Rain-Flood Model of Pakistan

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CS166: Modeling and Analysis of Complex Systems

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December 14, 2022

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Purpose

The purpose of this simulation is to model the water flow during the monsoon season in Pakistan and find whether the country is susceptible to floods or not. In case there is susceptibility to floods, the simulation will aim to find a solution that can reduce the occurrence of floods in the country. The reason this simulation is important is that this year, Pakistan has experienced the worst flash floods and landslides due to water flow in the past 30 years with almost 10 million children in need of life-support due to diseases, homelessness, etc (UNICEF, 2022). With the impacts of climate change becoming more prominent with each passing year, this issue needs to be addressed as soon as possible (Economist, 2022).

For this simulation, I take information from Salma et al.'s paper from 2012 which studied rainfall patterns in Pakistan. They divided Pakistan into five different zones based on annual rainfall in each of the cities so that they could be grouped. Moreover, I studied the general flood path that is followed in Pakistan taken from (UN OCHA, n.d.). Looking at the path, I took five cities from each of the zones, trying to make them as equidistant as possible while also choosing cities for which data was available in the paper or could be found through Google searches.

In the simulation, we will measure the water levels in each of the cities as well as the state of flooding which we will keep track of to see what path the flood takes in the country as well as try to counteract it. Finally, we will explore the probability of natural drainage i.e. the probability with which water is displaced within the soil naturally has an impact on the percolation threshold i.e. transition of flood from the North to the South.

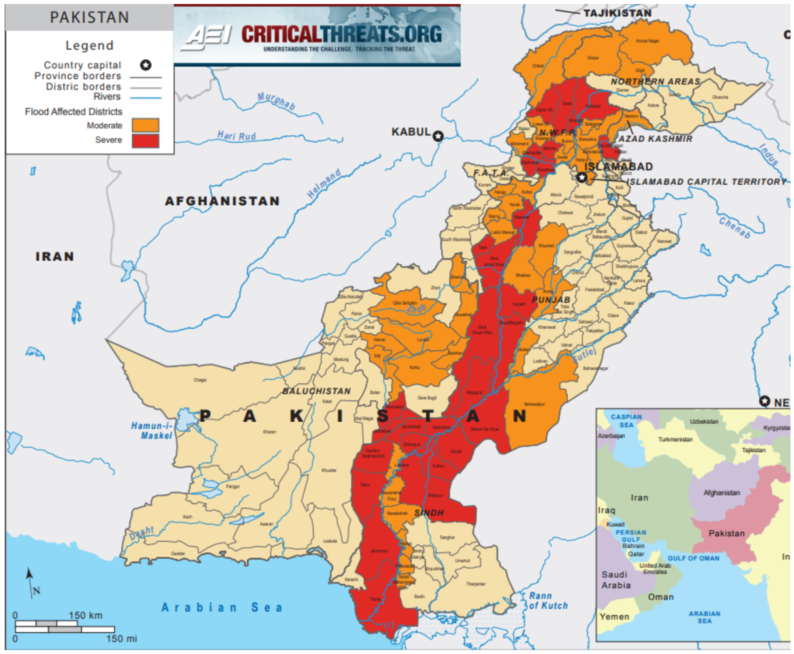

Figure 1: Flood route map of Pakistan from UN OCHA. The blue lines represent the flow of the flood from the mountains and hills of the north all the way to the Arabian sea in the south.

