon and Krahulec, 2009; Gwynn, Krahulec, & Berg, 2011; USGS, 2018; figure 7, table A1). Data on annual brine extraction and salt laydown from 1998 to 2016 for BSF north of I-80 ("northern leases") were made available upon request by the BLM - West Desert Field Office (figure 8, table A2).

Shallow brine groundwater was encountered at 46 of the 69 sample sites during the 2016 salt crust thickness study field work (Bowen and others, 2018). Depth to brine was measured and contours of brine depth were calculated using ordinary kriging and mapped together with previously published contours of brine depth for the shallow brine aquifer (McMillan, 1974; figure 9).

Well depth data from the brackish, alluvial fan aquifer adjacent to BSF (#404554113585801) was accessed through the United States Geological Survey (USGS) water data portal. This brackish well was one of six that served as industrial water supply for mining and brine laydown operations (figure 10). Monthly climate data were accessed through the National Climate Data Center for the Wendover Auxiliary Air Field (Station: KENV). For examining a normalized water balance, a Standardized Precipitation Evaporation Index (SPEI) was implemented from daily climate records for 1960 through 2016 using the Thornthwaite method for calculating evaporation (Thornthwaite, 1948; Vicente-Serrano and others, 2010; Santiago and Vicente-Serrano, 2017). The methods and application of SPEI to Wendover, Utah, climate records and BSF water balance was discussed in Bowen and others (2017). In general, a positive SPEI value suggests a relatively "wet" water balance and negative value suggests a "dry" water balance (figure 10).

BSF SALT CRUST EXTENT AND THICKNESS CHANGES

Changes in BSF salt crust volume in the Anthropocene are of interest for the management and stewardship of public lands, the preservation of a cultural resource, and in understanding the impacts of potash mining. Past investigations of salt crust change at BSF have delineated the area of the salt crust as the extent of visible surface halite either from field observations or satellite imagery (table 1). However, Bowen and others (2017) observed that interseasonal and interannual variability in surface halite extent is sensitive to the timing and magnitude of precipitation, strong wind events, and evaporation of surface brine. It is clear that the variation of surface halite extent is not just limited to between years of salt crust studies, but also occurs across seasons within those same years (figure 3). Furthermore, the surface footprint of halite at BSF is only a surface veneer in some areas, and thus is not an appropriate boundary for constraining individual calculations of total volume.

