A Geodesign Analysis for Rainwater Harvesting in the Corpus Christi Downtown Area with 3D Roof

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Key Words: Corpus Christi, Rainwater Harvesting, Toilet Flush

Background Introduction

Limited supply of water resources has become a more and more critical issue in urban development. While naturally available water supplies are expected to remain stagnant or decline in the future, population growth demands an increase in water to support every sector of our society. During last year's drought, the the worst one in Texas's recorded history, nearly 100 km^3 of water is lost(Maidment, 2012). Thus alternative source of water supply is needed to ensure community development and economic growth. Rainwater harvesting, an ancient technique which could date back to 6,000 years ago in China is enjoying a revival in popularity as a new source of water supply(Gould & Nissen-Peterson, 1999). In central Texas alone, more than 400 full-scale rainwater harvesting systems have been installed and gained great benefit as a means of conserving water(TWDB,2005). In this case, we will look into Corpus Christi downtown to measure the potential of rainwater harvesting in this urban area.

Corpus Christi, Texas is a growing city consumes vast amount of water. As the fifth largest port of the States, Corpus Christi's population is projected to grow from 326,058 in 2010 to 470,523 in 2060(TWDB,2011) as shown in Figure 1, while projected water demands of the city is to grow from 2.02×10^{10} Gallon to 2.83×10^{10} Gallon(TWDB,2011) as shown in Figure 2.

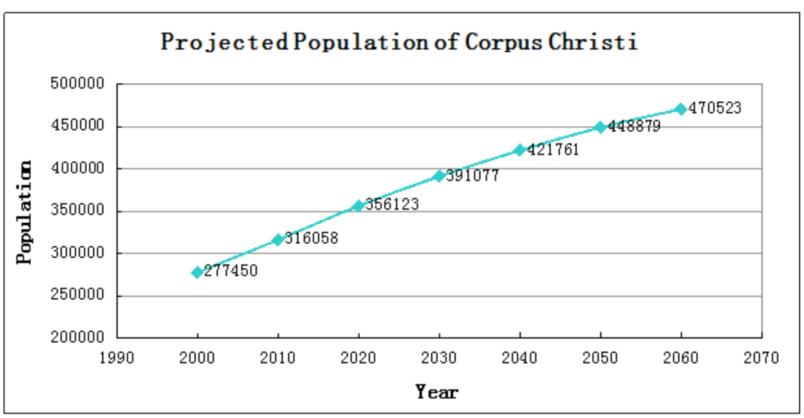

Figure 1 Projected Population of Corpus Christi

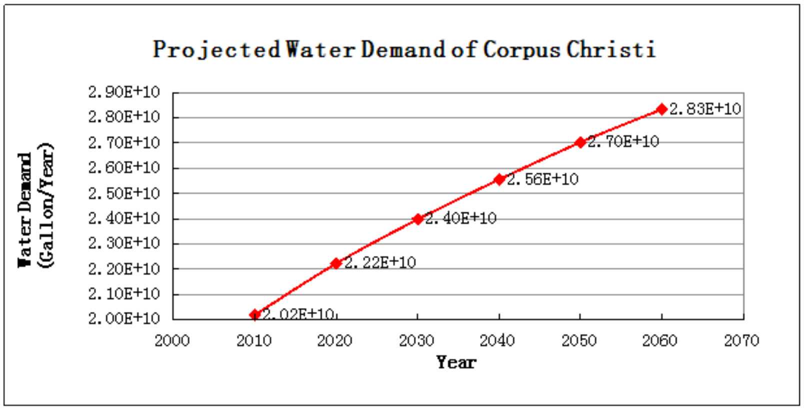

Figure 2 Projected Water Demands of Corpus Christi

However, conventional water supply is facing critical decline. Over the past decades, water level in lake Corpus Christi, the main source of the city's water supply declined as is shown in Figure 3(TWDB, 2012) and Figure 4(TWDB, 2012). Thus, additional water source such as rainwater is needed for the development of Corpus Christi. In this report, I will measure the feasibility of using rainwater as toilet flush water source for commercial buildings in downtown Corpus Christi.

