MSDS 460-57 Homework Assignment 4: Monte Carlo Simulation Reed Ballesteros
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May 22, 2022 Lena Lu
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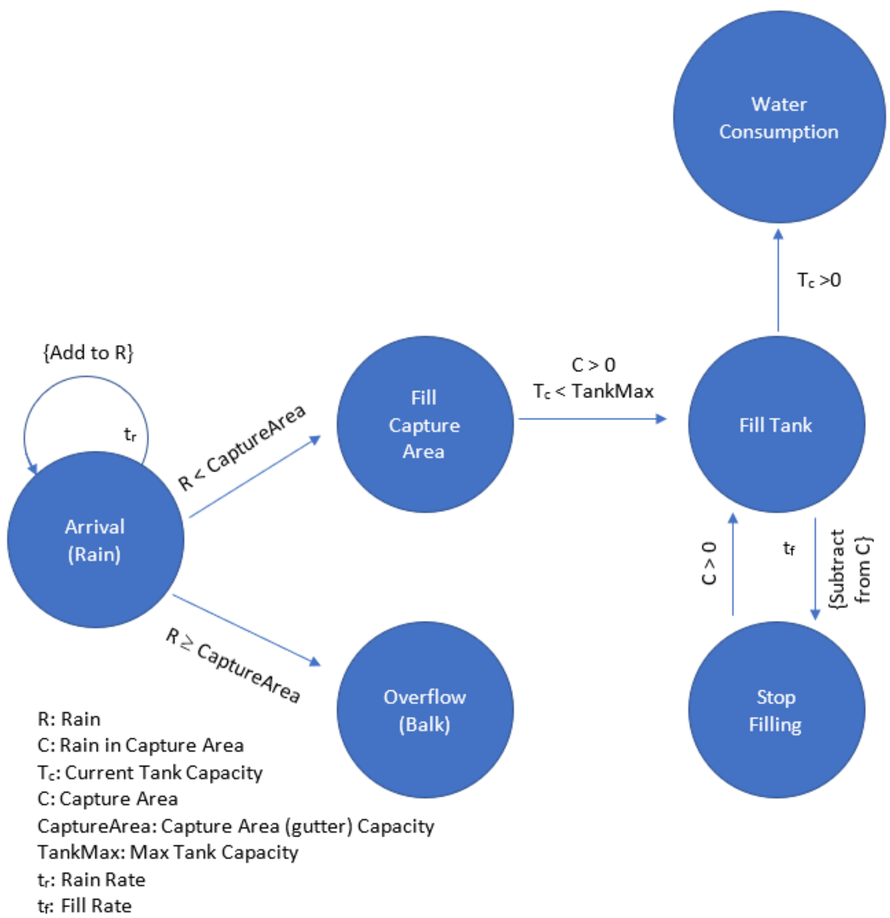
**1.** The flowchart below represents the rainwater harvesting and recapture system for our Monte Carlo simulation. Inputs begin with the arrival of rain in the capture area, then branch to two separate events, either continuing to fill the capture or overflow. The filling of the roof capture (gutter area) then moves to the next event, filling the tank. The capture area will fill the tank only if the current tank capacity is less than the tank max; therefore, the rain will overflow out of the capture area if the tank is at max capacity. Once it fills the tank, water consumption events are restricted to the amount of tank water available and reduce the tank water level. The tank level cannot be negative, so usage requirements exceeding supply will result in a shortage computation.



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Our model begins with the computation of rainfall collection. Rainfall is measured in inches, and the amount of rain collected for a given month is based on the square footage of the capture area. $7.48\ gal = 1\ ft^3$ so $7.48\ gal\ /\ 12\ in = 0.623\ gal/(ft^2 in)$. Our roof capture is $3000 ft^2$, meaning it can capture 1,869 $gal/in$. We expect the capture to be 90-98% efficient; therefore, our final monthly capture computation becomes:

$$efficiency\ \%\ *\ capture\ area\ (ft^2)\ *\ precipitation\ (in)\ *\ 0.623\ gal/(ft^2 in) = gal$$

Note when the tank fills to the max capacity of 25,000 gallons, the water in the capture area can no longer fill the tank and is represented in our model as overflow. In contrast, water usage exceeding tank water level is represented by a shortage computation. We use the Monte Carlo simulation for 1,000 simulations based on a random sampling of the following three variables: inches of rainfall from the Texas water CSV data (method explained in detail in the section below), efficiency multiplier of uniform distribution between 90-98% to account for variations in the severity of downfall, and the uniform distribution of usage amount between 4,000-5,200 gallons.