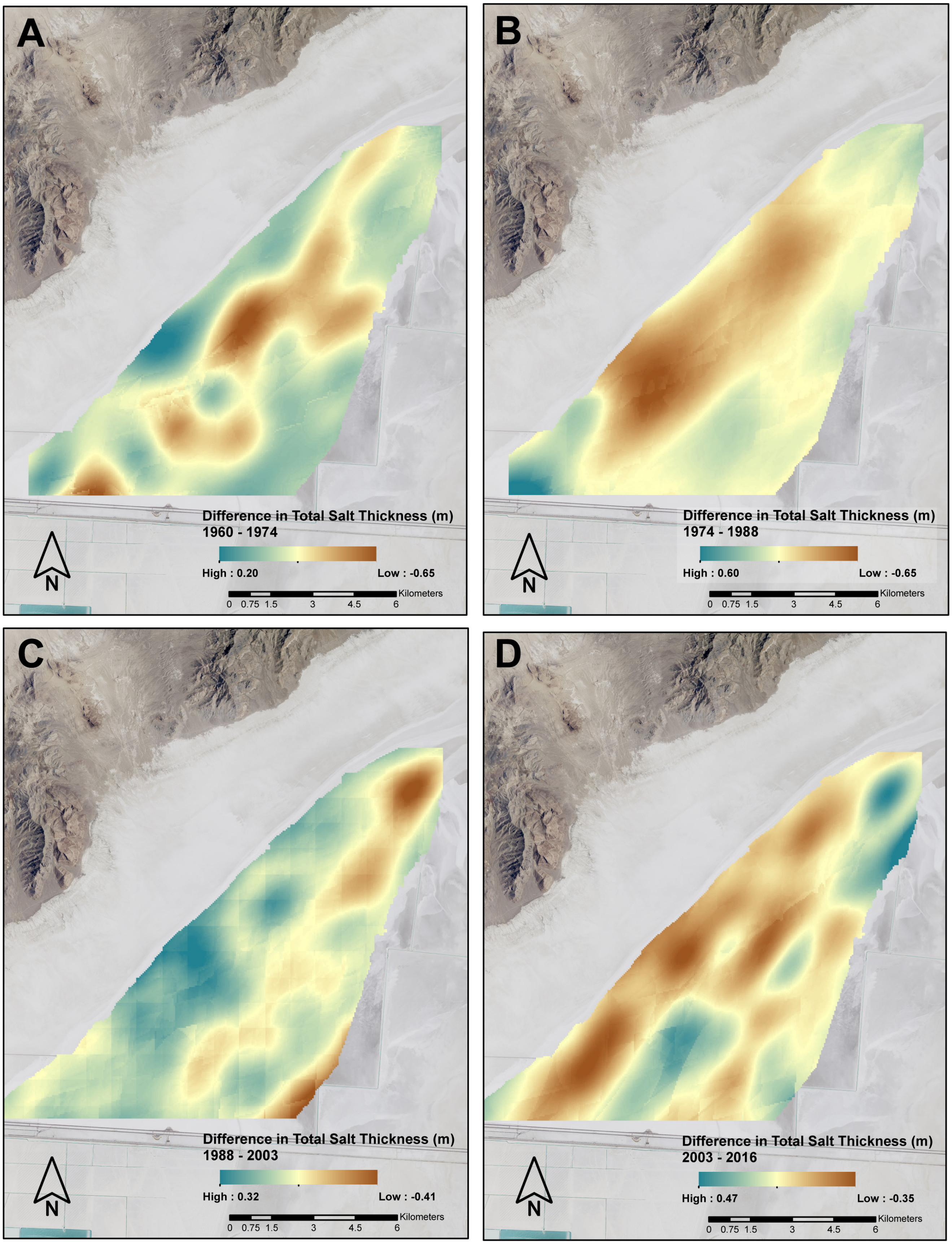

Figure 5. *Mapped differences in total salt crust thickness show increases (teal) and decreases (brown) between studies A) 1960-1974, B) 1974-1988, C) 1988-2003, D) 2003-2016. The spatial arrangement of observed changes varies throughout the six-decade observation period.*

Figure 6. *A comparison of 3-ft (0.91-m) thickness contour areas between salt crust thickness studies showed a recession from the 1960 contour (faint dots) in 1974 (faint dashes), 1988 (faint double dashes), and 2016 (bold line). The 3-ft contour expanded in area between 1988 and 2003 (faint line; after Brooks, 1991; White and Terrazas, 2003, Bowen and others, 2018).*

