MODELING THE EFFECTS OF AIR QUALITY FROM THE GREAT SALT LAKE

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Abstract. The Great Salt Lake has experienced a rapid decline in water level in recent decades, with a looming threat of completely drying by the end of this decade at current rates of decline. Hidden beneath the Great Salt Lake, however, lie toxic metals embedded from millenia of natural erosion and more than a century of human pollution. We model the toxic debris released from the exposed lakebed of the Great Salt Lake as a function of time, including as the Great Salt Lake continues to decline in water level and the lakebed erodes. We examine the health risk posed to those living in the Salt Lake Valley due to air quality resulting from this potential local natural disaster.

1. Background/Motivation

Since reaching its high-point in 1986, the Great Salt Lake has experienced a continuous and rapid decline in water level due to a combination of environmental and human factors. After setting a new record-low in November, 2022, local researchers forecast that at the current rate of water loss, the entire Great Salt Lake would vanish within five years[1].[1] Aside from devastating an entire ecosystem and causing severe financial repercussions, many have warned this poses a great threat to the health of those in neighboring communities. Large deposits of toxic metals have been carried by runoff into the Great Salt Lake, and there has been a concerning rise of arsenic and other toxic particles being blown from the dry lakebed as more than 60% of the nautral surface area and more than 73% of the total lake volume has already been lost [1].

Rising concern over the Great Salt Lake is not without precedent. Most notably, Owens Lake in California once supported a variety of industries, small towns and a local Native-American population. However, in 1913, the Owens River was diverted completely into the Los Angeles aquaduct, causing Owens Lake to entirely evaporate by 1926. Despite a multi-billion-dollar effort spanning the last several decades, Owens Lake continues to emit millions of tons of toxic dust debris each year, making it the single largest source of dust pollution in the United States [15] [16]. The clear lesson learned from Owens Lake is two-fold: (1) the pollution caused by

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[1]To see the difference in water levels from July 1986 to July 2022, see https://www.usgs.gov/media/before-after/great-salt-lake-comparison-1986-and-2022

a dried lakebed can endanger local residents for generations, and (2) once dried, we do not have the infrastructure or knowledge to reverse the damage to both the environment and humans. Owens Lake, at its fullest, covered approximately 100 square miles of land, while the Great Salt Lake has more than 800 square miles of exposed lakebed already.

In the last half-decade, several efforts have been made to model the particulate spread from the Great Salt Lake, with myriad purposes and conclusions. In 2022, researchers modeled the geographic shadow of toxic debris for various levels of the Great Salt Lake [4]. This was one of the most comprehensive models to date and found the decreasing water level has had the greatest impacts on socio-economically-deprived communities. This corroborates previous findings from NASA [5] and the University of Utah [6], [8]. This suggests a troubling trend of minorities and the financially-disdvantaged facing even greater impacts from the Great Salt Lake's disappearance.

Independent of others and more recently, Dr. Kevin Perry, professor of atmospheric sciences at the University of Utah, modeled forecasts of dust storms up to 36 hours in advance while factoring in the unique soil composition of the now-evaporated Farmington Bay [7]. Taking an accumulation of previous efforts, University of Utah assistant professor Albert Garcia estimated a current cost of $30 million annually to the local economy, and climbing.

While research covering particulate matter more broadly than our approach finds no significant increase in pollutants in the Salt Lake Valley, there are harmful particles that aren't recorded which are abundantly present in the Great Salt Lake [9]. This provides insight into the possible bias that affects current, past, and future research, as there is great ecological, economical, and political investment in the Great Salt Lake. Consequently, there is much literature available that is incomplete or contradictory, and very few methodologies have been explicitly given to be reviewed and critiqued. Most models were developed to advocate for change, and in consequence, their efforts were focused on more qualitative than quantitative methods/results. Thus, much public data is missing or incomplete, so future scientific research is necessary and ongoing [3].

