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# Climatization—Negligent Attribution of Great Salt Lake Desiccation: A Comment on Meng (2019)

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Comment

# Climatization—Negligent Attribution of Great Salt Lake Desiccation: A Comment on Meng (2019)

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**Abstract:** A recent article reviewed data on Great Salt Lake (Utah) and concluded falsely that climate changes, especially local warming and extreme precipitation events, are primarily responsible for lake elevation changes. Indeed climatically influenced variation of net inflows contribute to huge swings in the elevation of Great Salt Lake (GSL) and other endorheic lakes. Although droughts and wet cycles have caused lake elevation changes of over 4.5 m, they have not caused a significant long-term change in the GSL stage. This recent article also suggests that a 1.4 °C rise in air temperature and concomitant increase in the lake's evaporative loss is an important reason for the lake's decline. However, we calculate that a 1.4 °C rise may have caused only a 0.1 m decrease in lake level. However, since 1847, the lake has declined 3.6 m and the lake area has decreased by ≈50%, despite no significant change in precipitation ( $p = 0.52$ ) and a slight increase, albeit insignificant, in river flows above irrigation diversions ( $p = 0.085$ ). In contrast, persistent water extraction for agriculture and other uses beginning in 1847 now decrease water flows below diversions by 39%. Estimates of consumptive water use primarily for irrigated agriculture in the GSL watershed suggest that approximately 85% (2500 km<sup>2</sup>) of the reduced lake area can be attributed to human water consumption. The recent article's failure to calculate a water budget for the lake that included extensive water withdrawals misled the author to focus instead on climate change as a causal factor for the decline. Stable stream flows in GSL's headwaters, inadequate temperature increase to explain the extent of its observed desiccation, stable long-term precipitation, and the magnitude of increased water consumption from GSL together demonstrate conclusively that climatic factors are secondary to human alterations to GSL and its watershed. Climatization, in which primarily non-climatic processes are falsely attributed to climatic factors, is a threat to the credibility of hydrological science. Despite a recent suggestion to the contrary, pressure to support Earth's rising human population—in the form of increasing consumption of water in water-limited regions, primarily to support irrigated agriculture—remains the leading driver of desiccation of inland waters within Earth's water-limited regions.

**Keywords:** Aral Sea Syndrome; Anthropocene; agriculture; water balance; saline lake; global change

## 1. Introduction

Meng [1] examines the water balance of the Great Salt Lake (GSL), Utah, USA, and determines that “climate changes, especially local warming and extreme weather including both precipitation and temperature, drive the dynamics (increases and declines) of the GSL surface levels,” contradicting a large body of research implicating human water consumption as the primary driver of shrinkage among lakes in Earth's water-limited regions [2–18]. We therefore critically examine the methods and claims of [1].

## 2. Errors of Prior Publication

### 2.1. Mistaken Water Balance

Meng's [1] definition of inflows is erroneous in that it fails to account for how human water consumption reduces river discharge. Instead the river discharge term is mistakenly assumed to be free of human influence. Water withdrawals for agricultural and municipal uses in the GSL watershed can be substantial, and appropriately accounting for them is standard practice when developing stream flow reconstructions. Reconstructions of important GSL tributaries (i.e., Logan River, Weber River, and Bear River) have all focused on upper headwater gages for precisely this reason [19–21]. Meng [1] incorrectly states the water balance of GSL as:

“GSL water level = inflow (precipitation + river discharge)—outflow (human water use + evaporation)”

This water balance equation is in error as the units are inhomogeneous, with water level in units of depth and flows in units of volume. The standard water balance equation balances changes in storage in the control volume ( $\Delta S$ ) with volumetric inflows ( $Q_{IN}$ ) less outflows ( $Q_{OUT}$ ), all in units of volume per time:  $\Delta S = Q_{IN} - Q_{OUT}$ . Consumptive water uses reduce inflows to Great Salt Lake rather than increase outflows from the lake as [1] asserted.

### 2.2. Impacts of Rising Temperatures

Meng [1] claims that “from the early 1970s, there is a significant trend of local climate warming in the GSL region, which is primarily driving the declines of the GSL.” While the temperature trend since the 1970s is legitimate, it is in part a local manifestation of global warming. Meng [1] provides no quantitative evidence that lake evaporation flux rates have in fact increased or if so, by how much. Nevertheless, a 1.4 °C increase in air temperature has likely increased lake evaporation and contributed to the decline in lake level, but far less than implied by [1]. Following the approach of [22], a modified Penman equation was used to estimate open water evaporation as a consequence of warming air temperature while accounting for reduced evaporation rates due to increased lake salinity. The reported 1.4 °C rise in temperature would have lowered the lake 0.12 m, whereas lake elevation actually fell 0.81 m (USGS data) over the last 46 years. Consequently, increases in lake evaporation due to temperature increases are important, but are insufficient to explain the decline in the Great Salt Lake. Any future changes in air temperature due to global climate change would have additional impacts, although these are likely to have a larger influence on evapotranspiration in the watershed than on the lake itself [23]. Other studies have empirically correlated temperature increases with the shrinkage of lakes [24–28]. However, those studies that have also quantified the role of rising temperature on agricultural evapotranspiration have found that warming-driven lake evaporation changes remain of lesser importance, relative to agricultural water consumption, given the level of observed warming at present [17].

Meng [1] makes a variety of additional claims concerning temperature increases that are unsupported by past research:

In contrast to the claim that “evaporation caused by the increases in temperature can be the dominant water loss of saline lakes,” past work has shown that: (1) Predicted increases in lake evaporation are small in the near-term (0.1–0.25% per year [29]); and (2) a range of factors control evaporation from open water, of which temperature is only one. Thus, ref. [30] found that evaporation was lower on warmer days when the wind was weaker as a result of synoptic weather conditions. Additionally, lake evaporation is the product of lake area and evaporative flux. With lakes in water-limited systems shrinking globally [18], evaporative fluxes decrease proportionally to lost lake area [31], and with increasing salinity [22,32].