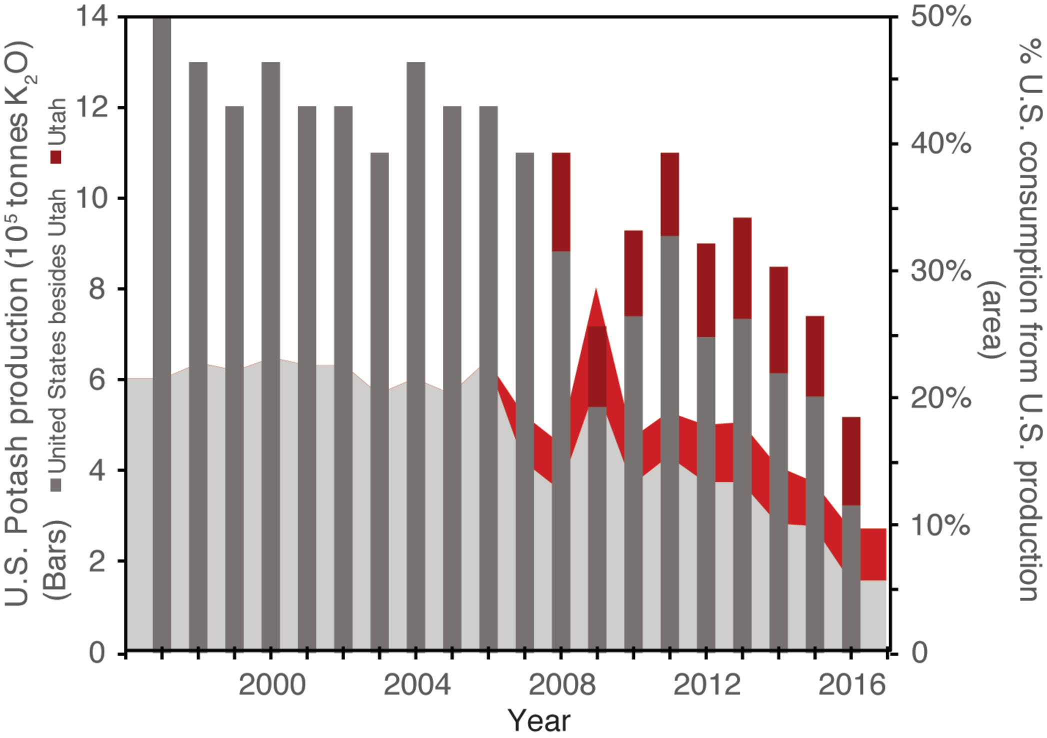

Figure 7. *Annual production of potash (10^5 tonnes) in the United States (gray bars) from 1997 to 2016 and U.S. production as percentage of annual domestic consumption (gray shading). The fractions of U.S. domestic production for the state of Utah (red bars and shading) from 2008 to 2016 are broken up as contributions of total U.S. production.*

For comparable estimates of salt crust volume between years a consistent study area of BSF was selected in these analyses. Volumes were recalculated over a study area ranging from 9.25 x 10^7 to 9.32 x 10^7 m^2, a difference < 1 km^2. Volume calculations vary slightly from those previously reported (figure 4). This calculation of salt crust volume showed 9.34 x 10^7 m^3 in 1960. From 1960 to 1974 a 16.1% loss of salt crust was calculated. An additional loss of 12.5% from the 1960 salt crust volume was calculated from 1974 to 1988, an increase in salt crust volume from 1988 - 2003 of 4.5%, and a further decrease in volume from 2003 - 2016 of 3.6%. Bowen and others, (2018) showed a 7% decrease in total salt crust volume from 2003 to 2016, and a 27.7% or 25.9 million m^3 decrease in volume compared to the 1960 total volume calculated by Brooks (1991).

Table 1. *Reported salt crust area from thickness studies.*

Year	Area (sq. m.)	Reported By
1960	9.71 x10^7	Brooks, 1991
1974	8.49 x 10^7	Brooks, 1991
1988	7.75 x10^7 (1.09 x 10^8)*	Brooks, 1991
2003	9.97 x 10^7	White and Terrazas, 2006
2016	9.53 x 10^7	Bowen and others, 2018

*Area derived from 1988 Landsat 5 imagery by White and Terrazas (2006).

While changes in calculated salt crust volumes do not provide large differences from those previously reported, they highlight that the largest changes to salt crust volume are observed from 1960 to 1988. From 1988 to 2016, estimates show a slight net increase in salt crust volume. Assuming a halite density of 2160 kg/m^3 and that all observed differences are changes to halite strata, the total salt loss from 1960 to 2016 would account for 55.9 million tonnes. While changes in the amount of gypsum sediment are likely to have occurred (e.g., surface deposition and erosion of wind-blown gypsum sand) and may account for some of the overall changes in volume, many of the changes are likely due to dissolution and growth of halite through time. Halite is more soluble than gypsum, and both growth and dissolution processes would more likely involve halite than gypsum. Uniformly spread over the entire study area the observed changes in salt crust would account for ~28 cm of salt crust thickness reduction (as halite) between 1960 and 2016. However, raster products of differences in salt crust thickness between studies show that the loss of salt crust has not been spatially uniform through time (figure 5).

