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Article

Evaluating the predicted eruption times of geysers in Yellowstone National Park

Daniel J. Rhee[1], Ka Yee Yeung[2]
[1]Interlake High School, Bellevue, Washington
[2]University of Washington Tacoma, Tacoma, Washington

SUMMARY

Yellowstone National Park was the first national park in the United States and is known for its geothermal features, consisting of many popular geysers such as Old Faithful. Geysers are fascinating to national park visitors because their eruptions range from small bubbles to jets of water hundreds of meters high, and their eruptions last from seconds to hours. To help tourists plan their visits, the US National Park Service and other independent groups (such as GeyserTimes) publish predicted eruption times of popular geysers. We hypothesized that the models developed by the US National Park Service are accurate with little discrepancy from our independent analysis, due to park rangers monitoring the geysers constantly and likely adjusting their models over time according to observed patterns and changing conditions underground. In our study, we focused on Old Faithful and Beehive Geyser by downloading eruption time data and conducting statistical regression analyses using linear, exponential, and logistic regression methods, with the ultimate goal of evaluating the accuracy of different statistical models. Contrary to our hypothesis, our results demonstrated that the official predictions from the US National Park Service are variable in accuracy. Specifically, we showed that the predicted eruption times for Old Faithful from the National Park Service and our own regression models are highly consistent, while the official predictions from the National Park Service for Beehive Geyser were less precise than our predictions.

INTRODUCTION

Yellowstone National Park, was the first national park established in the United States in 1872. One of the main attractions in Yellowstone is hydrothermal vents, such as geysers. There are more than 10,000 hydrothermal features at Yellowstone, including 500 geysers, making up around half of the total geysers in the world (1). Most of the geysers within Yellowstone reside in the Upper Geyser Basin (2). The Upper Geyser Basin is perhaps the most famous attraction of Yellowstone, including the Old Faithful, Grand, and Castle geysers, with over 150 hydrothermal features in one square mile (1).

Geysers are pools of boiling water, around 93°C at the surface, which are constricted near the ground level (3). The water that geysers expel is heated from magma, as Yellowstone is an old volcano that resulted from eruptions more than 640,000 years ago (3). The underground water is prevented from freely flowing and heat builds up below the surface, while the pressure from the rocks prevents the water from boiling (3). Eventually, the underground water pressure forces the surface water out through the rocks and water is expelled through the top, thus rapidly emptying the pool of water below ground. Eruptions may last from seconds to hours, with geysers such as the Steamboat Geyser releasing a steam of water reaching over 300 feet high (4).

Geothermal features such as geysers are formed through a complex series of earthquakes that create deep underground channels which feed water into the pools, before being heated and expelled out of geysers, or boiled off in smaller bubblers. Since much of the water inflow is connected and the underground channel network is constantly evolving, it is difficult to predict how fast the heating process is and when a geyser may have enough water to erupt (5). It is near impossible to determine the pathing of the underground channels by simply sending autonomous mapping robots because of the extreme underground heat, which is why a vast majority of the Yellowstone underground piping remains unknown (6). Due to the complex and random nature of naturally formed piping, it is extremely difficult to predict the eruption time of geysers. The dynamics of geyser eruptions at Yellowstone have fascinated scientists for more than two centuries (7).

Very rarely are there geysers such as Old Faithful that erupt in highly predictable intervals, hence the name being "Old Faithful" (10). However, many geysers are predictable primarily due to a form of an indicator. Specifically, geysers such as the Beehive Geyser are predictable due to a second smaller geyser that spouts water prior to an eruption, and the Grand Geyser is predictable due to a boiling pool that bubbles prior to eruptions.