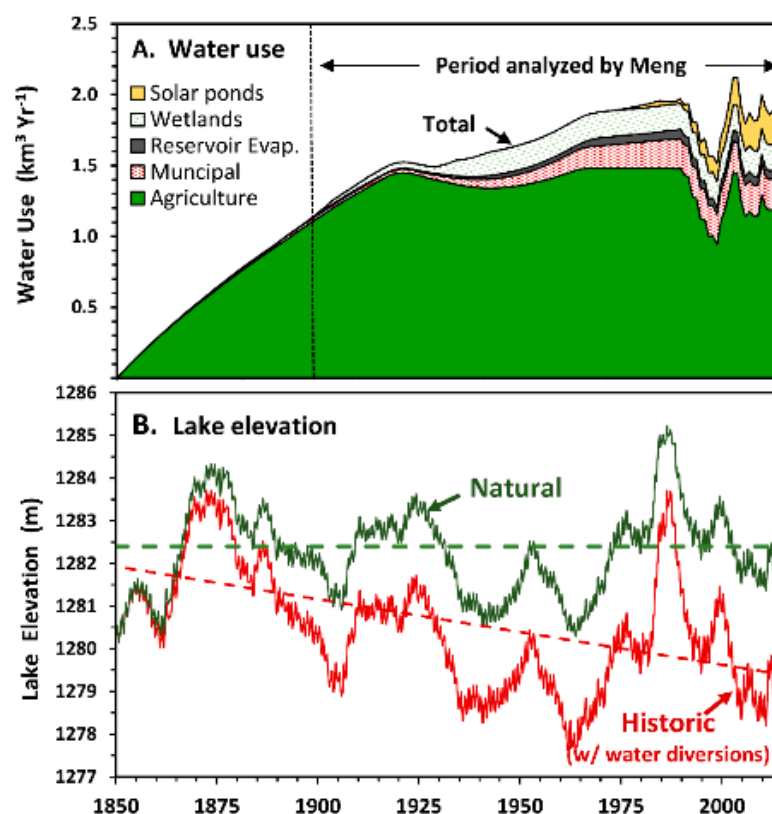
The claim that “climate changes, especially increasing temperature, have caused significant water loss through evaporation in semi-arid regions” confuses substantial future increases in lake evaporation

predicted to transpire by the end of the century [33] with substantially smaller increases in evaporation from lakes that may have actually already occurred [17,29].

The suggestion that “increasing evaporation rates caused by climate warming have resulted in approximately 40% of Australia’s total water storage capacity loss every year” is also misleading as this loss is not a result of anthropogenic climate change, but rather primarily a consequence of natural conditions of high evaporative demand [34].

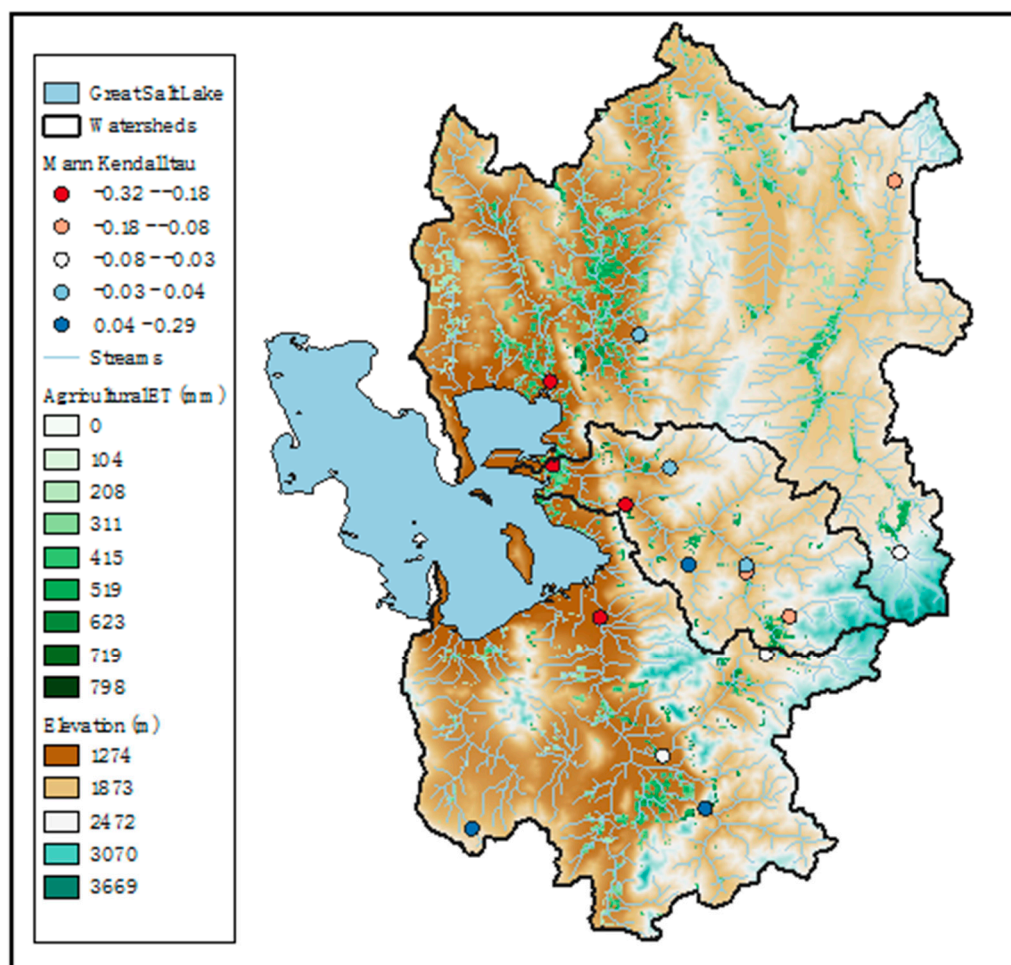
### 2.3. Drivers of Changing Streamflow

Meng [1] postulates that “reduced river discharge is directly caused by the declining precipitation and snowfall,” even though ref. [18] found that there has been no significant decline in precipitation in the basin over a long timeframe (1875–2015;  $p = 0.52$ ). They also found that there was a slight upward trend, albeit insignificant ( $p = 0.085$ ), in headwater streamflow above irrigation diversions since pioneers began developing water resources in the mid-1800s. In contrast, river flows reaching the Great Salt Lake have decreased by 39% due to water development for agriculture and other human uses, which has significantly ( $p < 0.0001$ ) reduced lake elevation by 3.6 m (Figure 1) [18]. Meng’s [1] analysis of the 1904–2016 precipitation, temperature, and lake level records is misleading because it ignores the data showing that approximately 80% of water development for agriculture and other uses occurred before 1904 (Figure 1) [18].



**Figure 1.** (A) Estimated water use for agriculture and other applications in the Great Salt Lake watershed from 1850–2013. Note that [1] failed to analyze the period from 1850–1903, during which approximately 80% of water development occurred. See [18] for methods. (B) Yearly and long-term changes in the actual elevation of the south basin of Great Salt Lake derived from the U.S. Geological Survey data (red). Droughts and wet years emphasized by [1] cause large swings in lake elevation but cannot account for the significant ( $p < 0.001$ ) decline since water development began in the basin. The green line shows [18] estimate of the natural lake elevation if consumptive water use had not occurred. The lake has declined approximately 3.6 m due to consumptive water use.

Additional analyses show that when all long-term and active stream gages in the Great Salt Lake watershed are considered, Meng's [1] assertion that decreasing precipitation is reducing streamflows is erroneous (Figure 2). In low order headwater streams above agricultural diversions, streamflow is stable. In contrast, in higher order rivers proximal to irrigated agricultural areas, streamflow decreases are observed. Indeed, such a pattern is a telltale sign of increasing agricultural water consumption over time [5]. As of 2015, GSL had shrunk by 2874 km<sup>2</sup> from 5966 km<sup>2</sup> [35]. In the Great Salt Lake watershed, 3894 km<sup>2</sup> of agricultural land is irrigated [36]. MODerate resolution Imaging Spectroradiometer (MODIS)-derived annual evapotranspiration (ET) for irrigated areas in the GSL watershed suggest mean ET is 370 mm·yr<sup>-1</sup> [37], implying an annual consumption of water for irrigated agriculture in the GSL basin of  $1.5 \times 10^9$  m<sup>3</sup>·yr<sup>-1</sup>, similar to the estimate by [18]. If evaporation excess (evaporation—direct precipitation) from the lake's surface is 0.61 m·yr<sup>-1</sup> on average [22], then approximately 2500 km<sup>2</sup> of the reduced lake area can be attributed to irrigated agriculture, over 85% of the observed lake area loss.