From 1960 to 1974 the greatest decrease in salt crust thickness occurred in the center of the salt crust. This was different from 1974 to 1988 where the greatest

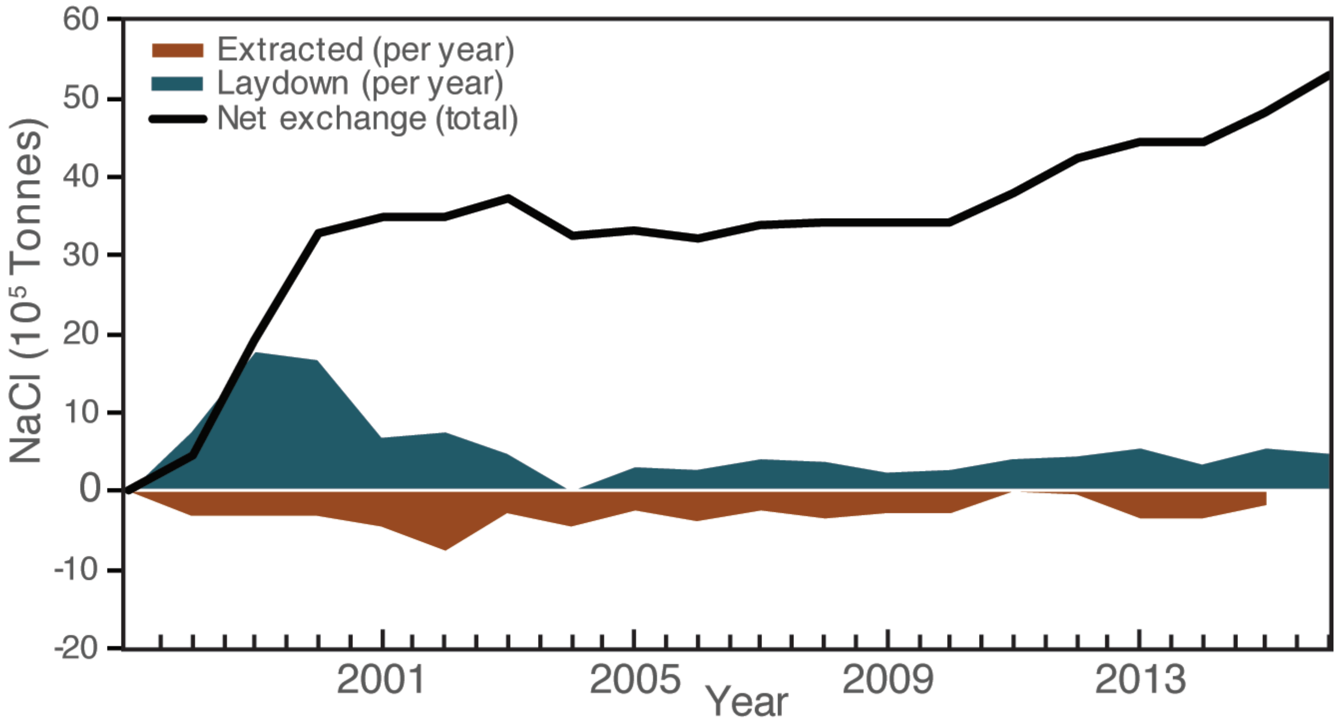

Figure 8. *NaCl mass balance at BSF for brine extraction from shallow brine of "northern leases" (brown shading) and annual brine laydown (teal shading) from 1998 to 2016. The cumulative net addition of NaCl during this period exceeded 5 million tonnes.*

Figure 9. *Kriged brine depth contours (solid lines) of 38 boreholes sampled during 2016 salt crust thickness study shows the depth to brine beneath the surface. This is in comparison with contours of brine depth contours from similar measurements between 1960 (faint dots) and 1974 (faint dashes; after McMillan, 1974).*