**2.** Since the monthly rainfall data only includes 2000 through 2011, we are limited in the amount of the population for sampling. We used the bootstrap sampling method by sampling each month with itself and its shoulder months (the month before and after the current month) for a 50% sample with replacement. The current month is weighted twice as much as its shoulder months to simulate variability. For example, for April's population, March and May are weighted at 50%. The population becomes normalized due to the central limit theorem. We then simulate precipitation for each month using random number generation from a normal distribution with mean and standard deviation equal to that of the bootstrapped samples. Our resulting first table below shows the statistics by month. As expected, the largest rainfalls occur

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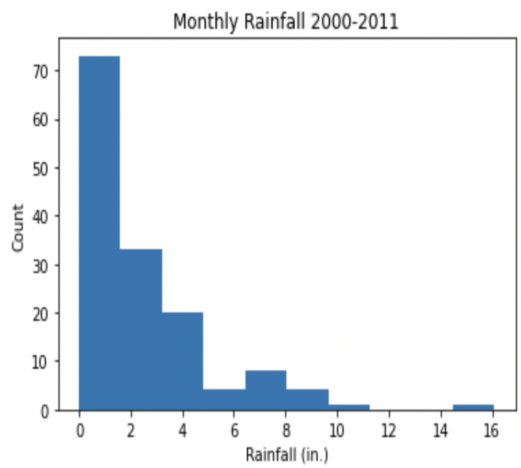
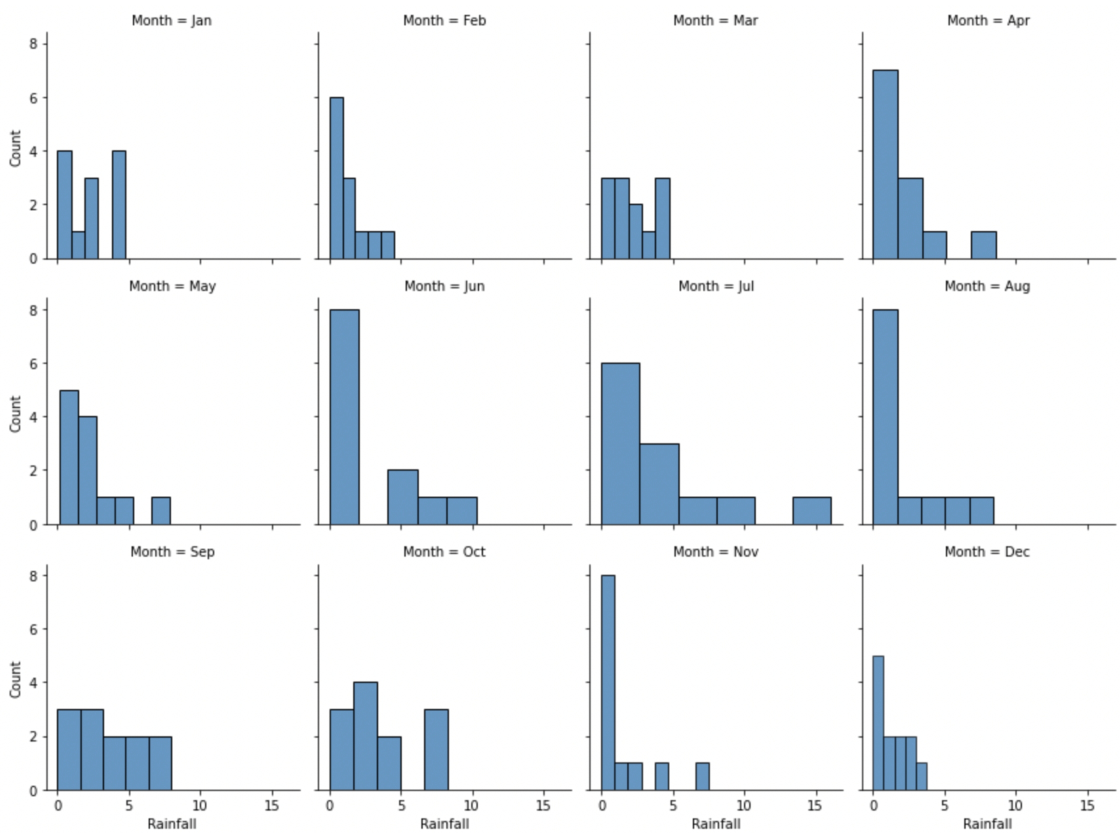
during non-winter months. The second bar plot shows the total distribution of rainfalls in inches, and the third breaks it down by months.