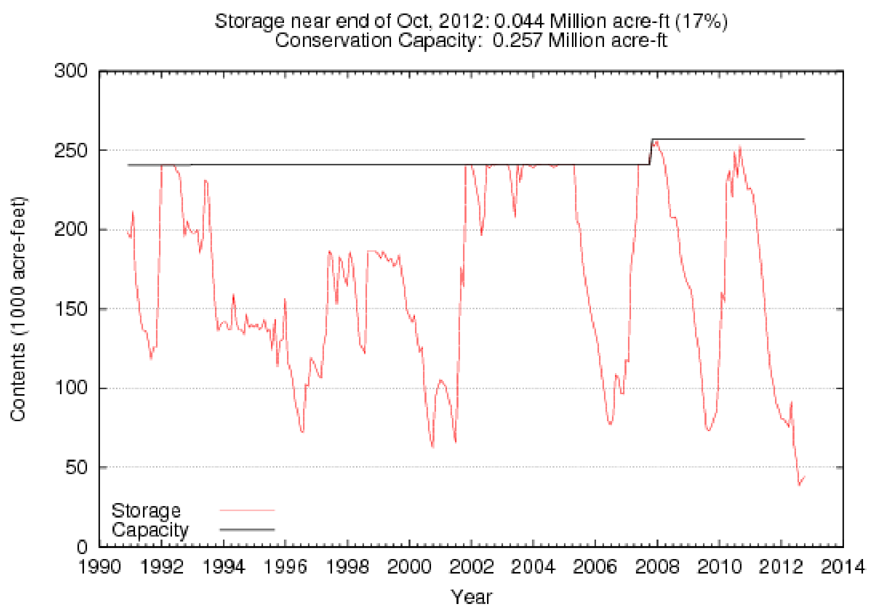

Figure 3 Lake Corpus Christi Storage(TWDB, 2012)

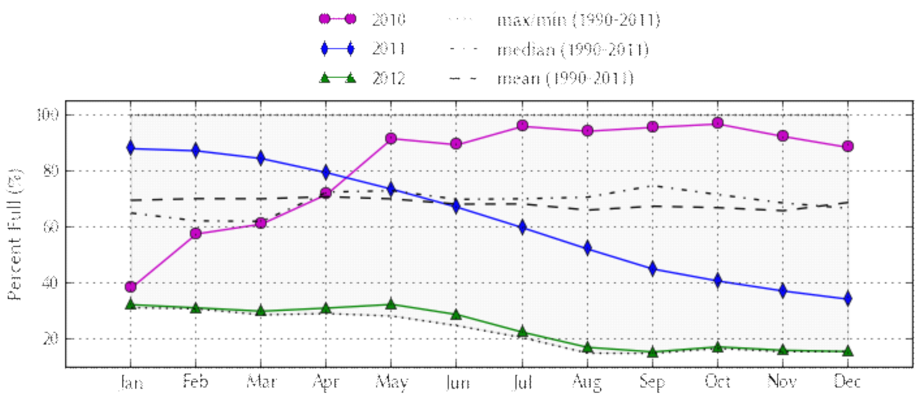

Figure 4 Water Level of Lake Corpus Christi(TWDB, 2012)

Main Data Sources

3D roofs model in downtown corpus Christi, 237 buildings in total, provided by CyberCity3D, Inc.

Monthly rainfall data for Corpus Christi, from The Texas Manual on Rainwater Harvesting, TWDB, 3rd Edition, 2005

Toilet water need data, from Residential End Uses of Water, AWWA, 1999

Calculation Methodology.

Method overview

In order to examine the potential of rainwater harvesting in downtown Corpus Christi. Calculation based on water catchment area, monthly rainfall data, toilet water use will be conducted to get the cistern volume for each building. Cistern volume will be used to judge the feasibility of rainwater use for each buildings as the highest cost of most rainwater harvesting system is the storage cistern(TWDB, 2005) and huge cisterns are unacceptable in downtown areas.

Rainwater captured

The collection surface is the footprint of the roof(TWDB, 2005). In this study, collection surface area is the given in the field of Surface_Area_Total_XY in unit of m^2.

As suggested by the texas manual on rainwater harvesting, two different estimation of monthly rainfall are commonly used: average rainfall and median rainfall. Average annual rainfall is calculated by taking the sum of historical rainfall and dividing by the number of years of recorded data. Median rainfall is the amount of rainfall that occurs in the midpoint of all historic rainfall totals for any given month. Median rainfall provides for a more conservative calculation of system sizing than average rainfall as the median value is usually lower than the average value since large rainfall events tend to drive the average value higher. For planning purposes, median monthly rainfall can be used to estimate water availability to a reasonable degree of certainty(Krishna, 2001). In this report, I will use median rainfall data recommended by the texas manual on rainwater harvesting, as is shown in Table 1 and Figure 5.