In this study, we focused on Old Faithful and Beehive Geyser in the popular Upper Geyser Basin. Old Faithful is one of the most famous and most visited geysers in the world. Old Faithful is so popular that the park runs off the "Old Faithful clock" where activities and programs are planned around the eruption of the geyser, due to its predictable nature and grand spectacle. This makes generating precise predictions of eruption times for Old Faithful important. Beehive Geyser is not the largest or grandest geyser in the park; however, it is situated on the same boardwalk as Old Faithful, and can erupt more than once a day, making it a popular location for tourists (8). In addition, the smaller geyser Beehive Indicator erupts before the Beehive Geyser, which is a different method of prediction to further diversify the methods of prediction. Interestingly, Beehive Geyser is part of a larger underground network of piping, unlike Old Faithful which is independently piped adding another layer of complexity (9).

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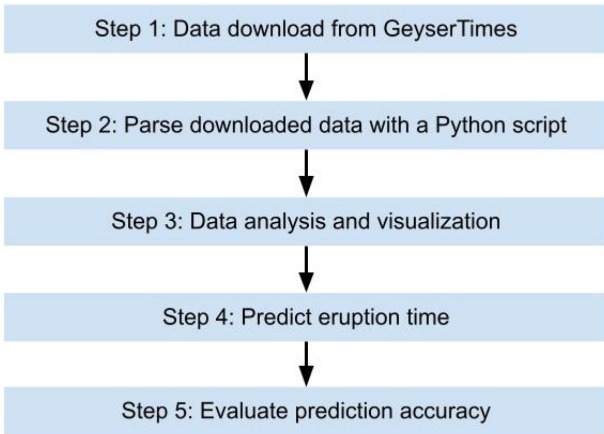

Figure 1: Summary of the steps of research procedure. The first two steps are data download and filtering of missing, incomplete and overlapping data. The third and fourth steps consist of data analysis, visualization, and statistical models. The last step is assessment in which the accuracy of model predictions is compared to the published, predicted, and actual eruption times.

RESULTS

To help tourists plan their visits, the US National Park Service and other independent groups, such as the GeyserTimes app, publish predicted eruption times of popular geysers (11). The goal of this study is to evaluate the accuracy of predicted eruption times of geysers at Yellowstone. Improving the accuracy of predicted geyser eruption times would help millions of tourists who visit Yellowstone every year to better plan their visits. This could also advance the understanding of the underground interconnections between geysers. We hypothesized that the models developed by the US National Park Service are highly accurate with little discrepancy from independent analysis. In addition, because researchers in the park rely on these predictions, the models would need to be fine-tuned to ensure that no unnecessary effort or resources are wasted in probing the geysers for variables such as temperature and acidity. Contrary to our hypothesis, our results demonstrate that the official predictions from the US National Park Service are variable in accuracy. Specifically, we show that the predicted eruption times for Old Faithful from the National Park Service and our own regression models are highly accurate, while the official predictions from the National Park Service for Beehive Geyser are less precise than our predictions.

The first two steps of our research procedure focused on data download, processing and filtering (**Figure 1**). The third and fourth steps focused on data analysis, visualization and statistical models. In the last step, the accuracy of our predictions was compared to the published predicted and actual eruption times. Specifically, we downloaded data consisting of eruption start time, duration of eruption, height of eruption, water temperature, and pH from GeyserTimes (11). This downloaded data includes missing and incomplete data. Therefore, we wrote a Python script to filter out missing and incomplete data resulting in complete datapoints for Old Faithful and Beehive Geyser (**Figure 1,** step 2).

Old Faithful has been noted to exhibit correlation between the duration of an eruption and the time between eruptions (9). The relationship between the time between eruptions (y-axis) and the duration of the previous eruption (x-axis) (**Figure 2)**. We used three types of regression methods, namely, linear, exponential, and logistic, to capture this observed relationship. Specifically, time of the next eruption is predicted using the duration of the previous eruption as the independent variable. To evaluate the accuracy of these models, we calculated the percentage of the time a prediction