In this paper, we model the arsenic particulate spread in the Salt Lake Valley as the Great Salt Lake, and its lakebed, erode over time. We first clean and accumulate as much relevant public data as possible, then report the specific values we find in our model of arsenic debris. We use this data, combined with historic air quality records, to evaluate the potential health risk posed to those living in the Salt Lake Valley. In this way, we provide a clear, comprehensive, quantitative backing to many of the qualitative claims made in mainstream discourse.

2. Modeling

We now proceed with our models of the effects of the Great Salt Lake's dust on air quality. Our first model evaluates the change in air pollution due to the flux (or net change) in air being blown through the area due to weather, as well as new particulates introduced by dust blown from the Great Salt Lake. Our second model improves this idea by enhancing our analysis of flux and introducing a factor that monitors how much dust remains in the air from one day to the next. Our final model introduces a more sophisticated estimate of dust blown from the Great Salt Lake, based on factors such as local soil composition and varying surface area of exposed lakebed.

We provide our justifications and explanations for each attempt at modeling airborne particulate matter (PM_{10}). Note that PM_{10} represents airborne matter $\leq 10\mu$m and often triggers respiratory issues. Because dust is most likely to be categorized as PM_{10}, and there is no available data for arsenic levels in the air on the scale we need, we primarily focus on PM_{10} when modeling and analyzing our results. For our modeling purposes, we use the wind speed and air particulate concentrations provided by the Environmental Protection Agency [14].

2.1. **Standard Model.**

We begin with several necessary assumptions. First, we ignore potential sources of pollution inside our area of interest due to a lack of available data and because internal pollutants are generally consistent from one day to the next. Similarly, without sufficient available data to account for all sources of pollutants, we assume the concentration of external pollution being blown into our region is the same as the United States average. Moreover, we are only interested in the overall effect on our system's airborne pollutant concentration from the Great Salt Lake, so the remaining sources of pollutants is ultimately beyond the scope of our model.

Additionally, in order to determine the concentration of airborne pollutants over time, we must begin by considering their movement in the air. At the most basic level, this includes the inflow of external pollutants (like dust blowing in from an external region) and the outflow of pollutants in our modeled environment. Wind speed and direction are also very important factors to consider. Unfortunately, wind data with direction for the Salt Lake Valley is not publicly available. We therefore assume wind direction follows a typical west-to-east pattern and select a general environment near Salt Lake City (east of the Great Salt Lake). This is because there is more public data available for this location; however, our results generalize similarly regardless of the direction of the wind (as dust will blow regardless of the direction it travels) and the local region is populated all around the Great Salt Lake, meaning individuals are impacted regardless of wind direction. We monitor the average wind speed on a given day to determine the overall flux of pollutants (in *or* out of our system). The max wind speed will be used to determine the amount of dust that has been blown from the lake.

Previous studies near the Great Salt Lake have shown wind speeds of 18 mph or more can cause dust storms from the dried lakebed [7]. As data was recorded at hourly intervals, it is impossible to know for how long wind speeds were above a certain amount. Thus, we make the assumption that the duration of high winds does not affect the amount of particulate matter blown from the lake on a given day. This could pose as a weakness, but it does provide potential insights into how important mere "gusts" of wind are in modeling pollution from the lake.

With these considerations in mind, we first propose the following equation for our first (standard) model of the increase in airborne pollutants (concentration) on day t:

$$P'(t) = I(\eta S(t) - P(t)S(t)) + f(t) \tag{1}$$

$P(t)$: concentration of the airborne pollutant of interest in the region on a given day t

$P'(t)$: change in concentration in the region on day t

I : concentration increase per wind speed increase per day

η : average concentration of the airborne pollutant in the U.S.

$S(t)$: average wind speed on day t

$f(t)$: increase of concentration of our airborne pollutant from the lake on day t.

We model the daily increase of airborne particulate matter from the exposed Great Salt Lake (in concentration) as follows:

$$f(t) = \begin{cases} l & \text{if } S_{max}(t) \geq 18 \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

l : some constant

$S_{max}(t)$: max velocity on day t.