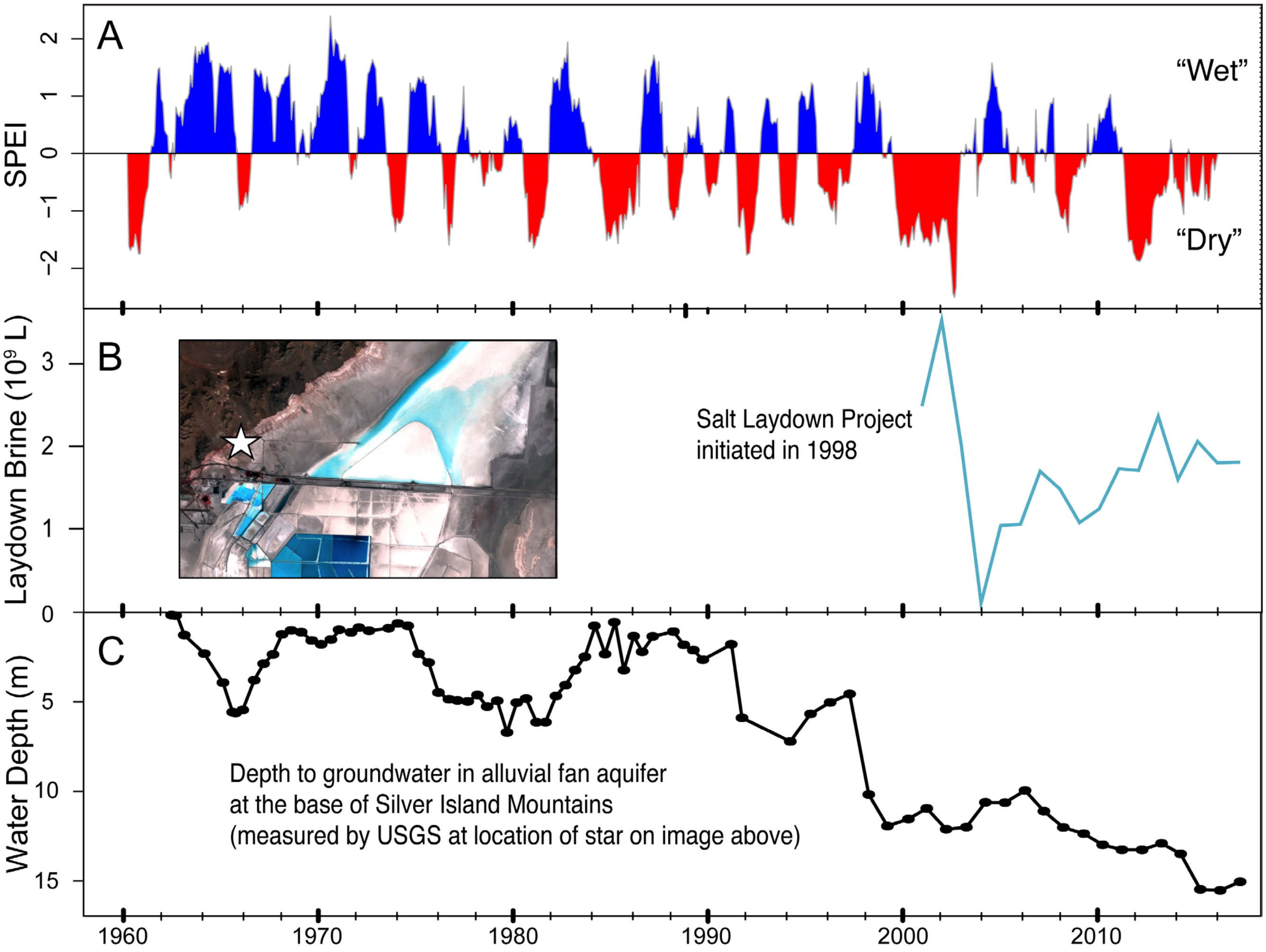

Figure 10. *A) SPEI, a normalized water balance, using daily climate data from Wendover, Utah, during 1960 to 2016. B) The volume (10^9 L) of undersaturated brine that was laid down each year from 2001 to 2016. C) The drawdown (m) seen in the brackish, alluvial fan aquifer adjacent to BSF where six wells have been pumped for industrial water supply. While the climate record may be reflected in some well level measurements, such as 1980 to 1984, the impacts of industrial usage, specifically for the production of laydown brine beginning in 1997, are apparent.*

reductions in thickness were observed along the western margin and 1988 to 2003 where the greatest reductions were observed in the southeast and northeast. While the relative volume change calculated from 2003 to 2016 was not very large, results showed that changes were more spatially distributed than any other year. Such a spatial pattern could either indicate a volumetric balance of distributed processes differentially altering salt crust thickness or a variation in measurements due to variable methods between studies.