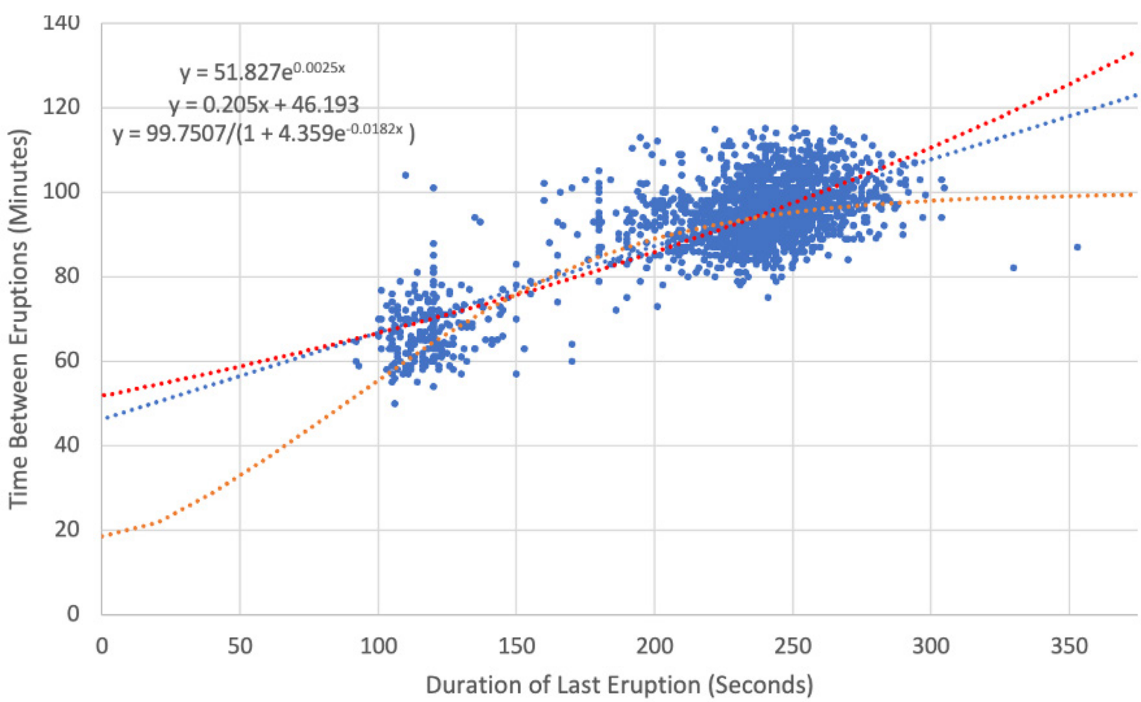

Figure 2: Relationship between time between eruptions and duration of the last eruption for Old Faithful. This graph shows three regression models, namely linear, exponential, and logistic regression, were fitted to the data points (n = 2028) downloaded from GeyserTimes. We calculated these regressions using an online Desmos graphical calculator.

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+/- Amount of minutes in each direction	Percent accurate within x min (Linear)	Percent accurate within x min (Logistic)	Percent accurate within x min (Exponential)	Percent accurate within x min (NPS)
1	12.4	12.9	5.57	15.5
2	22.8	24.9	22.6	26.2
3	33.6	35.2	33.7	36.7
4	44.2	45.6	42.9	46.7
5	52.8	53.8	52.0	56.1
6	60.1	62.5	59.5	63.5
7	68.3	70.3	67.4	70.9
8	74.5	76.7	73.4	76.9
9	80.2	82.6	79.0	82.0
10	**84.9**	**86.1**	**84.0**	**86.1**
11	89.3	89.2	87.6	88.9
12	91.9	92.1	90.9	91.1
13	94.2	94.0	93.2	92.9
14	95.3	95.4	94.9	94.5
15	96.5	96.4	96.0	95.9

Table 1: Comparison of different regression models on Old Faithful Geyser Eruptions. This table compares regression model accuracy within a certain time interval, ranging from 2 minutes (+/- 1 minute) to 30 minutes (+/- 15 minutes). The US National Park Service (NPS) target uncertainty range (+/- 10 minutes) is shown in bold.

was within a range of the actual eruption time. The percentage of time each model accurately predicted the geyser within a certain time range, starting at 2 minutes (+/- 1 minute), and going up to a window of 30 minutes (+/- 15 minutes) is shown in **Table 1**. Since a smaller time range implies high accuracy, the percentage of time each model accurately predicted the eruption time increases as the time range increases (**Table 1**).