The Data

	Names	Altitude in meters	Annual Precipitation in meters	Rainy days as %age	Average Rainfall in meters	Soil	Flooded	Water Body present?	Barrage
0	Swat	980	0.67	50	0.022333	0	False	0	0
1	Skardu	2228	0.67	50	0.022333	0	False	0	0
2	Kohistan	1650	0.67	45	0.024815	1	False	0	0
3	Gilgit	1500	0.67	50	0.022333	0	False	0	0
4	Muzaffarabad	737	0.67	45	0.024815	0	False	0	0
5	Swabi	340	0.65	30	0.036111	0	False	1	0
6	Mianwali	210	0.65	30	0.036111	1	False	1	0
7	Gujrat	1110	0.65	30	0.036111	1	False	1	0
8	Nowshera	552	0.65	30	0.036111	1	False	1	0
9	Jhelum	234	0.65	30	0.036111	1	False	1	0
10	TTK	149	0.33	20	0.027500	0	False	1	0
11	Chiniot	179	0.33	20	0.027500	1	False	1	0
12	Lahore	217	0.33	20	0.027500	0	False	1	0
13	Bhakkar	159	0.33	20	0.027500	0	False	1	0
14	Jhang	158	0.33	20	0.027500	0	False	1	0
15	Lodhran	106	0.22	10	0.036667	0	False	1	0
16	Muzaffargarh	123	0.22	10	0.036667	1	False	1	0
17	Multan	122	0.22	10	0.036667	0	False	1	0
18	DGK	390	0.22	10	0.036667	0	False	1	0
19	Bahawalpur	118	0.22	10	0.036667	0	False	1	0
20	Karachi	10	0.29	15	0.032222	1	False	1	0
21	Sukkur	67	0.29	15	0.032222	1	False	1	0
22	Larkana	147	0.29	15	0.032222	0	False	1	0
23	Nawabshah	34	0.29	15	0.032222	0	False	0	0
24	Kashmore	66	0.29	15	0.032222	0	False	0	0

Rules of the simulation

We have set up the system using two-dimensional Cellular Automata. The rules of the system are relatively simple:

1. If the water level of the soil is below ground level, water drains away internally with a certain probability (drainage probability).
2. If water is at ground level, the soil becomes water-logged.
3. If the water level rises above ground level i.e. flooding occurs, the excess water is displaced to the nearest neighbor with the steepest descent.
4. If there is a water body e.g. river near the neighbor, only a certain percentage of water flows into the city soil, the rest drains away into the river.
5. The updating rules follow a Von-Neumann neighborhood model with water flow possible towards the North, South, East, or West but not diagonally. This rule is important as Pakistan's natural water flow system is North to South with canals being made horizontally to supply water to further away areas.

Modeling Assumptions

The model makes quite a few assumptions about certain things. The first assumption comes with modeling the system as Cellular Automata as this means that we assume the cells (cities) are equidistant from each other. This assumption might not hold in practice but I have tried my best to choose cities that are equidistant from each other. The second assumption is the choice of neighbors. The model uses a Von-Neumann neighborhood which is the best fit that I could find to the actual terrain of Pakistan which is in practice quite complex forged over years of natural water flow.

The model also assumes that the excess water will only flow to the steepest descent neighbor. Here I took inspiration from sampling methods such as MCMC samplers. Again, this might not be true as water flow to neighbors follows particular patterns based on topography but for the sake of the model, we shall assume that it flows to the neighbor with the steepest descent.

The rainfall in each city is assumed to follow a Gamma distribution centered at the mean amount of rainfall during the Monsoon season which I took from Salma et. al. The reason behind choosing a Gamma distribution is that rain as a variable is theoretically continuous and constrained to be positive even if that might not be the case in practice where most rainfall is under a certain range. The Gamma distribution has the same range as the theoretical value of rain and has a light tail meaning that big variations are less-likely though still possible. This also brings in the assumption that the rain each day is independent of the previous days. Again, this assumption is used for modeling purposes even though rain on a certain day might increase the chances of rain on the next day in practice.

Next, we consider the assumptions for the amount of water that flows from one cell to another. If a water body is present, only 30% of the water is assumed to reach the neighbor. This value is chosen by me based on my knowledge of how water bodies can help to reduce floods. Furthermore, barrages are assumed to completely block water flow which is a valid assumption in my opinion as only big floods rather than those caused by rain can overcome barrages.