Note that $I(\eta S(t) - P(t)S(t))$ is the change in flux on a given day if we ignore lake-caused pollutants. Based on various model iterations, we choose 37.0 as the value of our constant l. Later, we explore more arguments for the amount of pollution created by the lake. η is the average PM_{10} concentration in the U.S. [10].

As shown in Figure 1, this initial model captures the average air pollution of PM_{10} in the region well, but fails to capture both the daily variations and the spikes caused by large dust storms. This is because each of our terms rely on constant values with only slight variation due to wind, leading to our relatively constant result throughout the year, based on recorded wind data from a Salt Lake City weather station in 2024.

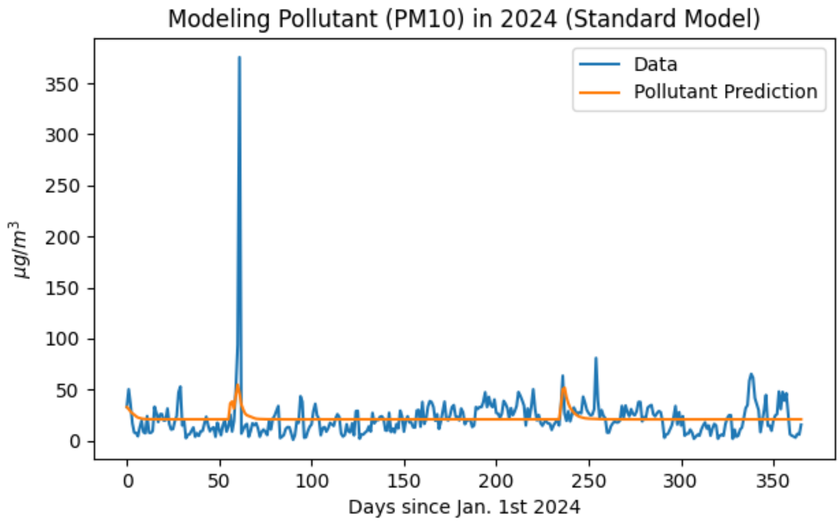

FIGURE 1. Standard Model predicting the PM_{10} pollutants based on wind data in 2024

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2.2. **Second Model.** To address the lack of variability, we begin to improve our standard model by considering how long particles remain airborne in our environment. Our previous model assumed particulates are only removed when blown from the region. We now introduce a *settling factor* representing environmental dust returning to the ground.

Additionally, we attempt to add variability to our model by allowing the constant c in our standard model to be represented by two constants: one associated with the concentration *increase* and the other with the concentration *decrease*. This allows us to adjust to different concentrations of pollutants being introduced to our environment as those leaving (e.g., due to inversions or the inflow/outflow airstreams having different air qualities). With these new assumptions (and the same as before for variables which haven't changed), we have our second model:

$$P'(t) = \alpha\eta S(t) - \beta P(t)S(t) - \kappa P(t) + f(t) \tag{3}$$

α : concentration increase per wind speed increase per day

β : concentration decrease per wind speed increase per day

κ : ratio of concentration settling per day given an amount of concentration.

We show our second model's predictions of the PM_{10} level in Figure 2. One obvious weakness is that although we consider the settling factor, it is still not dependent on wind speed, even though wind significantly slows the rate at which dust can settle. However, this still marks an obvious, even if subtle, improvement over our standard model, increasing our variation and more accurately modeling the multi-day impact of dust storms.