The National Park Service attempts to have 90% of the Old Faithful predictions fall within a 20-minute range of the predicted time because they have determined this is the correct balance of reliability and range (12). This 20-minute range is shown as (+/- 10 minutes) and in bold in **Table 1**. However, none of the regression methods nor the official predictions manage to have 90% accuracy within a 20-minute window. While the National Park Service's model does provide the most accurate predictions for windows up to 16-minutes (+/- 8 minutes), the logistic regression model creates more accurate predictions beyond this time range. While the logistic regression model is comparable to the National Park Service's model within the 20-minute window, it is more accurate than the official model when the range increases. Therefore, our results confirmed our initial hypothesis that the models developed by the US National Park Service are very accurate is correct for windows up to 16-minutes (+/- 8 minutes).

Beehive Geyser was chosen as the next geyser for analysis, as it is situated near Old Faithful and is also known to be predictable (13). Beehive Geyser has an indicator known as Beehive's Indicator that creates a smaller eruption prior to the main eruption. This is because the indicator is used to relieve pressure preventing the main geyser eruption until the channel to the indicator is blocked. Different statistical methods were used to predict the eruption time of Beehive Geyser due to the existence of the indicator.

To measure if the time between the indicator and main eruption had changed over time, we calculated the difference between the eruption time of Beehive Geyser and the eruption time of Beehive Indicator for each eruption, and plotted this difference against the order of eruption, as shown in **Figure 3**. Adding a trendline onto the graph revealed a gradual decrease of this time difference with less than a minute over 50 years, thus showing little change in this difference over time. Therefore, we assume a constant time interval between