With regard to the soil, it is assumed that once a city's soil is water-logged, it will remain in that state as it takes quite a few years for the soil to displace that water with air. Moreover, we assume that the natural drainage probability mentioned above is 60%, while 40% of the time, it drains a certain amount of water but not all of it. Also, if the soil is water-logged, the natural drainage probability is reduced by a factor of six, a number chosen by me to model differences between water-logged and non-water-logged soils. Finally, I assume that non-water-logged soils can absorb up to 2 meters of water while water-logged soils can only absorb 0.6 meters.

Finally, we assume that percolation only occurs vertically as compared to diagonally. As Pakistan's natural water cycle flows from the North to the South and our model only models a certain part of it, this assumption appears to be valid as the diagonal flow would take the water into neighboring countries which are beyond our concern for the sake of this simulation because these cases are not reported in real life.

Parameter(s)

Since the simulation is for a specific region, the model doesn't have a lot of parameters that can be altered. I have made the natural drainage probability a parameter for the sake of this simulation which can be changed by an expert using this later on with more knowledge than me[1].

Outputs

I keep track of various attributes for each of the cells including their flooding status which is done using a Boolean variable, and their water levels at each point to keep track of how much water the soil has. These two values used together can help us find a target threshold for percolation as that is the thing that we are trying to stop. If we find a threshold for the average water level after which Percolation always occurs, we can implement measures to keep the average for all cities below this level and ensure that the flood can be contained.

Python Implementation

For the code, I have used Object-Oriented Programming to keep track of my simulation. The two classes in the code are Grid and Cell. The Cell class keeps track of each city including its attributes and its own independent rain. Meanwhile, the Grid class has methods that allow it to find the neighbors, keep track of water flow, return values to us at any point for a certain

[1] My parameter was based on reference from (University of California, 2009)

attribute, make plots for a certain attribute, and analyze whether Percolation has occurred or not at any stage. It does this by making a grid of instances of the Cell class with each instance/object representing one city. For more details, please refer to the Appendix where all of the code is present.

For theoretical proof of how the simulation works, please refer to Appendix A.

Strategies

Since Pakistan is a developing country, the strategy that I have used is Barrages which are relatively cheap to build so they aren't a burden on the economy as well as provide extensive cover from floods. The strategy is used already in Pakistan and I suggest which cities we should enclose so as to stop Percolation.

Choosing which cities need to be protected can be done by just plotting the cases where Percolation occurs and look which route is most impacted. Let us first look at the plot for the initial conditions when flooding occurs.

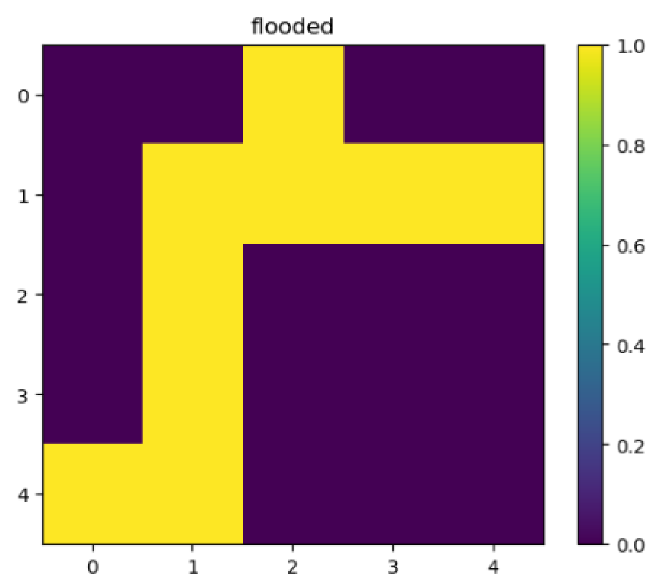

Figure 2: Color plot showing the status of flooding in cells after two months of simulation. While this specific run does not have Percolation, we can see that the second and third columns are most susceptible to it, especially the second column.