| Month | mean | median | std | q75 | q90 | max |
|---|---|---|---|---|---|---|
| Nov | 1.434167 | 0.550 | 2.238195 | 1.3300 | 3.784 | 7.50 |
| Feb | 1.306667 | 0.740 | 1.381398 | 1.9900 | 2.758 | 4.51 |
| Jun | 2.525000 | 0.750 | 3.429539 | 4.2425 | 7.427 | 10.28 |
| Aug | 2.098333 | 1.015 | 2.824136 | 2.6500 | 6.088 | 8.43 |
| Dec | 1.260000 | 1.045 | 1.259928 | 2.0900 | 2.663 | 3.74 |
| Apr | 2.047500 | 1.320 | 2.454310 | 2.7900 | 3.966 | 8.58 |
| May | 2.410833 | 1.780 | 2.133054 | 2.8700 | 4.532 | 7.85 |
| Mar | 2.163333 | 1.950 | 1.592125 | 3.1525 | 4.264 | 4.75 |
| Jan | 2.202500 | 2.250 | 1.718933 | 3.9800 | 4.100 | 4.75 |
| Oct | 3.360833 | 2.610 | 2.931368 | 5.4825 | 7.245 | 8.30 |
| Jul | 4.036667 | 2.655 | 4.625535 | 4.6850 | 8.348 | 16.10 |
| Sep | 3.427500 | 3.025 | 2.483620 | 5.0400 | 6.714 | 7.94 |



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**3.** We utilized Pandas to make a dataframe of our simulations. We iterated through 12 months for 30 years 1,000 times to create the following columns: iteration number (1,000 iterations total), year, month, starting fill, monthly usage, monthly capture, ending fill, shortage (ending fill is less than zero), overflow (ending fill is greater than 25,000 gallons), efficiency multiplier, and the precipitation for that month. We wrapped our simulation into a function with four input parameters for easy variability (number of iterations, tank max capacity, initial water level, and rooftop square footage). For each monthly iteration, we used a random number generator (random.uniform) for our usage between 4,000 to 5,200 gallons and our efficiency multiplier between 0.90 to 0.98. Essentially, our program will start with our initial water level, decrease with every monthly usage, increase with monthly rainfall, and end with our ending fill. Our starting fill of the next monthly iteration is the ending fill of our previous iteration. We prevented our ending fill from going below zero since we cannot have negative water levels. In addition, our tank capacity cannot exceed our tank max capacity input. We observe where we go below zero water levels, which helps us determine a more efficient water harvesting system, as explained in our section below in detail.

**4.** Our simulation shows the rancher's current dimensions resulting in several iterations where water usage outpaces water collection. In the aggregate time series chart of average ending fills per month and year (Figure 1), the average dips very close to zero, and the likelihood of not having enough water occurs ~36.5% of the time. With the default size capture area, the monthly average fill never increases beyond its initial level across all 30 years. Therefore, the rancher needs to collect more water to reduce the number of shortages, which means focusing on the capture area rather than the size of the tank. When increasing the capture area to 3500 cubic feet while keeping the other parameters the same, shortages decrease to less than 0.1% of months (Figure 2). However, the tank frequently reaches its capacity with this roof size and overflows 13% of months. Increasing the tank size with the larger roof may be beneficial to protect against drought. We ran one final simulation with the tank size increased to 30,000 in addition to the increased roof area. This simulation yielded a similar probability of a shortage and a marginally smaller decrease in overflows, though overflow amounts did decrease in size, so the rancher could get away with an even larger tank depending on its cost.