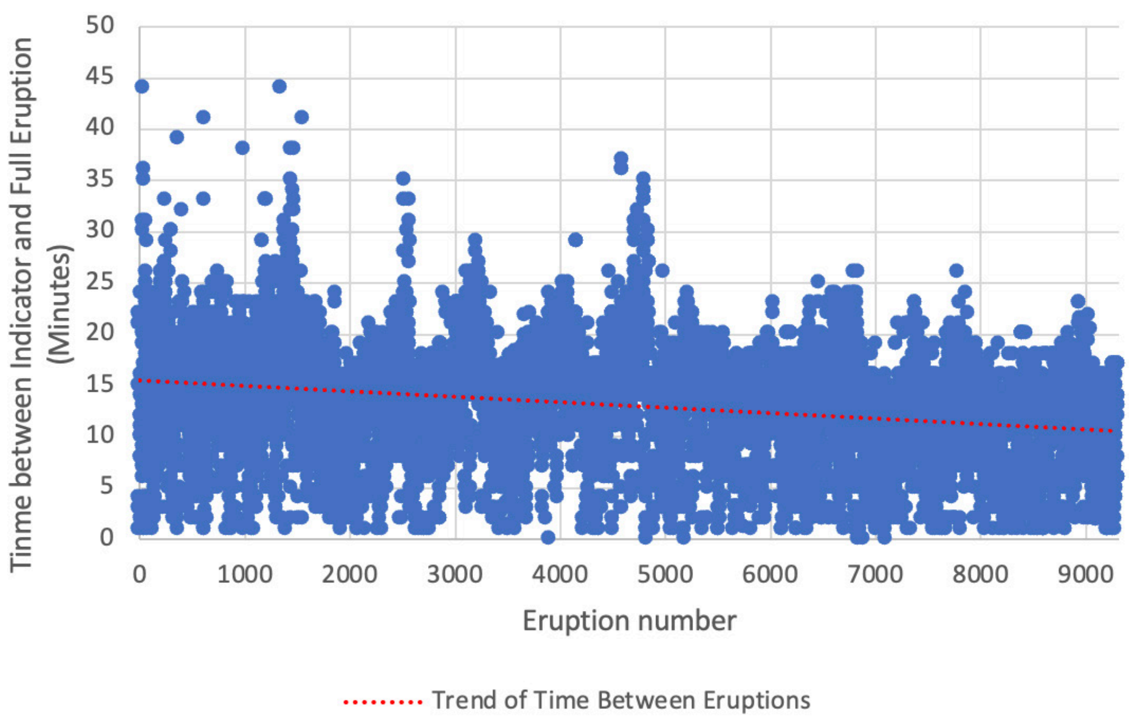

Figure 3: Difference between eruption time of Beehive Geyser and Beehive Indicator. The trendline shows a gradual decrease of eruption time between Beehive Geyser and Beehive Indicator with less than a minute over 50 years. After downloading the data from GeyserTimes, we calculated the difference between the Beehive eruption time and the indicator eruption times in minutes using Excel. These time differences were ordered against eruption numbers as shown on the x-axis.

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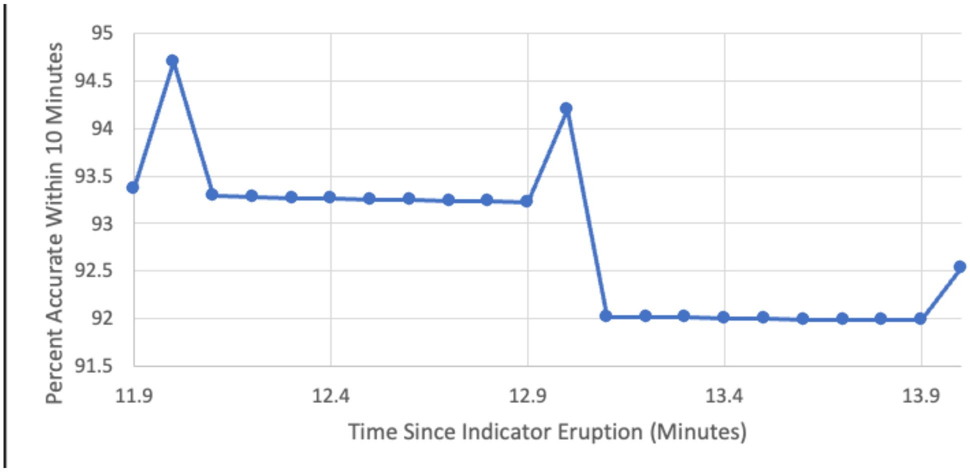

Figure 4: Accuracy for actual Beehive Geyser eruption times. Percent accuracy for actual Beehive Geyser eruption times within 10 minutes after the Beehive Indicator erupted when the constant added varied between 11.9 to 14 minutes. The optimal constant was determined as +12 minutes following the eruption of Beehive Indicator, with a peak at 94.7% chance that the geyser will erupt during this time. This constant was calculated using Excel.

the eruption of the Beehive Indicator and the Beehive Geyser. We estimated this constant by computing the mean, median and mode of the differences between Beehive eruption times and indicator times across all eruptions to determine which method would be the best predictor of this constant. The mean was 13.3 minutes, the median was 13 minutes, and the mode was 14 minutes. These are in contrast to the 17 minutes adopted by the National Park Service (13). We added these estimated constants using the mean, median and mode to the Beehive Indicator eruption time to predict the Beehive Geyser eruption time.

The percentage time that the actual Beehive eruption occurred within 10 minutes after the Beehive Indicator eruption, when the estimated constant added varied between +11.9 minutes to +14 minutes is shown in **Figure 4**. The optimal constant was determined as +12 minutes following the eruption of Beehive Indicator, with a peak at 94.7% chance that the geyser will erupt during this time (**Figure 4**). The percentage of the time each method (mean, median, mode, optimal constant) accurately predicted the geyser within a certain time range was calculated and shown in **Table 2** for each method ranging from a window of 2 minutes (+/- 1 minute) to a window of 30 minutes (+/- 15 minutes). The same target range (+/- 10 minutes) as Old Faithful (20-minute) was shown in bold. In the optimal constant estimate, 12 minutes were added to the eruption of Beehive Indicator to predict the eruption time of Beehive Geyser. Our results show that the National Park Service model of adding 17 minutes to the Beehive Indicator eruption time is 9.4% less accurate than our optimal estimate.