The last three rows in the grid represent the provinces which are mainly plains and easy to build on. Keeping this in mind, the strategy that I have implemented is introducing barrages in the last three rows of the second and third columns of the grid to look at how that impacts percolation.

Results

Below, I will compare two kinds of histograms for both the current conditions and the new strategy.

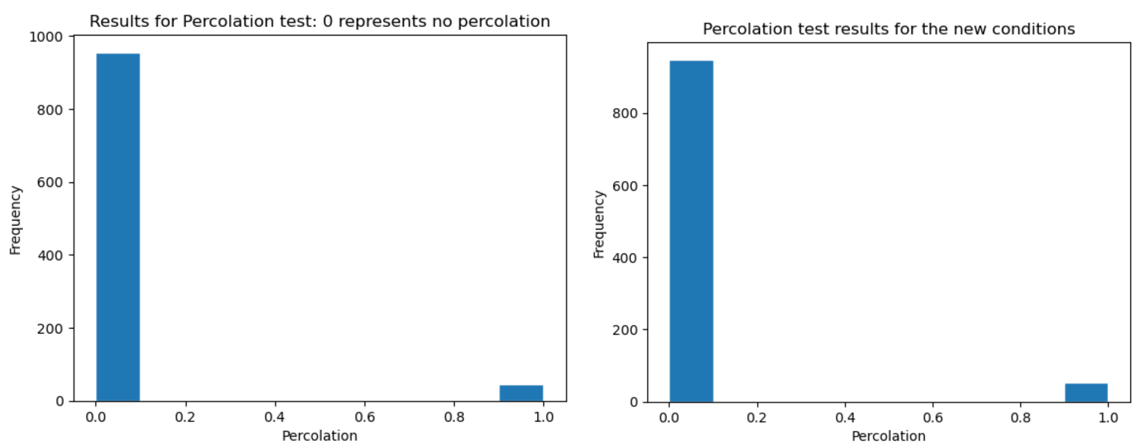

Figure 3: Histograms representing percolation in both conditions, current conditions on the left, after barrages are built on the right. There is almost no noticeable difference between the two conditions.

Next, let us compare the average water levels for the soil at the end of the simulation.

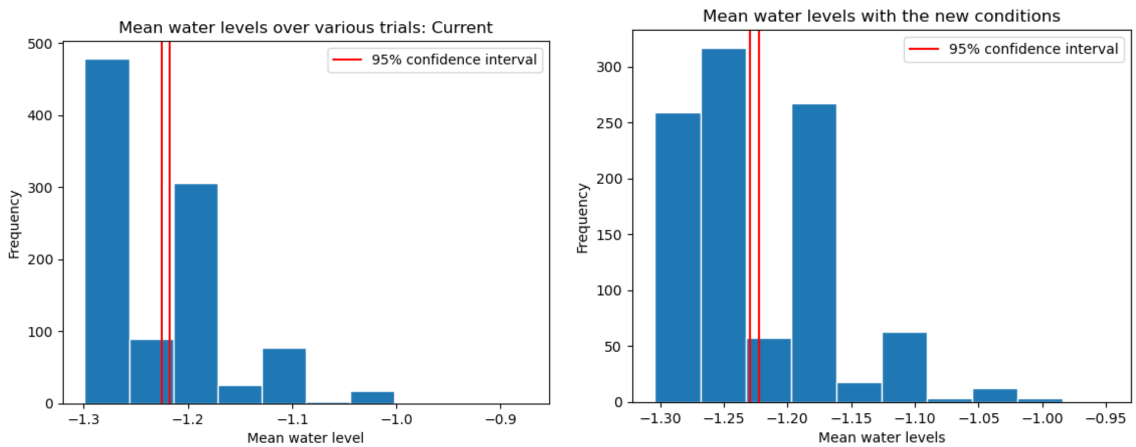

Figure 4: Histograms showing average water levels in the soil at the end of the simulation. We can see that the strategy has managed to contain the water within cities as shown by more values being closer to 0 as compared to the current conditions.