Table 1 Month Rainfall of Corpus Christi(TWDB, 2005)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Median	0.99	1.36	0.78	1.39	2.70	2.43	1.04	2.64	4.00	2.60	1.34	0.90
Average	1.54	1.85	1.36	2.03	3.12	3.16	1.80	3.28	5.21	3.50	1.57	1.59

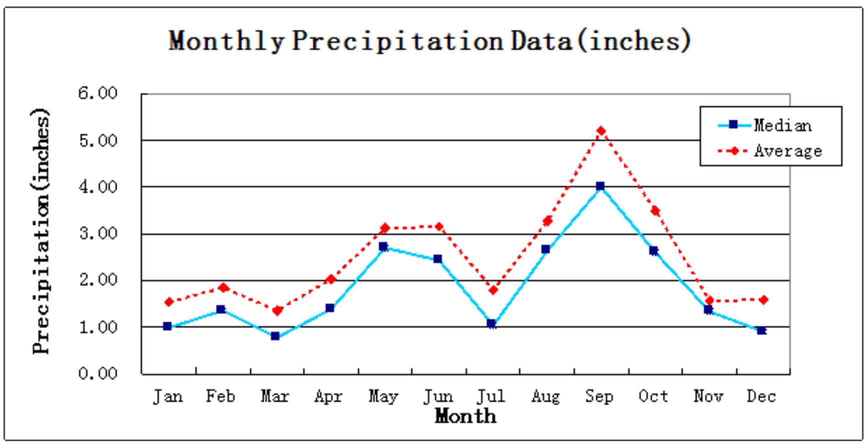

Figure 5 Monthly Rainfall of Corpus Christi(TWDB, 2005)

Then we could calculated the rainwater captured for each month. By open attribute table of the given layer, we could exert field calculator by using the equation below:

$$\text{Rainwater Captured}_{m^3} = \text{Rainfall}_{\text{inches}} \times \text{Collection Surface Area}_{m^2} \times 0.0254_{\text{m/inch}} \times \text{CollectionEfficiency}$$

In this equation:

Rainwater Captured: Rainwater captured for the given month(m^3)

Rainfall: the median rainfall for each month(inch)

Collection Surface Area: value in the field of Total_Surface_Area_XY(m^2)

0.0254: Unit conversion, 1 inch = 0.0254 m

Collection Efficiency: 0.75~0.90, we use 0.85 here

For example, in the case of the building of objectID = 1, EGID = cc00000011 as shown in Figure 6, rainwater captured for the January can be calculated as:

$$\text{Rainwater Captured}(m^3) = 0.99(\text{inch}) \times 109.19(m^2) \times 0.0254(\frac{m}{\text{inch}}) \times 0.85 = 2.334(m^3)$$

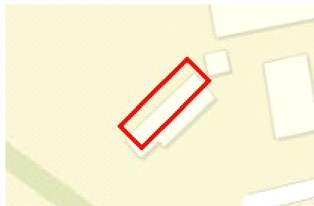

Figure 6 Building with ObjectID=1

By conducting the same process of calculation for all 237 buildings over all 12 months, we could get the rainwater captured for each building for each month. For example, a map of rainwater captured for all the buildings in September is shown as Figure 7.