DISCUSSION

We analyzed the eruption times of two geysers, Old Faithful and Beehive Geyser, with available predictions from the Yellowstone National Park in this paper. Our initial hypothesis was that the predictions from the National Park Service for both geysers are likely to be accurate. However, our results demonstrated that the official predictions from the US National Park Service are variable in accuracy. In particular, the highly accurate predictions for Old Faithful from the National Park Service and our own regression models could be because it is one of the only geysers in the park that is constantly monitored, and the prediction algorithm is being adjusted constantly to ensure maximum precision. In contrast, the official predictions from the National Park Service for Beehive Geyser are less precise than our predictions that estimated the constant time to be added to the Beehive Indicator eruption time using the mean, median, mode or optimal methods.

We observed that the eruption time of Beehive Geyser was also highly predictable. The best way to ensure being able to witness an eruption is to time the indicator eruption time and then expect an eruption in around 12 minutes. On the other hand, since Beehive Indicator and Beehive Geyser are on the same boardwalk, our recommendation for tourists is to go there immediately after the indicator goes off and

+/- Amount of minutes in each direction	Percent accurate within x min (Mean)	Percent accurate within x min (Median)	Percent accurate within x min (Mode)	Percent accurate Within x min (Optimal)	Percent accurate within x min (NPS)
1	15.8	21.5	22.1	19.7	17.4
2	30.6	35.6	36.5	33.3	28.7
3	44.1	48.3	48.7	45.0	40.2
4	55.2	58.1	59.7	56.0	50.0
5	64.6	67.4	67.3	65.6	58.9
6	71.8	74.8	74.1	74.6	66.6
7	78.5	81.3	80.4	80.7	72.8
8	84.3	86.3	85.6	86.1	77.3
9	88.5	90.4	89.4	91.1	81.3
10	**92.0**	**94.2**	**92.5**	**94.7**	**85.3**
11	95.1	96.8	95.5	97.3	88.9
12	97.4	98.5	97.7	98.1	91.6
13	98.9	98.9	99.1	98.5	94.0
14	99.2	99.1	99.2	98.9	96.5
15	99.2	99.2	99.4	99.1	98.4

Table 2: Comparison of different regression models on Beehive Geyser Eruptions. This table shows the percentage accuracy within a time range for each prediction method for the eruption time of Beehive Geyser by adding the computed mean, median, and mode to the eruption time of Beehive Indicator. The US National Park Service (NPS) target range is (+/- 10 minutes) is shown in bold.

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wait for an eruption. In contrast, the National Park Service predictions generally overestimate the time interval between the Beehive Indicator and Beehive Geyser eruptions, which could lead to tourists arriving too late to see the beginning of an eruption.

The difference between the National Park Service model of adding 17 minutes to the Beehive Indicator eruption time and our optimal estimated constant of 12 minutes may be due to the definition of Beehive Geyser eruptions or inconsistent calculations of time intervals (whether counting started when Beehive Indicator erupted, or when it ended). This discrepancy could also be caused by other factors such as the eruption of the Beehive South Bubbler. However, it remains undocumented on the National Park Service's website whether there is any correlation between the eruption time and the Beehive South Bubbler.

This study focused on the Old Faithful and Beehive Geyser in the Upper Geyser Basin, as it is one of the more popular areas of Yellowstone. A limitation in the selection of geysers is due to the limitation of available data. GeyserTimes is the only source, and it provides few attributes, generally only including a time stamp, eruption duration, and eruption height (11). While it appears that the Geyser Conservancy had a database that was used to provide further data including the temperature and pH, it is no longer available for download and cannot be accessed online, thus vastly limiting the possible selection of geysers.