Looking at both the plots above, it is hard to arrive at a conclusion as to whether the new strategy has helped improve the situation or not. Finally, we will compare the two metrics with respect to one another to see if there is a relationship between them.

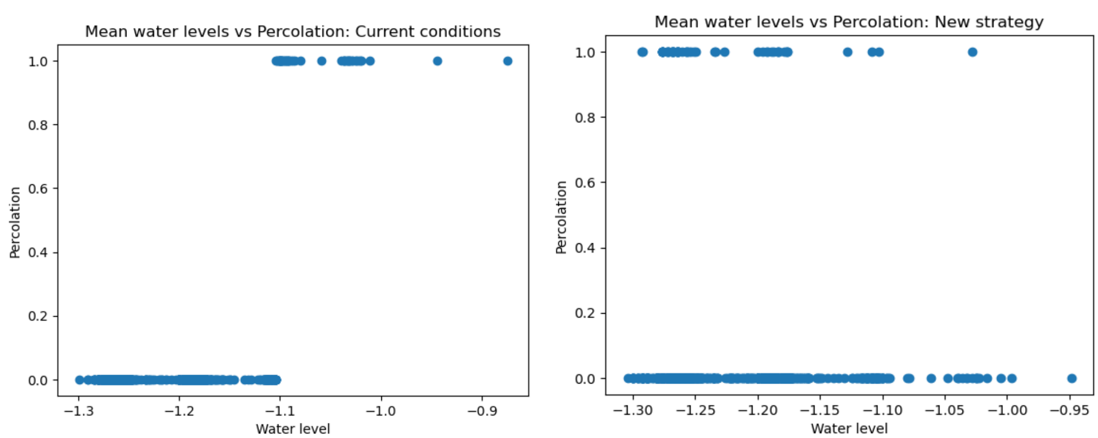

Figure 5: Scatter plots showing trends of how Percolation changes with average water levels in both cases.

As we can see in the figure above, currently we have a threshold appearing clearly for an average water level after which Percolation occurs. However, for the new strategy, there is no evident threshold indicating that the Percolation occurs only because of random occurrences rather than certain conditions being met. This is because the water is contained and Percolation is only occurring in the rare cases that each city on its own is flooded by the amount of rainfall it is receiving which is something outside of our control.

Based on the results above, my advice is to build barrages along the following cities: Chiniot, Lahore, Muzaffargarh, Multan, Sukkur, Larkana. These barrages should help to stop floods from flowing all across the country and actually enable us to contain them which could lead to more concentrated efforts in these particular cities.

Uncertainty

If we look at the 95% confidence interval for the average water levels, the intervals represent how certain we are of the results. The closer the intervals are, the lesser the uncertainty.Here, the intervals for the old strategy are: [-1.2249, -1.2175]. Meanwhile, the intervals for the new strategy are: [-1.2291, -1.2220]. The small size of the intervals show that our simulation is quite stable and we can be quite confident in our results since the intervals are quite narrow. Running for more steps might bring these intervals down even more and we could do this given the availability of computational resources.

References

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Appendix A

Let probability of having a lower altitude neighbor be p

If we have only one cell, the probability of flow across that cell is 1

If we scale this to a $2x2$ grid, we have 4 possible situations. We can have any number ranging from 1 to 4 for lower altitude neighbors in the grid.

If we have 1 lower altitude neighbor, we can't percolate. Hence, we can ignore these.

If we have 2 lower altitude neighbors, we have 2 cases of percolation, shown below.

If we have 3 lower altitude neighbors, we have 4 cases of percolation, shown below.