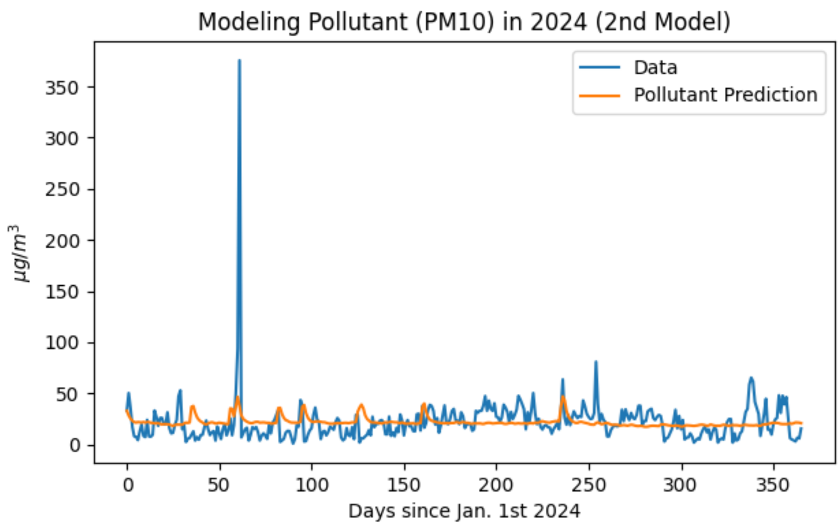

FIGURE 2. Second Model predicting the pollutants based on local wind data from 2024

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2.3. **Third Model.** In order to model the most significant health consequences caused by the Great Salt Lake, we focus our final model on arsenic as the primary pollutant from the lake contributing to PM_{10} levels. This is verified by extensive research discussed in Section 1 that lake-blown biohazards typically are categorized as PM_{10} and arsenic is by far the toxin of greatest concern from the Great Salt Lake.

Further, neither of our previous models estimated the surface area of exposed lakebed as a factor contributing to the dust blown during a dust storm. Therefore, we now consider varying amounts of lakebed exposure, as well as the wind's max velocity, concentration of arsenic in the soil, and other atomic properties of arsenic to specify our predictions specifically to the unique factors of the Great Salt Lake and the particulate of greatest interest. We use public data for the surface area of the lake [10] [11].

We consider all surface area that is exposed when the Great Salt Lake is below a "healthy level" (defined generally as its natural level) to be surface area that could produce harmful dust[12]. While we also considered the moisture content of the soil to be a contributing factor, this data has not been kept and is almost impossible to estimate reliably, so it was not included in our final model.

Consider the following updated equation for $f(t)$:

$$f(t) = \begin{cases} \frac{c\rho A(t) S_{max}(t)}{m} & \text{if } S_{max}(t) \geq 18 \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

$$\begin{aligned} c &: \text{concentration of arsenic in the soil} \\ \rho &: \text{atomic density of arsenic} \\ A(t) &: \text{surface area of the lake on day } t \\ S_{max}(t) &: \text{max velocity on day } t \\ m &: \text{atomic mass of arsenic.} \end{aligned}$$

Note this new f is now dimensionally consistent, with the rest of our model using C as the units of concentration:

$$\left[\frac{c\rho A(t) S_{max}(t)}{m}\right] = C\frac{M}{L^3}L^2\frac{L}{T} = CT^{-1}.$$

This matches the dimensions of $P'(t)$ (concentration over time). Also note that if we examine the dimensions of the other components of our system, our model remains dimensionally consistent:

$$[\alpha\eta S(t)] = \frac{CT^{-1}}{LT^{-1}}LT^{-1} = CT^{-1}, \qquad [\beta P(t)S(t)] = \frac{CT^{-1}}{LT^{-1}}LT^{-1} = CT^{-1},$$

$$[\kappa P(t)] = CT^{-1}.$$

We now analyze equilibrium solutions of $P'(t) = \alpha\eta S(t) - \beta P(t)S(t) - \kappa P(t) + f(t)$. Setting to $P'(t) = 0$, we see that if $P(t)$ was zero, $f(t) = -\alpha\eta S(t)$. This is only true if both sides are zero, but the right side will never be zero since $S(t)$ cannot be zero for all t. Thus, the only two cases left to consider are when $f(t) = 0$ and $f(t) \neq 0$. If $f(t) = 0$, the combination of flux and dust settling in our system would have to be constant. Likewise, if $f(t) \neq 0$, then the in-flow, out-flow, settling of internal dust, and the pollution added by the lake would have to be perfectly balanced. This would be the only way for our model to have an equilibrium solution, and we note how unlikely that would be to occur in both the real world and our model due to the high variability of local wind and weather patterns.