**Figure 2.** River discharge trends and irrigated agriculture in the Great Salt Lake watershed. Dots show long-term ( $\geq 50$  year) discharge trends through 2018 in 16 rivers. Streamflow is steady in low order headwater streams. Only higher order rivers that discharge into the lake have sharply decreasing streamflow. This is consistent with increasing water consumption from irrigated agriculture. (Mann Kendall tau values indicate the strength and direction of a trend over time).

#### 2.4. Time Scales

Meng [1] highlights extreme weather events, which he suggests support an extremely changing point analysis of “the so-called current declines of the world’s saline lakes”. He describes “extreme weather events” as those that are more than  $\pm 2$  S.D. of the mean. Meng [1] is correct that periods of



extreme precipitation or drought cause large changes in runoff and the level of Great Salt Lake. This is true for all closed-basin lakes (e.g., Lake Abert—[9]; Lake Urmia—[3]). For example, above average precipitation in the Great Salt Lake watershed from 1967–1981 increased the lake level by 2.0 m and then back-to-back 100-year precipitation events of 1982 and 1983 increased the lake level by another 2.4 m. This phenomenal increase, however, was followed by a 5.0 m decrease from 1987 to 2016, when the lake reached its lowest recorded level of 1277.5 m [18]. Meng incorrectly indicated that the lake's lowest level was in 1963 because he failed to calculate changes in both the north and south arms of the lake that are divided by a causeway [38]. Meng's analysis highlights the importance of weather-induced changes in the quasi-cyclic elevations of saline lakes, but without conducting a careful water balance analysis, he failed to identify the more important long-term driver of change in most saline lakes: persistent water withdrawals from their tributaries for agricultural and other forms of evaporative consumption [2,5–10,12,18,39,40].

### 3. Conclusions

The dominance of water development, rather than climate change, for influencing most saline lakes has important implications for managers. A warming climate and changes in precipitation will have very important consequences for saline lakes and other ecosystems. Managers should not, however, let climate change and the high variability of these ecosystems obscure the very real desiccation of saline lakes caused by water development. Meng's erroneous analysis is an example of climatization, in which primarily non-climatic processes are falsely attributed to climatic factors [13,15,16,41], thus absolving local governments of responsibility for sustainable management. In many cases, discriminating between climate impacts and water development [2,12,18,42] will only be understood with more thorough analyses than those attempted by [1]. Managers must be aware of this issue and support thorough water balance analyses, and then take the appropriate actions to preserve these ecosystems [43]. We support the recommendation of [44] that: "Aquatic ecosystems may be most effectively managed in the context of global climate change if both the more pressing anthropogenic threats [of water development] and the occurrence of extreme events are considered and incorporated into management plans."

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Communication

# Climate Change and Extreme Weather Drive the Declines of Saline Lakes: A Showcase of the Great Salt Lake

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**Abstract:** A viewpoint of a temporal trend with an extremely changing point analysis is proposed to analyze and characterize the so-called current declines of the world's saline lakes. A temporal trend of a hydrological or climate variable is statistically tested by regressing it against time; if the regression is statistically significant, an ascending or declining trend exists. The extremely changing points can be found out by using the mean of a variable, adding or subtracting two times of its standard deviation (SD) for extremely high values and extremely low values, respectively. Applying the temporal trend method to the Great Salt Lake's (GSL) relationship between its surface levels and precipitation/temperature in the last century, we conclude that climate changes, especially local warming and extreme weather including both precipitation and temperature, drive the dynamics (increases and declines) of the GSL surface levels.

**Keywords:** dynamics of saline lakes; extremely changing points; extreme weather; temporal trend

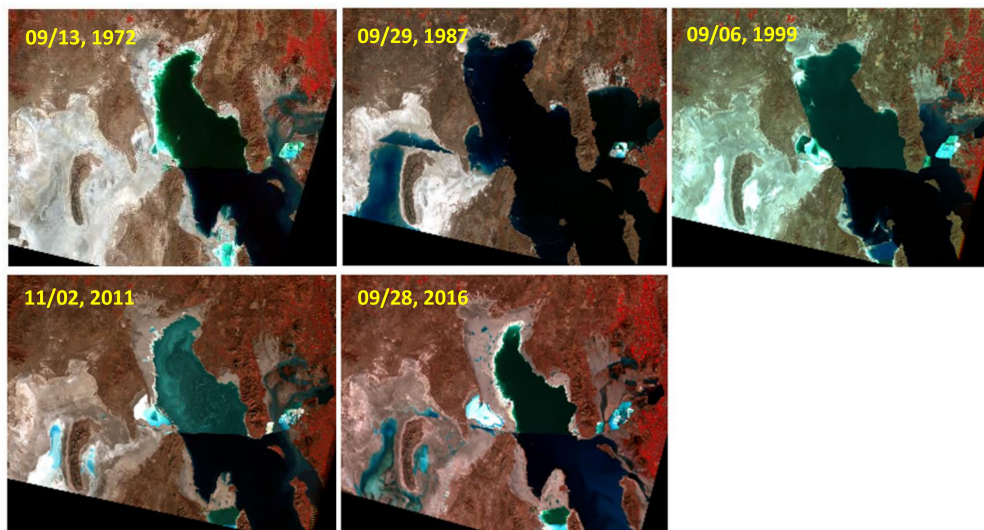
## 1. Introduction

The declines of saline lakes were recently highlighted in research and media. The Great Salt Lake (GSL), a remnant of Lake Bonneville, existed from about 30,000 years ago to 16,000 years ago, and is now approximately 4402.98 km<sup>2</sup> (1700 square miles) with a length of 120.70 km (75 miles) and a width of 45.06 km (28 miles) at its average water level [1]. It has no outlet, with dissolved salts accumulated by evaporation. Laying on a shallow playa, small changes in water surface levels typically result in large changes of the GSL area. The lake drainage basin is about 90,649.58 km<sup>2</sup> (35,000 square miles), where the human population is now more than 1.5 million. The GSL seems to be an ideal lake to study to understand the impacts of changes in climate on water resources.