The recession and progression of the 0.91-m (3-ft) thickness contour shows the largest changes occurring along the long axis of BSF (figure 6). These results show where salt crust had been lost and that the edges did not change as dramatically as the interior. The geometry of the salt crust wedge shrank along the long axis with the three-foot contour shifted towards the southwest. The smallest area of the 3-ft contour was seen in 1988 and then expanded outward in 2003. This is particularly notable as the salt laydown experiment began in 1997 and this shift in geometry suggested that the salt laydown process may have served to help stabilize the progressive dissolution of the salt crust. Interestingly, these observations align with those from the racing community where past tracks of stable surface halite exceeded 21 km in length along the long axis of the BSF salt crust, but with increasing limitations in the availability of track length in recent years.

IMPACTS OF HUMAN USE OF EVAPORITE MINERAL RESOURCES

There are many different factors and processes that could contribute to the observed decreases in volume of salt over time at BSF. Natural processes including the overall water, energy, and solute budgets and eolian processes contributing to deposition and erosion are important in shaping this landscape. In addition, these changes are likely linked to the impacts of human activities on this managed and altered landscape. The human processes that appear to most directly impact BSF today include: 1) landscape modifications such as roadways and berms, 2) mining activities related to potash production, 3) experimental salt crust mitigation ("salt laydown"), and 4) the impact of motor vehicles driving on the surface.

Landscape Modifications

Throughout the history of BSF as a managed landscape, the construction of railways, roads, canals, and berms have altered the land surface. Most notably, the construction of I-80 starting in the 1960s physically divided the surface of the salt crust. Wind-driven transport of seasonally-ponded brine became hampered by raised roadways and depressed retention ditches. Similar effects can be observed from both the ground and in satellite imagery concerning berms in the center and along the edges of the salt crust. The construction of canal systems is suggested in altering pathways of subsurface flow and directly relate to mining activities at BSF (Kaliser, 1967; Mason and Kipp, 1998). The observed difference in the timing of volume decreases at BSF, with the greatest change between 1960 and 1974, may suggest that the major landscape modifications made in association with the building of I-80 played a pivotal role in altering the BSF system.

Mining Activities

Potash is a non-renewable natural resource critical to the food-water-energy nexus. As mined product, either mineral or brine, potash is mainly used as an additive for agricultural (NPK) fertilizers and industrial processes, ~85% and ~15% respectively (USGS, 2018). In the United States, annual consumption exceeded 5 million metric tons (tonnes) for all years between 1997 - 2016, except 2009, with less than 25% of consumed potash being produced domestically. Since 1997, domestic production of potash has declined from 1.4 million to 520,000 tonnes (figure 7). Of the six potash producing operations in the U.S., three are in the state of Utah, accounting for production ranging from 3.5 to 7.9% of annual domestic consumption. From 2008 to 2016, Utah potash production ranged from 175,000 - 234,000 tonnes. Throughout the past twenty years, Utah's production has become increasingly important as a domestic source of potash.

At BSF, the potash production currently includes the extraction of deep brines from confined aquifers and the pumping and transport of shallow brines through a large network of surface canals. These dense brines from the shallow aquifer (200-320 g/L) are dominated by major ions of sodium and chloride, but also include concentrations between 1 and 10 g/L of potassium, magnesium, calcium, and sulfate. The evaporation of brines in large "ripening" ponds and the movement of increasingly saturated brines in series lead to the sequential precipitation of sodium, potassium, and magnesium chloride salts. The extraction of brines from the shallow subsurface of BSF "northern leases," those canals north of I-80, total > 4.5 million tonnes of NaCl from 2001 to 2015 (figure 8). Values for the historic extraction rates of brine from 1960 to 2000 are unavailable, but assuming a relatively constant rate of extraction through time, it is possible that more than 17 million tonnes of NaCl were removed from the BSF system through canals between 1960 and 2016. While this is a large amount, it is a fraction of the potentially 56 million tonnes of total salt lost from the observed volume decrease, suggesting that this process alone is not likely the only factor impacting the loss of salt at BSF for the past six decades.