We demonstrate our final model's improved performance in Figure 3. Note that while our model still does not capture the small variations in day-to-day air pollution levels, it represents the magnitude of dust storms with great precision. Moreover, because we do not have directional wind data, our model assumes all wind storms blow dust directly toward our environment (whereas the true data reflects that some wind events may have occurred with wind blowing in different directions), resulting in fewer spikes at our data's geographic station. This is fine as our model is more broadly concerned with the rise in pollutants in the Salt Lake Valley and not in any specific location.

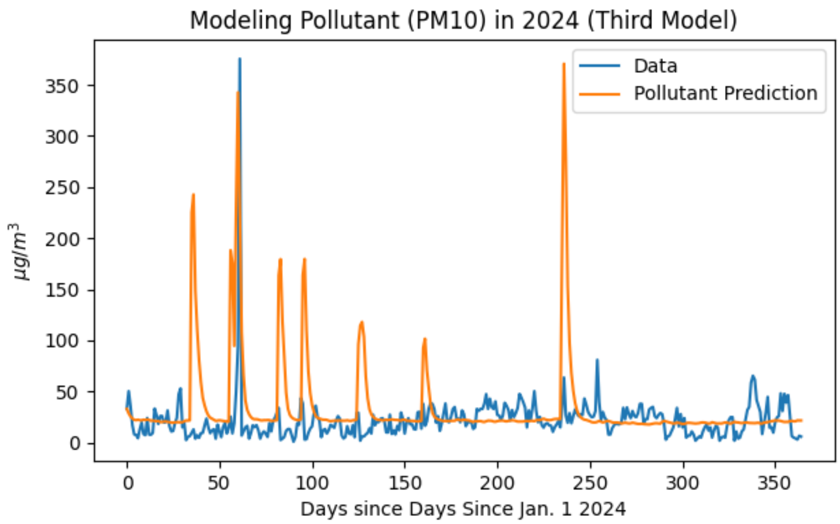

FIGURE 3. Third Model predicting the pollutants using regional wind data from 2024

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3. Results

From the data available in 2024, we find several dust storms with more PM_{10} than the World Health Organization's 24-hour guideline of 45 $\mu g/m^3$ [13]. The largest and most threatening of these storms was accurately predicted by our third (final) model. Using this model on varying levels of the Great Salt Lake, we draw two meaningful conclusions:

- Should the Great Salt Lake vanish entirely, frequent dust storms would cause imminent, life-threatening events for millions living in the Salt Lake Valley, along with likely increases in myriad long-term health consequences. We found a solution to our model with the same wind conditions as in 2024 with the assumption that there was no water in the Great Salt Lake. This resulted in our model forecasting multiple storms that year with more than $1500\mu g/m^3$.
- In contrast, using a similar approach with a natural and healthy water level of the Great Salt Lake resulted in our model forecasting no threatening storms to public health at all (never exceeding the WHO 24-hour guideline).

Our final model is still preliminary and relies upon incomplete data sources due to a lack of available data. Public records have not caught up with the rapid decline, including studies on lakebed soil composition and complete public data of local maximum wind speed and wind direction. It is for these reasons we made several aforementioned simplifying assumptions based on available averages, resulting in our model failing to capture all daily fluctuations in the concentration of air particulates. However, our model does accurately describe the magnitude of regional dust storms and the amount of air particulates such storms would introduce into the local environment. Thus, our model does quantitatively reflect the potential consequences of the Great Salt Lake either returning to its healthy level or continuing its decline until drying entirely. Because of a lack of wind direction data, we cannot confidently predict which areas will receive the greatest impact from these storms; however, we do have an accurate model for the PM_{10} concentrations of dust storms around the Great Salt Lake.