**5.** We considered the effects of climate change, such as droughts similar to 2008, and considered increasing the size of the roof capture to 3,500 square feet and the max water tank capacity to 30,000 gallons since this will create a reserve for at least six months of no water collection (Figure 3). This suggestion depends on the feasibility and cost of increasing a tank. An August 2016 report from the United States Environmental Protection Agency (EPA) suggests that climate change will most likely increase the quantity and intensity of rain in Texas as the rainfall has increased 15% during the rainy season over the last 50 years and is expected to continue to increase. To simulate this, we increased rain by 10% and reduced efficiency by 5% (85-93%) to account for the rainy season's increased severity (June-October). With the original setup, we found that as the initial model, the capture area is still too small, and the 10% increase does not result in a sufficient increase in the storage of water (Figure 4). To more realistically model climate change, the simulation could gradually increase the amount of rainfall over time instead of immediately starting with a 10% increase. Additionally, more research to determine actual changes to rainfall and collection efficiency would be beneficial.

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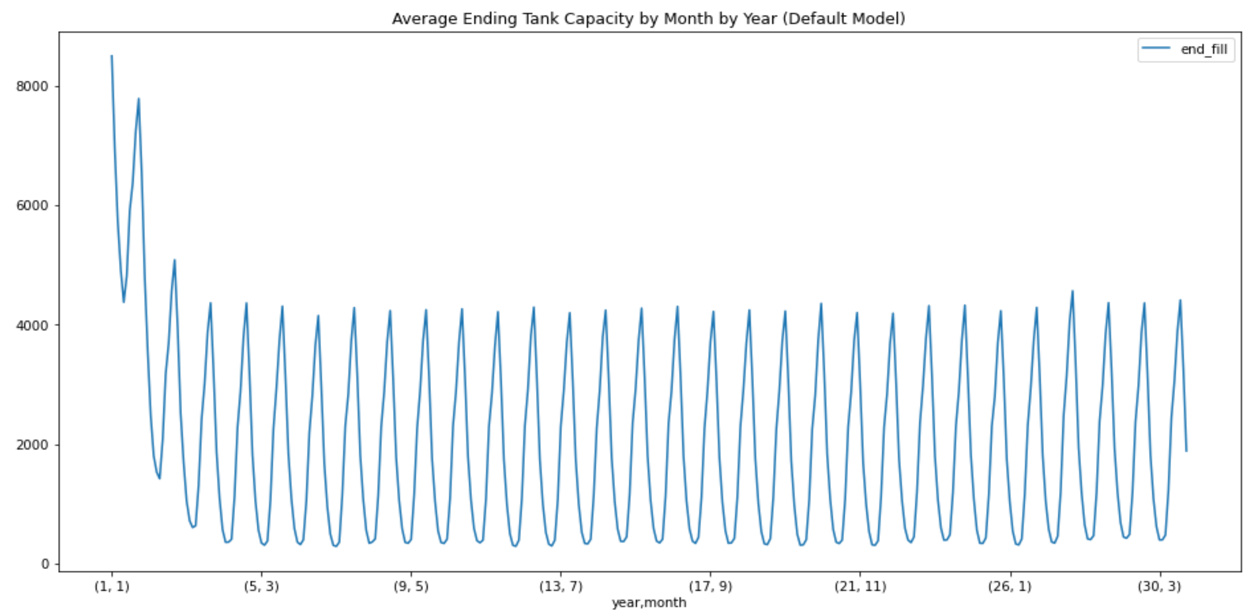
## Appendix:

### Figure 1




### Figure 2:

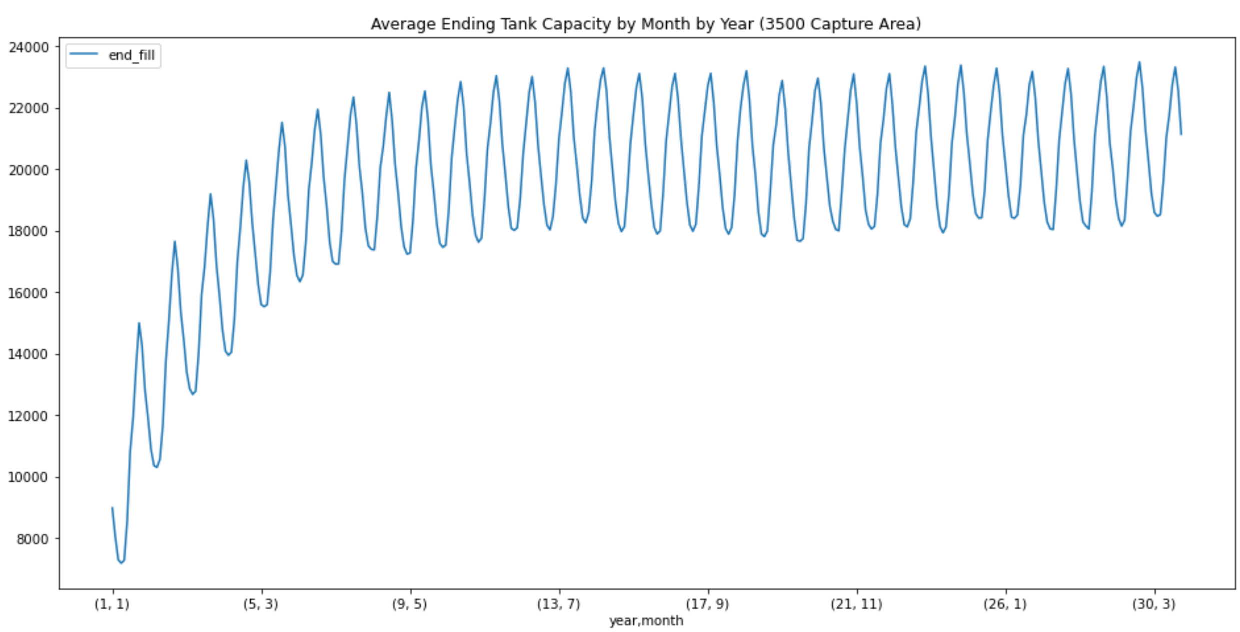


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**Figure 3:**

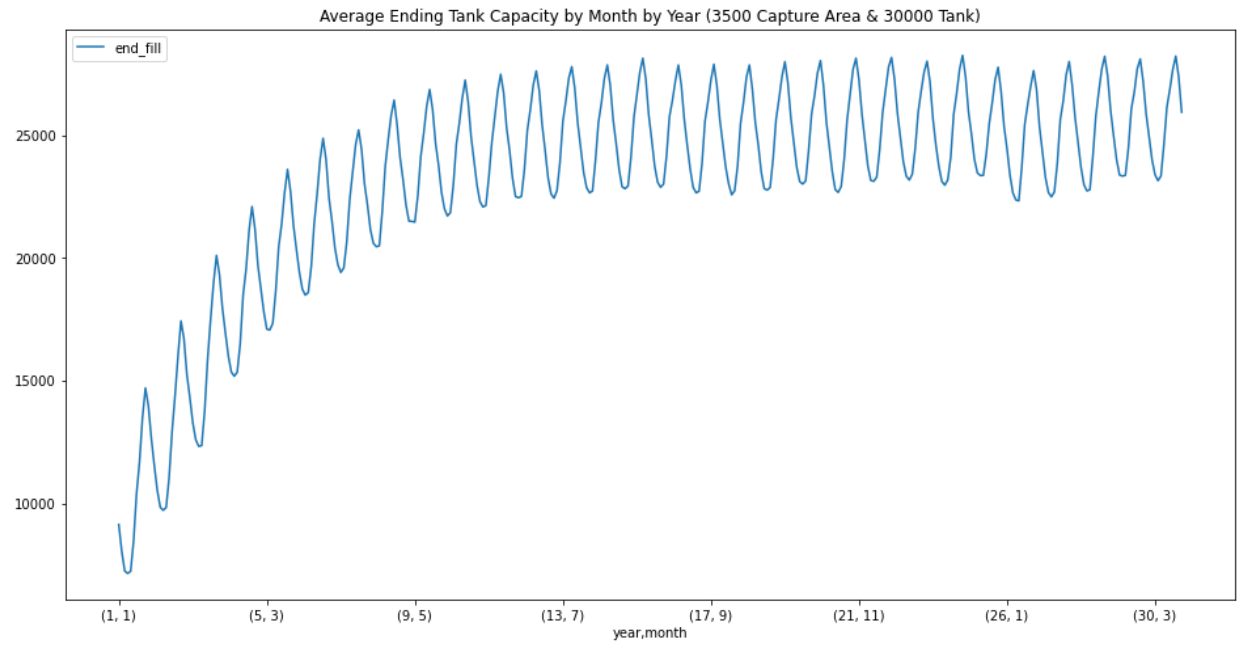


**Figure 4:**