In terms of future work, analyzing additional geysers in the Upper Geyser Basin, such as the Castle and Grand Geyser, would further evaluate the accuracy of different predictive methods. With more data from other forms of indicators such as bubbling pools for Castle Geyser, refined predictions could allow people to enjoy the beauty of Yellowstone National Park. In addition, reducing the uncertainty of predicted eruption times would also improve the experience. Currently most predictions are measured with an uncertainty of 20 minutes, however decreasing this could allow visitors to experience even more of the park, as well as reduce over-crowding and waiting times prior to eruptions.

Despite the extensive work undertaken to predict the eruption time of Old Faithful, there has been limited analysis of the water temperature and the height of the eruption. While the height of each eruption is sometimes recorded by the National Park Service, the current data collected is limited in availability and exhibits high uncertainty of 10 meters. The water temperature of the water in the Old Faithful basin used to be recorded as well; however, this data is no longer available from the National Park Service nor GeyserTimes. Both the height and temperature could be added as independent variables in regression models to further refine predicted eruption times of Old Faithful. Like Old Faithful, Beehive Geyser's analysis could benefit from incorporating additional variables in the regression models. Data from other geysers associated with the Beehive Geyser such as the Beehive Geyser South Bubbler could also be included in the analysis to generate even more accurate predictions for Beehive Geyser.

Another area of further work is to map out the tunnels underneath the geysers. Many of the geysers are connected underground and eruption times of these connected geysers may exhibit certain patterns (3). Recently, Fagan et al. applied machine learning methods to study the pairwise interactions between geysers in the Upper Geyser Basin (14). Since challenges emerge as the paths are constantly changing, it may be also possible to use eruption data over time to learn how the underground interconnections may have changed, and thus, further advance the understanding of geysers as well as refinement of predictions.

Our results demonstrated that the official predictions from the US National Park Service are variable in accuracy. In particular, the official predictions for Old Faithful from the National Park Service are highly accurate while predictions for Beehive Geyser are less precise. Independent predictions from GeyserTimes and many other apps on both the Google Play Store and the Apple App Store provide independent predictions that may be more accurate than the official predictions from the National Park Service. It is likely that the discrepancy in their predictions has been noticed. We suggest that the US National Park Service publish more public data to allow better analysis and incorporate other independently published models into their predictions.

MATERIALS AND METHODS

We summarized the major steps of our study in Figure 1. In the first step, we retrieved all data for the geysers from the GeyserTimes database (11). While having only one source of data increases uncertainty, it is a publicly available data source recommended by the National Park Service and consists of recent data for multiple geysers. In the second step, we wrote a Python script to systematically filter the data. The script removed records that included missing data, such as the duration, as well as identified gaps in the data by using the National Park Service's range of times between eruptions to prevent the possibility of large gaps skewing the predictions.

Data download and filtering for Old Faithful (steps 1 and 2)

Using GeyserTimes, we downloaded over 175,000 datapoints of Old Faithful eruptions from 1970 onwards. Since the frequency of Old Faithful's eruptions has decreased over time due to a combination of earthquakes and vandalism, we only used data from 2010 onwards in this study (15). A typical interval between eruptions is expected to be in the range of 34 to 110 minutes, so we removed outlying datapoints and preliminary spurts by eliminating any eruptions that fell outside of this range (9). GeyserTimes included datapoints with variable precision in hours, minutes, or seconds. Therefore, we removed datapoints measured in hours, and kept datapoints in minutes and seconds to reduce uncertainty of measurements. We implemented these data filtering criteria in step 2 in a Python script. The resultant data consisted of 2,029 separate eruptions from January 2010 to July 2022.

Analysis for Old Faithful (steps 3 and 4)

Software used included Microsoft Word and Excel to create charts and filter data, and the Python programming language to reduce the size of the data and convert the data into a spreadsheet format. The Python scripts used are available in our project GitHub repository at https://github.com/DanielRhee/Yellowstone-Geyser-Prediction.