Human water use might be an important factor driving the declines of world saline lakes. Using the GSL as an example, some researchers concluded that human water uses, specifically consumptive water uses for agricultural, salt pond mineral production, and municipal and industrial purposes determine the declines of saline lakes [2]. Although the US freshwater withdrawals have declined since 1980, (i.e., Trends in estimated water use in the United States, 1950–2015, <https://water.usgs.gov/watuse/wutrends.html>), and the current consumptive water uses in agriculture, salt pond mineral production, and industry can be much larger than that in the 1950s, in the last century the GSL had experienced a number of times of significant continuous declines, such as 1925–1936 and 1952–1963; furthermore, the current 2016 decline is much better than its situation in the 1960s. In other words, in the long term, human water use could be important, but it is questionable to only just attribute saline lakes' decline to human/consumptive water uses (i.e., agricultural, mineral municipal aspects, and others).

The Landsat images, which are available from 1972 to current years, as shown in Figure 1, indicate that the worst decline situation was in 1972 compared to 1987, 1999, 2011, and 2016. Human water

use, including agricultural, salt pond mineral, and municipal and industrial purposes in the 1970s was much less than those in the 1980s, 1990s, and 2010s. Human water use, thus, is not the main driving force of declines in the GSL in the past 100 years.



**Figure 1.** Landsat images (1972, 1987, 1999, 2011, and 2016) displayed in false color for the Great Salt Lake (GSL) and the GSL desert that is on the left side of the lake in the imagery. Sources and more details are available at <http://Earthshots.usgs.gov>, Earthshots: Great Salt Lake.

The recent changes of GSL water levels in the last three years 2016, 2017, and 2018 (details are available at <http://greatsalt.uslakes.info/Level.asp>) further reject the above conclusion that human water use resulted in the GSL water loss. The average water levels in 2017 or 2018 are 0.91 meters higher than those in 2016. Given the current lake area 4402.98 km<sup>2</sup>, it means that about 4,006,711,800 m<sup>3</sup> more water was added into the GSL in 2017 or 2018 than in 2016. Given the fact that the changes of human water use in 2016, 2017, and 2018 are barely due to no significant changes in population, agriculture, industries, and other human activities, human water use, hence, is not the dominant factor for GSL water loss or water level dynamics in the short term.

Considering the water budget of the GSL, we define the GSL water level using the equation below:  $\text{GSL water level} = \text{inflow (precipitation + river discharge)} - \text{outflow (human water use + evaporation)}$ . As discussed above, human water use alone cannot be thought of as the main driving force for water level dynamics or water loss. Thus, there are three remaining factors of precipitation, river discharge, and evaporation, which are all mainly related to climate factors of precipitation and temperature. Given this information, it is necessary to rethink the impacts of climate on the dynamics or declines of GSL water levels. Precipitation is the main and direct water source, and evaporation caused by the increases in temperature can be the dominant water loss of saline lakes.

## 2. Extremely Changing Point Analysis and Data

This short research proposes a new viewpoint of a temporal trend with an extremely changing point analysis in order to analyze and reveal the so-called declines of saline lakes. To the best of our knowledge, there is not a conception of an “extremely changing point analysis” in the literature, and hence it is proposed for applications to hydrology, climatology / meteorology, and environmental study to efficiently identify significantly changing observations in a data series.

In both climatology / meteorology and hydrology, time series are the data that are often analyzed, and extremely large or small records typically have their specific meaning in climate or hydrology. For instance, extreme weather has recently received more attention than before [3], and in the USA it is defined as unusual or unexpected severe weather at the extremes of the historical distribution, which typically are in the most unusual ten percent [4]. Studies have indicated that extreme weather

in the future will pose an increasing threat to the world, and three times the standard deviation were used to indicate extremely hot summer outliers [5]. Extreme values are key aspects of climate change, and changes in extremes are typically the most sensitive climate characteristics for ecosystems and societal responses [3,6]. Extremely increased or decreased records can be significantly large for seemingly modest mean changes in climate [7]. Most climate impacts mainly result from extreme weather events or the climate variables that are significantly above or below some critical levels, which hence affect biological behaviors or the performance of physical systems [3,6,8]. Intergovernmental Panel on Climate Change (IPCC) further stated that for important climate impacts, scientists are interested in the effects of specific extreme events or threshold magnitudes [3]. Therefore, it is necessary to apply an extremely changing point analysis to reveal the declines of GSL.

### 2.1. Extremely Changing Point

Whether a record is an extremely changing point is identified by using the mean of an attribute adding or subtracting two times of its standard deviation (SD). If an observation is larger than its mean plus two SD, it is an extremely high value point, while an observation smaller than its mean minus two SD is an extremely low value point.

Here, the extremely changing point analysis is based on the common statistical concept of the Z-score (or standard score) in statistics, which is defined as  $Z = \frac{x-u}{\sigma}$ , or written as  $x-u = Z * \sigma$  that is easily explained and understood, where  $x$  is the observations of an attribute  $u$  is the mean of the population, and  $\sigma$  is the standard deviation of the population; it describes how the observations are off the population mean. When Z-score is related to a normal distribution [9,10], the Z-score ranges from  $-3$  to  $+3$  covering almost the whole distribution by approximately 99.7%. The extremely changing point analysis proposed in this study is not limited by normal distribution, which in reality is often a special case, and for example, both mean and standard deviation require attention in order to understand extreme temperature [11]. Both two times the standard deviation and three times the standard deviation have been used to examine extreme temperature [5], although the gamma distribution is often used to model temperature measurements. In this study, we define  $Z = 2$  to determine if a record is far away enough from the mean, so that it can be defined as an extremely changing point;  $x$  can be either  $2\sigma$  larger than the mean or  $2\sigma$  smaller than the mean, although this method is used in statistics to find outliers.

As we know, a temporal trend can be statistically tested by an attribute regressed against time. If a trend is statistically significant with a  $p$ -value of its slope test less than 0.05, a positive slope indicates an increasing trend, while a negative slope indicates a declining trend.

We often emphasize a general trend for an environmental phenomenon, while extremely changing points (such as extremely high or low temperatures) and their effects are often overlooked, but they play significant and increasing impacts on the environment and human society as environmental changes become more global and frequent. Extremely changing point analysis not only adds more properties characterizing an environmental phenomenon that could not be disclosed by trend analysis, or mean as well as variance analysis, but also could reveal the relationship between geographic phenomena, such as extremely high precipitation which typically results in significant flooding inundation in space and time.