Overall, the results from our model are indicative enough to analyze and draw meaningful conclusions for the current landscape and future impact of the air pollution resulting from the drying (or restoration) of the Great Salt Lake.

4. Analysis/Conclusions

According to the National Ambient Air Quality Standards (NAAQS) for the United States, the 24-hour standard for coarse particles (PM_{10}) is 150 $\mu g/m^3$ [2]. It is important to note that daily standards are significantly higher than annual standards; for example, NAAQS has set the annual standard for particulate matter at just 9 $\mu g/m^3$. Moreover, there is no such thing as a "safe" level of air pollution, so standards vary. The World Health Organization recommends a maximum 24-hour PM_{10} exposure of 45 $\mu g/m^3$, less than a third of the NAAQS standard [13].

As discussed in Section 3, our model relies on incomplete data, which necessitates several simplifying assumptions and the use of data averages, where specific values (such as maximum wind speed) are more relevant. Thus, our model does not accurately reflect the minute daily fluctuations of PM_{10} in our environment. Our final model does, however, provide accurate results in terms of the magnitude of dust storms and the resulting rise in local PM_{10} levels (though we are unable to determine which locations around the Great Salt Lake will be most affected).

We began with a basic model which accounted for the amount of air pollution being blown into and away from the region, as well as an early attempt to model the dust blown from the exposed lakebed. This model captured the average pollution levels well, but remained almost entirely constant. We quickly realized this was due to a failure to account for the dust blown in one day that remains in the air the following day, as well as recognizing that the air quality being blown in is not always the same as the air quality being blown out from our region. This was reflected in our second model, which included a settling factor that allowed some (but not all) dust blown from the Great Salt Lake to remain airborne from one day to the next. We also changed the constant multiplying our air quality flux in our first model to instead be two separate constants, one for the air quality entering our system and the second constant for the air quality leaving our environment. This enabled a more accurate way to model the longevity of a dust storm impacting the air quality over time, rather than as a single-day spike.

Our final model included the modifications from our second model, but greatly improved our estimation of dust blown from the Great Salt Lake. Rather than a constant amount of dust blown, we updated our model to show dust blown as a function of (1) exposed lakebed surface area, (2) maximum wind speed (averaged over an hour), (3) soil composition and (4) atomic density of our particulate of interest, arsenic. In doing so, we saw our spikes increased significantly to match the same magnitude as previously recorded data. This teaches us that the amount of dust being blown is more dependent on gusts (i.e., the maximum) of wind than on sustained daily winds. Moreover, the amount of dust blown is highly dependent upon how much dust is available to be blown and the soil composition (e.g., the soil in the Great Salt Lake has high concentrations of silt, allowing it to be blown relatively easily). Each model demonstrated sound results for their attempts; taken together, they inform us of the complexity and instability of modeling dust-born air pollutants. However, it is worth noting that there were no visible improvements from our first model to our second model.

Our model would be much more informative if we had true maximum wind speed values (rather than hourly averages) and wind directions, in order to effectively forecast the impact of a dust storm and which people would be most affected. Moreover, given more time, we would investigate the unique soil compositions throughout the Great Salt Lake to better model regional impacts, as soil composition has already been shown to be a significant factor in our model. By piecing this together, we would map out the exact geographic areas under the greatest risk for varying levels of the Great Salt Lake, as well as provide forecasts ahead of time to warn local residents of potential risks in advance.

Despite their imperfections, our findings are reliable enough to validate the rising concern of ecologists, lobbyists, and community members alike, justifying the call to restore the Great Salt Lake to its natural water level through water conservation efforts. While the impact of the exposed lakebed is already measureable, the outright loss of the Great Salt Lake would cause devastating impacts to natural and human development, adversely impacting millions of residents who live near the Great Salt Lake and make the Salt Lake Valley unsuitable for human residents until the lake is restored.

This model is a useful tool in demonstrating the current impact of these effects and serves as a warning to the potential hazards that await unless the swift decline of the Great Salt Lake is reversed.

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