Old Faithful has been predicted as a bimodal geyser since 1959, meaning it generally erupts with two distinct durations (9). Old Faithful has been noted to exhibit correlation between

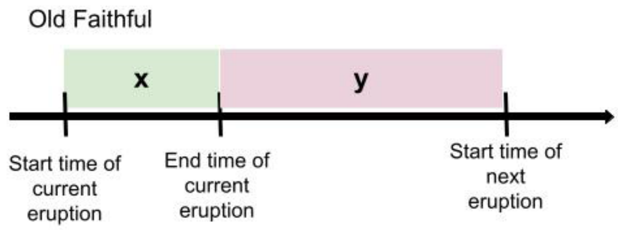

Figure 5: Illustration of regression models for Old Faithful. The independent variable (x) is defined as the duration of the current eruption. The dependent variable (y) is defined as the difference between the start time of the next eruption and the end time of the current eruption.

the duration of an eruption and the time between eruptions (9). We used three types of regression methods, namely, linear, exponential, and logistic, to generate predictions. In particular, we used a linear function to model the relationship of time between eruptions and duration of the last eruption in linear regression, and used a polynomial function with an exponent in exponential regression. Exponential regression is often used to model situations in which growth begins slowly and then rapidly accelerates. On the other hand, logistic regression uses a sigmoid function to convert predictions into probabilities that are between 0 and 1. We used logistic regression because of the bimodal nature of Old Faithful, making the eruption intervals categorical. In our regression models, we defined the independent variable (x) as the duration (difference between the end time and start time) of the current eruption. We also defined the dependent variable (y) as the difference between the start time of the next eruption and the end time of the current eruption (**Figure 5**). The detailed predictions for each eruption versus actual eruption time are available as a spreadsheet on the GitHub at https://github.com/DanielRhee/Yellowstone-Geyser-Prediction. We calculated these regressions using an online Desmos graphical calculator.

Evaluation of Old Faithful predictions (step 5)

To evaluate the accuracy of these models, we calculated the percentage of the time a prediction was within *z* minutes of the actual eruption time, where *z*=1, 2, 3…, 15. We chose this method over more traditional methods such as the root mean squared error because predicting the eruption time precisely is unrealistic, and instead a range of time better represents the uncertainty in geyser eruption intervals.

Data download and filtering for Beehive Geyser (steps 1 and 2)

Similar to Old Faithful, we downloaded data for Beehive Indicator and Beehive Geyser since 1970 from GeyserTimes (11). Beehive is known to go dormant for some periods, where it did not erupt, meaning that there is missing data. Nearly 10,000 datapoints were downloaded. Unlike Old Faithful, Beehive Geyser is not a bimodal geyser, meaning that there is no consistent time frame for the time between eruptions, nor the time between the Beehive Indicator and Beehive Geyser eruptions. Thus, no datapoints were removed as outliers.

Analysis for Beehive (steps 3 and 4)

After downloading the eruption times of Beehive Geyser and Beehive Indicator, we calculated the difference between the Beehive eruption time and the indicator eruption times in minutes using Excel. These time differences were ordered against eruption numbers (**Figure 3**). We computed the mean, median and mode of the differences between Beehive eruption times and indicator times across all eruptions to determine which method would be the best predictor of eruption time. The mean was 13.3 minutes, the median was 13 minutes, and the mode was 14 minutes. We calculated the mean, median and mode predicted eruption time of Beehive Geyser by adding 13.3 minutes, 13 minutes, and 14 minutes respectively to the Beehive Indicator eruption time. A spreadsheet showing these detailed results are available from our Github repository at github.com/DanielRhee/Yellowstone-Geyser-Prediction.

Evaluation of Beehive predictions (step 5)

Next, we calculated the accuracy of all differences between the Beehive eruption time and indicator eruption time in increments of 0.1 minutes using Excel. The percentage of the time each model (mean, median or mode) accurately predicted the geyser within a certain time range, from a window of 2 minutes (+/- 1 minute) to a window of 30 minutes (+/- 15 minutes), was calculated (**Table 2**).

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