### 2.2. The Data

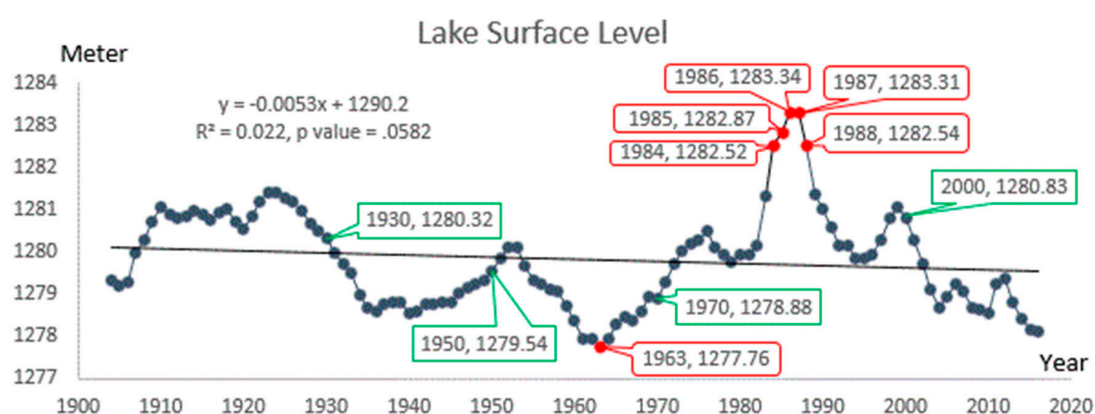
Using the GSL as a case study, the lake surface level data and climate data (including temperature, precipitation, and snowfall) are processed first from 1904 to 2016, given the snowfall data are available from 1904. The mean and SD of the four variables are calculated; then, the lower bound (i.e., mean minus two SD) and upper bound (mean plus two SD) are used as thresholds to respectively determine the extremely low and the extremely high values in each time series data of lake surface level, precipitation, temperature, and snowfall. Based on the lower bound and upper bound, the extremely low points and extremely high points of these four variables are recognized and summarized in Table 1.

**Table 1.** Climate, extreme weather, and the surface levels of the Great Salt Lake.

	Mean	2* SD	Lower Bound	Upper Bound	The Extremely Low Observations	The Extremely High Observations
Surface Level Meter	1279.82	2.33	1277.49 (1278.23)	1282.15 (1281.41)	1277.76 in 1963	1282.52, 1282.87, 1283.34, 1283.31, 1282.54 in 1984–1988
Precipitation Meter	0.395	0.173	0.223 (0.26)	0.568 (0.54)	0.221 in 1979	0.581, 0.616, 0.605 in 1982, 1983, 1998
Temperature K	284.31	257.15	282.53 (282.88)	286.09 (285.77)	282.15, 259.98 in 1964, 1983	286.76, 286.2, 286.65, 286.59 in 2012, 2014, 2015, 2016
Snowfall Meter	1.399	1.088	0.311 (0.57)	2.488 (2.29)	0.274 in 1973	2.682, 2.578, 2.979, 2.49, 2.51 in 1916, 1921, 1951, 1983, 1992

Note: The lower bound is determined by the mean minus two standard deviations (SDs), and the upper bound is the mean plus two SDs. Surface level data of the GSL are available at <https://ut.water.usgs.gov/greatsaltlake/elevations/>. Precipitation, temperature, and snowfall data are available at <https://www.ncdc.noaa.gov/IPS/lcd/lcd.html>. More details about these downloaded data are summarized in the Supplementary Materials. The values in ( ) are the 5th and 95th percentiles, respectively, compared with those lower bounds and upper bounds determined by mean and 2SD.

Some may question, why not use 5th and 95th percentiles to identify extremely changing points? In Table 1, the values of the 5th and 95th percentiles for surface level, precipitation, temperature, and snowfall are compared to the lower and upper bounds respectively defined by 2SD. Results show that the values of 95th percentiles are all much smaller than the upper bounds determined by mean + 2SD, as shown in Table 1, but the 5th percentiles are all much larger than the lower bounds determined by mean − 2SD. In other words, if the 95th percentile is used, there could be too many “extremely changing points” that in fact are not large enough to be extreme; while many more low values also can be added by using the 5th percentile, which are not small enough to be extremely low. Therefore, the 5th and 95th percentiles cannot make the extremely changing points as meaningful as it is defined to identify the extremely changing observations by using mean and 2SD. For instance, using the 5th and 95th percentiles, surface levels in 1923, 1924, and 1989 would be added as extremely high water levels to 1984, 1985, 1986, 1987, and 1988; surface levels in 1961, 1962, 1964, 1965, 2015, and 2016 would be added as extremely low observations in addition to 1963, as shown in Figure 2. In other words, mean and 2SD are more robust and effective than the 5th and 95th percentiles to identify extreme values.

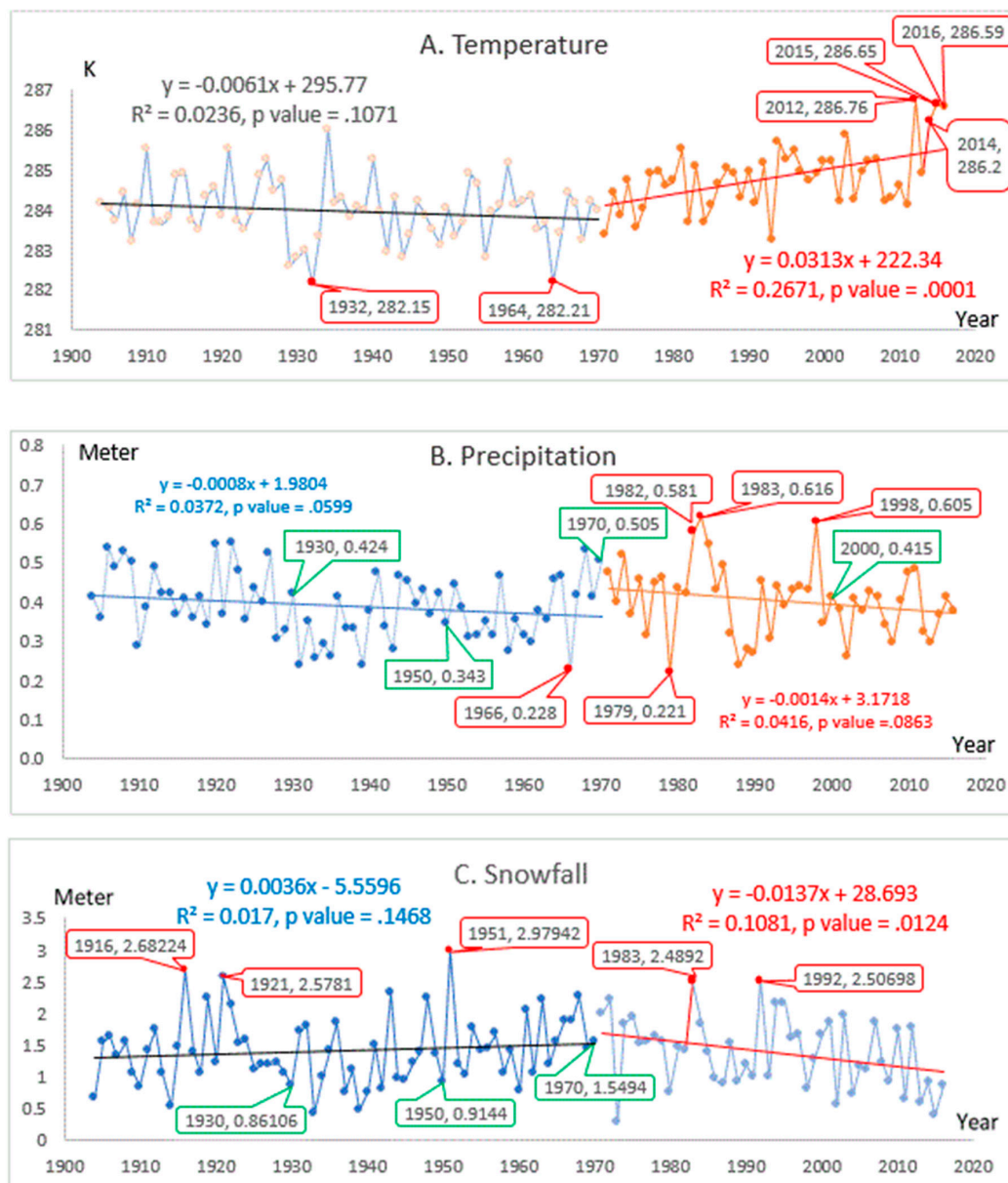


**Figure 2.** The general declining trend of the GSL surface level and the extremely changing points marked in red.

From the early 1970s, there is a significant trend of local climate warming in the GSL region, which is primarily driving the declines of the GSL, as shown in Figure 3. Therefore, the climate variables of temperature, precipitation, and snowfall are analyzed into two periods, from 1904 to 1970 and 1971