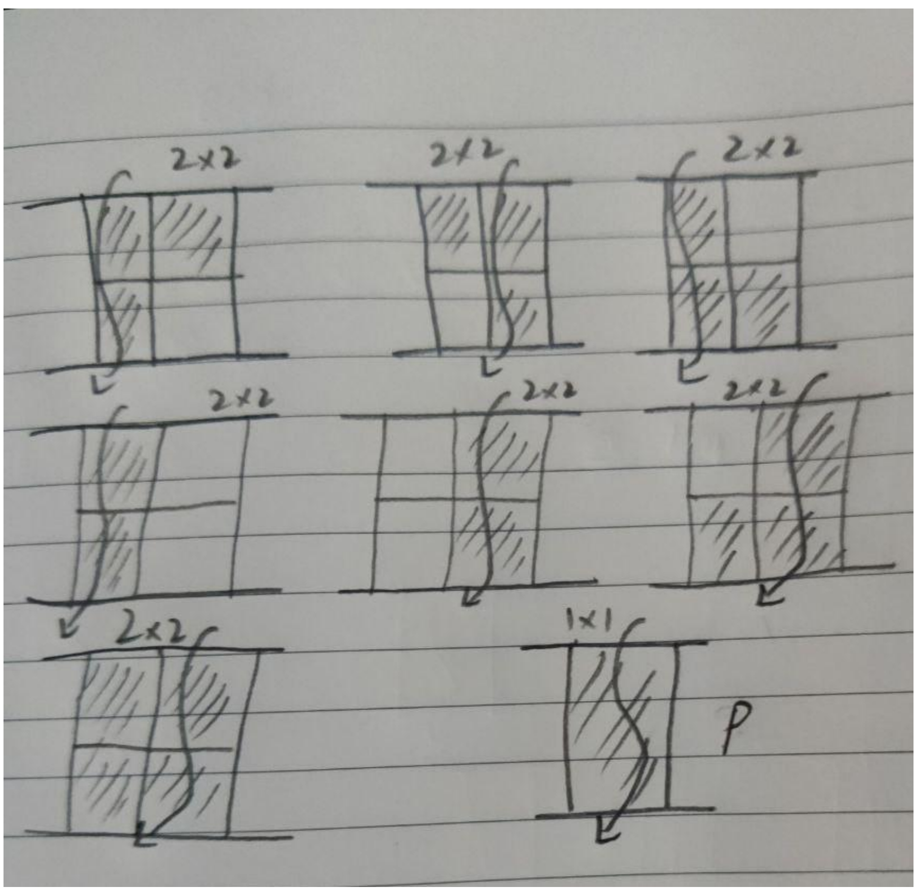
If we have 3 lower altitude neighbors, we have 1 cases of percolation, shown below.

This gives us the equation:

$$p_2 = p_1^4 + 4p_1^3(1 - p_1) + 2p_1^2(1 - p_1)^2$$

Generalizing this to bigger scales, we get

$$p_{s+1} = p_s^4 + 4p_s^3(1 - p_s) + 2p_s^2(1 - p_s)^2$$



We can make a cobweb plot, in which the intersection points will indicate the values of **p** where the threshold is possible.

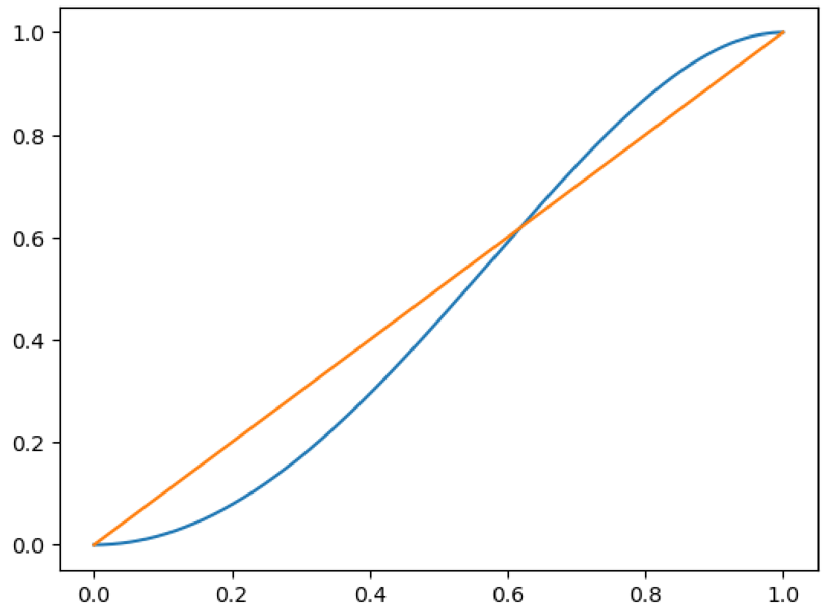


Figure 6: Cobweb plot showing potential percolation thresholds. We see that the intersection point is at 0.60.