Salt Laydown

Mine operators at BSF have performed an annual laydown of surface brine since November 1997, contributing more than 10 million tons of NaCl to the playa surface through the salt laydown experiment (figure 8). This brine adds to the winter flooding of the BSF playa typically seen from October to May (Bowen and others, 2017). While it was initially predicted that the laydown would lead to a 4-5 cm increase in surface halite, it has been suggested that solutes may have infiltrated and mixed with the shallow brine aquifer (White, 2004). White (2004) calculated that shallow brine could accommodate an additional 15.4 to 22.7 million tons of dissolved salts. These values are comparable with rough estimates of long term extraction, but significantly less than total salt crust reduction for 1960 to 2016. While the ultimate fate of these additional dissolved salts on BSF salt crust volume is presently unknown, the extent and hydrology of the subsurface shallow brine aquifer certainly plays a role.

In the 1960 and 1974 studies, along with thickness measurements of the salt crust, measurements of depth to shallow brine were taken. These data showed that in 1960 much of the salt crust had brine < 15 cm (6 in) under the surface and that by 1974 much of that same area had brine at depths > 30 cm (1 ft; McMillan, 1974). Results from kriging the 2016 data showed a similar 30 cm (1 ft) brine depth contour as seen in 1974 (figure 9). While the drawdown of brine in 1974 was widely spread across the salt flats, the largest gradient was apparent along the eastern and southeastern margin adjacent to mine collection ditches (McMillan, 1974; Mason and Kipp, 1998). In 2016, this same gradient was not apparent in the spatial modeling product, possibly indicating a reduction of brine extraction for mining associated with these canals or a different balance of recharge and outflow at the playa. These changes may give some indication to the difference in salt crust volume change from

1960 to 1988 compared with 1988 to 2016.

The brine laydown experiment has been an attempt to recharge solute to the playa, but also included the addition of > 1 billion liters of water to the playa surface over the annual ~2 month process, which could exceed 10% of estimated annual playa water recharge (Mason and Kipp, 1998). The laydown brine is produced by dissolving "waste" halite at the mine south of I-80 with industrial water (brackish groundwater) from aquifers adjacent to BSF. A major source of this industrial water is wells that pump from the alluvial fan aquifer adjacent to BSF. The fans discharge through evapotranspiration and subsurface discharge to the playa (Mason and Kipp, 1998). Thus, the water volume in this aquifer is subject to both hydroclimatological forcings and industrial use (figure 10). A drawdown in well level of the alluvial fan from a USGS observation well near the wells used for producing the laydown water is observed during the beginning of the laydown experiment in 1997, showing a decoupling from the local hydroclimate. This observed drawdown of the alluvial fan aquifer would likely impact the adjacent shallow brine aquifer, although the specific processes are the topic of ongoing research. This connection between solute recharge (laydown) and aquifer drawdown illustrates the limits of the salt laydown process as a method for potentially mitigating salt crust losses due to mining. The system is limited by the amount of available water, and fluxes of both solutes and water from the BSF system will drive changes in the solubility and saturation of evaporite phases.

Motor Vehicles

The impacts of racing on the salt flats have not been quantified, but possibly play a role in the changing salt crust. Each year as racers prepare for events, large heavy steel beams are dragged behind trucks along the areas to be used as tracks to smooth out irregularities and compact the surface. This process continues through the desiccation season until racing occurs, typically in the late summer and early fall. The location and orientation of this practice is correlated with the largest reductions in salt crust thickness from 1974 to 1988 and again from 2003 to 2016 (figure 5). This process compacts the surface salt crust and changes porosity and permeability, impacting evaporation, infiltration, and salt growth processes. The racing events bring tens of thousands of participants and spectators to BSF, all with motor vehicles that are driven out onto the salt. The role of this presence in modifying the landscape is unknown, but perhaps not insignificant. Racing season is not the only time that the public brings their cars to the salt flats; tracks are seen to accumulate on the surface throughout the year. This is especially significant during the flooding stage, when the surface is soft and more susceptible to changes in texture such as dissolution of the salt crust or weakening a halite surface cement that will impact future salt growth. BLM land managers have attempted to reduce the impact of cars on the salt during the wet season with signage and barricades. However, public lands with limited opportunities for oversight also challenge the effectiveness of limiting access.