to 2016, in which temporal trends are analyzed and extremely changing points are marked in red, as shown in Figure 3.



**Figure 3.** The dynamics of temperature, precipitation, and snowfall in the GSL area. (A) trend analysis of temperature; (B) trend analysis of precipitation; and (C) trend analysis of snowfall.

Trend analysis is also applied to the lake surface level, temperature, precipitation, and snowfall in order to highlight the efficiency of extremely changing point analysis in hydrological and climate data analysis. For example, whether the GSL has a significant declining trend can be analyzed as a regression model with years as a predictor. If we use the lake surface level as an indicator of GSL declines, we need to regress the lake surface levels against years. The results of trend analysis and the extremely changing points are plotted and marked in red, as shown in Figures 2 and 3.

### 3. Results and Discussions

In the last century, the GSL shows an apparent decreasing trend from 1904 to 2016 with the lowest level of 1277.76 meters in 1963, but its declining trend is not significant, as shown in Figure 2. In other



words, the significance of GSL declines is tested with a  $p$ -value of 0.0582 that is just a little beyond the significance level 0.05. However, the periodic changes of its surface levels in both increasing patterns and decreasing patterns are anomalous in the last century, as shown in Figure 2. This cannot be explained by the human water uses in agriculture, industry, and municipal purposes that were much lower in the last century than current days given the recently significant growth in agriculture, industry, and urbanization in the GSL basin. Instead, the GSL declines could be more clearly explained by climate change and extreme weather including both precipitation and temperature, which then are explained in the five sections below: local warming and evaporation, the impacts of radiation and wind on evaporation, precipitation, river discharge, and human water use.

### 3.1. Local Warming and Evaporation

Climate changes, especially increasing temperature, have caused significant water loss through evaporation in semi-arid regions [12–16]. Craig et al. reported that increasing evaporation rates caused by climate warming have resulted in approximately 40% of Australia's total water storage capacity loss every year [16]. Helfer et al. and Johnson and Sharma obtained similar results of climate warming on evaporation, demonstrating that increasing temperature results in the significant increases of annual average evaporation [13–15].

Specifically, Helfer et al. mentioned that a temperature increase range between 0.8 °C and 1.3 °C in 2030–2050 compared to 1990–2010 will result in an average annual evaporation from 1300 mm in 1990–2010 to an average annual 1400 mm in 2030–2050 [13]; in other words, an annual temperature increase rate of 0.02 to 0.0325 would result in an average annual difference of 100 mm in evaporation. Additionally, an annual temperature increase rate of 0.021 to 0.04 would cause an average annual evaporation difference of 190 mm, i.e., evaporation from 1300 mm in 1990–2010 to 1490 mm in 2070–2090 caused by a temperature increase range of 1.7 °C to 3.2 °C in 2070–2090 [13]. In the GSL region, the annual temperature increase rate is 0.0313 from 1971 to 2016, as shown in Figure 3A. Given an average annual evaporation amount  $E$  for the GSL before 1960 and the significant and consistent temperature increase from 1970 to 2016, as shown in Figure 3A, the average annual evaporation in 1970–1990 could be  $E + 100$  mm, and the average annual evaporation in 2000–2020 could be  $E + 190$  mm. Therefore, the GSL has lost a huge amount of water from evaporation in the last 50 years. The extremely high temperatures in the recent years 2012, 2014, 2015, and 2016 directly aggravate the significant declines of surface water levels of the GSL due to the enhanced evaporation with the addition of low precipitation in the recent few years, and the GSL hence reaches a relatively low level of 1278.13 meters in 2016, as shown in Figures 2 and 3. Therefore, evaporation and low precipitation are the main cause of the declines of the GSL.

### 3.2. Radiation, Wind Speed, and Evaporation

Some may still wonder if radiation and wind speed impact evaporation changes. Solar radiation increased significantly in the last century [17], which indicated that evaporation increased too. The effects of wind speed on evaporation are complex. At low velocity values, the first stage evaporation rate will increase when wind speed increases, but at the same time the transition time decreases; however, at high values of wind speed, evaporation rates will depend less on the wind speeds; additionally, no significance is found for the impact of the wind speed on the second stage evaporation rate [18]. In all, the effects caused by increasing radiation could be stronger than the effects of wind speed, and thus evaporation might increase in the last century; or the overall evaporation change caused by radiation and wind speed is not significant in the last century.

### 3.3. Precipitation

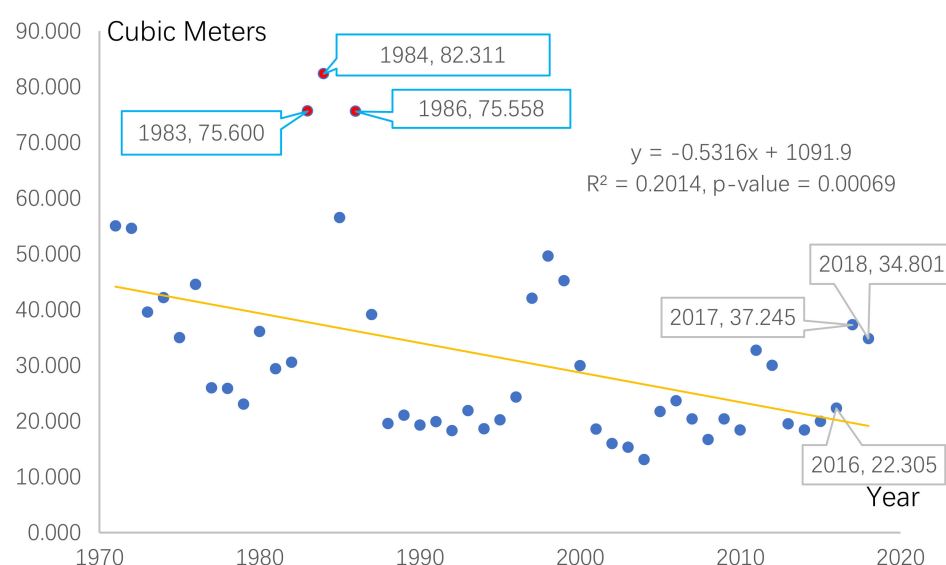
The temporal patterns of precipitation directly drive the general dynamics of GSL surface levels, which are then mainly modified by evaporation driven by temperature changes as discussed above. Both the periods from 1904 to 1970 and from 1971 to 2016 show apparent decreases in precipitation, but