If, for the entire grid, our probability of having a lower altitude neighbor is higher than 0.6, we should see that percolation is possible. For our simulation, this is 0.88 which means that percolation is possible.

However, our simulation has a lot of randomness which comes from various sources such as probability of rain, probability of water body being present, probability of barrage being present etc. This leads to a variation in our results. However, because percolation is possible, we see that there are still instances where we see flood water flowing across an entire column. This would not have been the case if our probability had been lower. Unfortunately, this is hard to prove because designing a grid with that exact probability is not feasible.

HC & LO Appendix

#PythonImplementation: I implemented a working simulation making sure that my model follows certain rules and then displayed the code as well. I displayed all the relevant plots along the way and made sure to use appropriate data structures as per my requirement. Moreover, I also implemented Object-Oriented programming in a very replicable way with a dataset.

#CodeReadability: I included docstrings and in-line comments for all of my code and made sure to label what is happening so that a person can read and understand it. Moreover, I also included parameters and attributes for all the methods and classes respectively so someone can further use my code. Finally, I also followed a consisten coding style so that a person doesn't get confused when reading my code.

#EmpiricalAnalysis: I ran the simulation 1000 times for each setting with each trial having 60 updates of its own to show the updates per day over the course of two months of Monsoon that Pakistan experiences. I made plots of the measurements and showed how they vary over time. Moreover, I also reported confidence intervals along with comments on what they mean, how wide they are, and how their width can be reduced.

#Professionalism: I used all the APA guidelines, and presented my report in a professional manner with suitable figure captions. I prepared my Jupyter notebook in a properly formatted manner and then merged it with my PDF so that it is easy flowing and easily referred to. Before submitting, I restarted my Kernel and ran all my cells to make sure that my code is running without errors.

#Modeling: I designed a model based on the given rules and conditions along with incorporating the region of interest by collecting data and then including that in my model. I outlined the assumptions and rules of my model clearly along with assessing the validity of these assumptions.

#TheoreticalAnalysis: I included a Renormalization Group Analysis from which I derived a percolation threshold. I showed the mathematical derivation along with a small explanation of what Renormalization Group Analysis gives us. Moreover, I showed a visual representation of how we get to our equation. Finally, I made a cobweb plot to find the threshold probability and then compared this to the value from our simulation to prove that my simulation is working correctly.

HCs

#Professionalism: I followed nuanced conventions of APA formatting including but not limited to double spacing, Times New Roman formatting in a 12 Font size, proper indentations, page numbers included in headers, and Figure captions being a font size smaller than 12.

#ConfidenceIntervals: I calculated the confidence intervals for the average water level across the grid at the end of the season and interpreted this. I also commented on the width of the interval along with how it can be reduced. Finally, I made an automated function that calculates the confidence intervals for any given list.

#Audience: While writing the paper, I kept in mind my audience and tried to tailor my explanations to someone who was reading the paper as a student of the class but at the same time making sure that someone with not as much knowledge would be able to understand it as well. This allowed me to make sure that my paper flows smoothly and conveys the exact meaning that I want it to a broader audience.

#Modeling: I clearly identified the assumptions and rules of my model and implemented a working version of it as well. I also evaluated the validity of the model using various sources and made sure to justify any constant that I was using either from a paper or clearly mentioning that this came from my knowledge and should be changed by a person more knowledgeable in the field than me.

Code Appendix