CONCLUSIONS AND FUTURE WORK

For nearly 60 years, the thickness and volume of the salt crust at BSF has been measured to better understand how the environment is changing. This work synthesizes all five studies and presents a new analysis of spatial patterns of changes in the amount of salt crust at BSF through time (figure 6). While it is impossible to confirm the accuracy and precision of measurements made during past studies, this work standardized the approach taken to convert field measurements into volume estimates. These results show that the salt crust has decreased in volume, particularly from 1960 to 1974, and not very much since 1988. The spatial patterns of change can help to elucidate the types of processes that may be responsible for contributing to the observed changes. The changes in salt crust morphology over decadal time scales will help to guide interpretation of processes that caused spatially heterogeneous evaporite deposition and preservation in the geologic record (Bowen and others, 2018).

Ongoing research to understand climatological and anthropological changes to the shallow brine explore brine chemistry, water balance, and hydrological flow paths. Specifically, work to understand the equilibrium between shallow brine and the salt crust will be described and modeled. The transport and mixing of laydown brine into the subsurface and the impacts of well and canal drawdown on the hydraulic gradients in the subsurface will be explored. This work on the hydrological and solute components of BSF are accompanied by research to describe the physical and chemical composition of Bonneville sediments. Analysis of microbial life in salt and brine, the behavior and impacts of recreationalists, and the effects on art and culture surrounding the changing salt crust are also being examined. While the impacts of human usage of the potash resource at BSF are certainly important to consider with regard to salt crust changes, there are also broader implications for the production and usage of potash in Utah and elsewhere.

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Table A1. *Annual production and consumption (tonnes) of potash in the U.S., as reported by U.S. Geological Survey, and annual production (tonnes) in Utah, as reported by Utah Geological Survey.*

Year	US Production (tonnes)	US Consumption (tonnes)	UT Production (tonnes)
1997	1400000	6500000	N/A
1998	1300000	5700000	N/A
1999	1200000	5400000	N/A
2000	1300000	5600000	N/A
2001	1200000	5300000	N/A
2002	1200000	5300000	N/A
2003	1100000	5400000	N/A
2004	1300000	6000000	N/A
2005	1200000	5900000	N/A
2006	1200000	5200000	N/A
2007	1100000	5900000	N/A
2008	1100000	6700000	214549
2009	720000	2500000	179623
2010	930000	5500000	186608
2011	1100000	5800000	181119
2012	900000	5000000	204570
2013	960000	5300000	227023
2014	850000	5800000	234008
2015	740000	5500000	175132
2016	520000	5300000	195589

Table A2. *Annual amount of NaCl extraction and laydown (tonnes) at BSF from water year 1998 – 2016. Extraction values for 1998 – 2000 are estimates based on mean extraction values during this period.*

Year	NaCl Extracted (tonnes)	NaCl Laydown (tonnes)	Cumulative Net Exchange (tonnes)
1998	-304185	748615	444430
1999	-304185	1782680	1922925
2000	-304185	1662937	3281677
2001	-460966	676914	3497625
2002	-759203	758472	3496894
2003	-271003	487968	3713860
2004	-459043	0	3254817
2005	-252886	308910	3310841
2006	-385746	281741	3206836
2007	-234794	414954	3386996
2008	-336273	376430	3427153
2009	-263998	245296	3408451
2010	-280246	277235	3405440
2011	0	402391	3807831
2012	-26083	444580	4226327
2013	-329983	544744	4441088
2014	-337148	346156	4450096
2015	-165403	529264	4813957
2016	N/A	466384	5280341