the significances are just above the significance level 0.05. Therefore, the declining trend of lake surface level is not quite significant. Since 1971 with about 10 years' high precipitation, the GSL reached an extremely high level in 1984 that continued to 1988, as shown in Figure 2, because of the extremely high precipitation in 1983, 1984, and the high precipitation in 1985 and 1986, as shown in Figure 3. Additionally, from 1904 to 1930, the GSL surface levels were most often above its average value (1279.82 meters), as shown in Table 1, because the precipitation in only 8 of 27 years was relatively lower than its average value of 0.395 meters, as shown in Figure 3. In the 40 years from 1931 to 1970, only two year's GSL surface levels (1952 and 1953) were relatively above its average level, because the precipitation in 27 years was much lower than the average precipitation, as shown in Figure 3; especially with 20 more years of low precipitation, and in 1963, the GSL reached its lowest surface level (1277.76 meters) that was still above its extremely low level bound (1277.49 meters). From 1971 to 2000, there were only 9 of the 30 years when precipitation was less than its average value, and therefore most of the years the GSL surface levels were above its average level. The extremely high precipitation in 1998 resulted in the second highest surface level in 1999, as shown in Figures 2 and 3. Although the precipitation in 1966 and 1989 was very low, respectively high precipitation following them continuously occurred for 7 or 8 years, which thus did not result in extremely low surfaces but relatively low water levels.

The continuously significant decreases in snowfall from 1971 to 2016 could be a secondary contribution besides the significant increasing temperature for the apparent declines of lake surface levels after 2000, as shown in Figures 2 and 3. The extremely high snowfall in 1983 (2.489 m) also secondly contributed to the extremely high records of lake surface levels in 1984 to 1987.

### 3.4. River Discharge

Bear River, Jordan River, and Weber River are the major surface water discharges into the Great Salt Lake, which account for 58%, 22%, and 15%, respectively, for the total inflows of the lake [2]. The U.S. Geological Survey (<https://waterdata.usgs.gov/>) provides inflows from 1971 to 2018 for the Bear River and Jordan River as displayed in Figure 4 below, which have 80% of surface inflows for the GSL. Because the continuous data for Weber River are only available after 1989, it is not included into this decadal analysis. In general, the surface inflows show a significant declining trend, which contributes to the decreasing water level in the same period, as shown in Figure 2. The reduced river discharge is directly caused by the declining precipitation and snowfall, as shown in Figure 3.



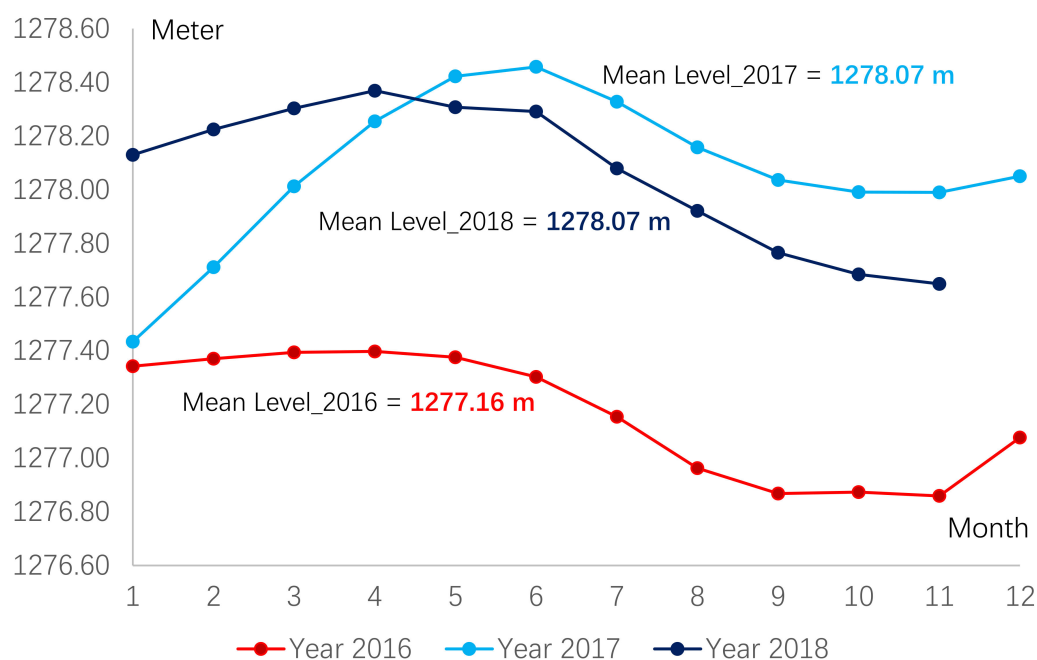
**Figure 4.** Surface inflows from Bear River and Jordan River into Great Salt Lake from 1971 to 2018. Data source: <https://waterdata.usgs.gov/>.

The extreme highest points of the observed discharge values in 1983, 1984, 1986, as shown in Figure 4, have significant contribution to the extremely high water levels, as shown in Figure 2. These extreme highest values are also coincident to the extremely high precipitation values observed in 1982 and 1983. This is a truth that we first observed highest precipitation, secondly observed highest surface inflows, and third detected highest lake water levels. In the GSL basin, climate changes generally drive the river discharge patterns.

### 3.5. Human Water Use

We understand that human water use could be another secondary contribution to GSL's water loss. However, the conclusion of "consumptive water use including agricultural, salt pond mineral production, and municipal and industrial uses rather than long-term climate change has greatly reduced its size for the Great Salt Lake's surface declines" [2], cannot explain the much lower surface levels in 1961, 1962, 1963, and 1964 that were lower than 2016's current record, the significant declines from the early 1920s to the late 1930s, the significant increasing trend from the mid-1960s to the mid-1970s, and other significant declining or increasing patterns in the last century, as shown in Figure 2.

Additionally, human water use even cannot explain the current GSL water level changes in 2016, 2017, and 2018, as shown in Figure 5. The average water levels in 2017 or 2018 are 0.91 meters higher than that in 2016. If human water use was the dominant driving force for GSL water loss or dynamics, it is impossible that in three continuous years, significantly less human water use has occurred, which then has resulted in such a huge amount of water increases in 2017 or 2018. Another recent study also showed worldwide declines of water storage in endorheic basins in the last 10 more years were caused by limited precipitation with high potential evaporation, which are then intensified by global warming and human activities [19]. Thus, human water use is not the dominant cause but could be a secondary factor of saline lakes' water loss.



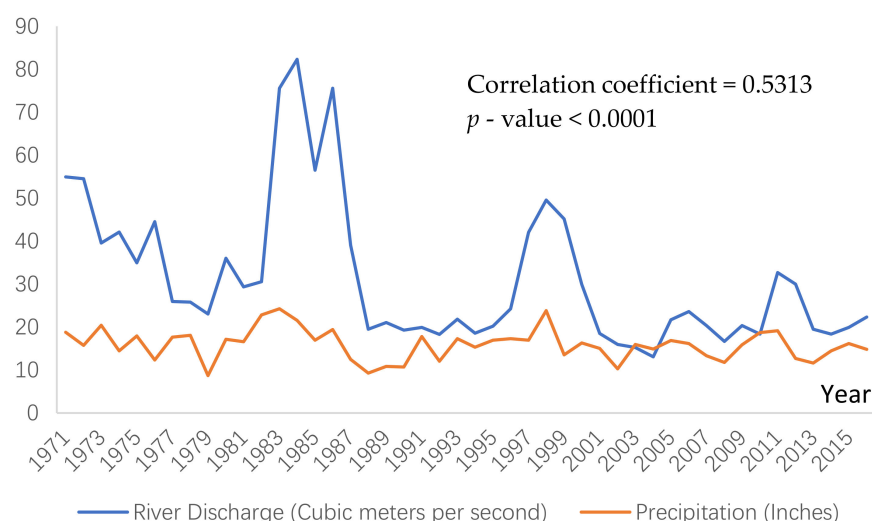
**Figure 5.** GSL monthly water levels in 2016 and the big increases in 2017 and 2018. This figure is plotted on a monthly scale from January 1, 2016 to November 30, 2018, which is calculated and processed using the GSL daily water level records that are available online at <http://greatsalt.uslakes.info/Level.asp> provided by [www.lakesonline.com](http://www.lakesonline.com).

### 3.6. Correlation between Temperature, Precipitation, Snowfall, River Discharge, And Gsl Water Level

The above analyses have showed apparent temporal patterns of temperature, precipitation, snowfall, and river discharge. Chang and Bonnette have recently examined the correlation between climate and water-related ecosystem services [20]. Here, we use the Pearson correlation coefficient to quantify a general relationship between temperature, precipitation, snowfall, river discharge, and GSL water level, as shown in Table 2. From 1971 to 2016, the significant increasing temperature is significantly and negatively related to GSL water levels. It coincides with the above analysis that local climate warming is a critical variable for water loss. Another significant relationship is between GSL water levels and river discharge. River discharge is significantly and highly correlated with precipitation, as shown in Figure 6, which further indicates that climate factors, especially precipitation along with temperature, are the dominant driving force of GSL water level dynamics.

**Table 2.** Correlation between temperature, precipitation, snowfall, river discharge, and GSL water level.

	Temperature		Precipitation		Snowfall		River Discharge
	1904–1970	1971–2016	1904–1970	1971–2016	1904–1970	1971–2016	1971–2016
Coefficient	0.19	−0.29	0.20	0.08	0	0.12	0.59
<i>p</i> -value	0.0666	0.0260	0.0521	0.2485	0.4979	0.2089	<0.0001



**Figure 6.** River discharge is highly and significantly related to precipitation.

## 4. Limitations

Many other studies recently have showed that the GSL water levels are primarily sensitive to climate cycles, given its main outflow is evaporation that is directly changed by lake area and salinity, and precipitation variations mainly drive the GSL water level variation [20–22]. Rather than following the previous research approaches, this proposed study, based on a simple water balance equation of inflow and outflow, explored how climate and weather factors could impact on inflow and outflow, and concluded that climate change and local extreme weather drive the dynamics of GSL water levels. This is not the primary objective of this short communication; we hope this short communication could encourage more high quality studies and inspire scientists to rethink water budget modeling, climate modeling, and hydroclimatological analysis, so that the driving force of water dynamics of salt lakes could be truly modeled and quantified, which then will provide useful and practicable information for water budget planning and water resources management.

We understand that there are many sophisticated models for climate and hydroclimatological analyses, but “all models are wrong, and some are illuminating and useful” [23,24]. Scientists cannot achieve a “correct” model by excessively elaborating modeling procedures and parameters; while

for great scientists it is significant to devise simple and evocative models, any overelaboration and over-parameterization is nothing but mediocrity [23,24]. There are some limitations in this short communication. For example, we do not directly examine the impacts of human water use on water level dynamics of GSL, while we analyze the remaining factors for water balance including inflow factors (i.e., precipitation, snowfall, and river discharge) and outflow factors (i.e., evaporation, temperature) that influence the water levels of GSL. We do not have direct measurements of evaporation in the GSL region, but evaporation estimations of water bodies of similar semi-arid regions in Australia are referenced to indicate the impacts of evaporation on GSL water loss. Long-term surveys of evaporation and measurement of human water use can be helpful in order to further analyze and quantify the primary and secondary factors driving the dynamics of saline lakes. Additionally, the 95th and 5th percentiles cannot effectively identify extremely high or low observations of water levels, precipitation, temperature, and snowfall, which further indicates our proposed extremely changing point analysis with mean and two standard deviations is a robust and promising method for hydroclimatological analysis.

## 5. Conclusion

The proposed temporal trend with the extremely changing point analysis is a promising method to clearly and concisely define and understand the characteristics of extreme climate/weather and their impacts on the declines of saline lakes. Extremes have become foundational information and projections for climate change, which has been highlighted 734 times in the current US Global Change Research Program's Climate Science Special Report [25]. Most often, an explicit definition of extreme is not provided in current research and management, but clearer definitions and quantifications of extremes can support interdisciplinary understanding and decision making of extreme events [6]. Defined by whether an observation is outside its two standard deviations of the mean, the extremely changing points indicate the substantial changes of a variable in its temporal patterns. Using the proposed temporal trend with extremely changing point analysis, this short communication adequately shows that climate change and extreme weather can be the primary driving factors of the dynamics/declines of the Great Salt Lake. Although the impact of one isolated extremely changing point could be limited, two more continuously or clustered extremely changing points can have elevated impacts on the environment. For example, extremely high temperature in 2012, 2014, 2015, and 2016 considerably enhances the continuously increasing evaporation of the GSL since the 1970s. The extremely low precipitation in 1979 is isolated, and therefore its effect was minimized by many of those much higher precipitation observations neighboring and close to it.

Climate changes, especially local warming and extreme weather including both precipitation and temperature, drive the dynamics of the GSL surface levels. Extreme weather, such as extremely high or low precipitation, directly causes the changes in surface levels, and the extremely high temperature in the last five years has resulted in much more water loss through evaporation that can be another main cause of the relatively low surface level in 2016. The increasing temperature trend since the 1970s, as shown in Figure 3, has become a critical role in water loss and hence the decline of the GSL surface levels. As discussed above, many studies have proven that climate warming has resulted in the main water loss through evaporation (i.e., each year about 40% of the total water storage capacity in Australia). The annual increasing rate of 0.0313 in temperature from 1971 to 2016 could result in more than 40% loss of its total water storage each year.

**Supplementary Materials:** The supplementary material is available online at <http://www.mdpi.com/2225-1154/7/2/19/s1>.

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