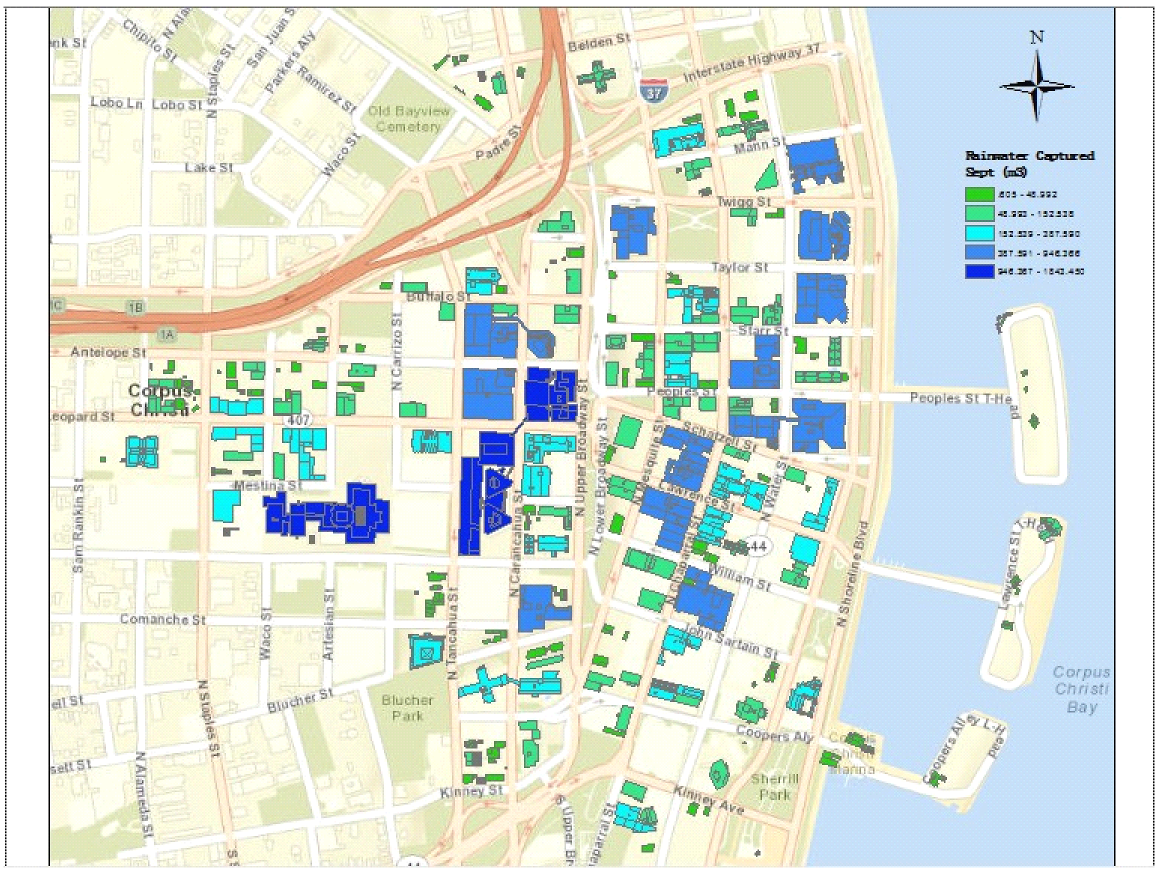

Figure 7 Rainwater Captured in September

Water Needs

We also need to calculate the water demands for toilet flush in each buildings. In this study, I will carry out this calculation based on capita counts. For each capita, daily toilet flush water use is shown in Table 2.

In this table, several assumptions are made. People will stay in the building 10 hours a day and during this time men will use the toilet 1 time and urinal 4 times while women will use the toilet 5 times(AWWA, 1999). As toilet uses 1.6 gallon water per flush (MWRA, 2006)and urinal uses 1.0 gallon water per flush(USEPA, 2010), we could compute the daily toilet water use for one person. By assuming a male to female ratio of 1to 1, we could get the daily toilet water needs as $\frac{(1.6\times 1+1.0\times 4)+1.6\times 5}{2}\times 3.8 = 25.84\mathrm{L/(cap\cdot d)}$. In the equation, 3.8 is the unit transform from gallon to liter and a water needs of 30L/(cap-d) is used as is shown in Table 2.

Table 2 Daily Toilet Flush Water Use

Gender	Male	Female
Time in the building(h/d)	10	10
Toilet Flush(times/d)	1	5
Urinal Flush(times/d)	4	0
Water per Toilet Flush(gallon/flush)	1.6	1.6
Water per Urinal Flush(gallon/flush)	1.0	1.0
Toilet Water Needs(L/d)	21.2	30
Toilet Water Needs(L/cap-d)	30.0	

Besides water used by toilet flush, lavatory faucets also contribute to common toilet water use. However, in this study, this part of water needs is not considered as water from the faucet has a direct contact with people thus should meet potable water standard. Required water treatment processes like disinfection would make the rainwater harvesting system much more complex and greatly increasing the cost. Under this scenario, rainwater is harvested only for toilet flush use which is more economically efficient.

In order to get the number of capita in each building, we will use the method by giving 25 m^2 building area to each person to get the capita value. Then we will use height of the building to get the stories of each building, and multiply this with Total_roof_area_XY, then the total building area is got.

$$\text{Capita in building} = \frac{\text{total building area}}{25\text{m}^2/\text{capita}}$$

$$\text{TotalBuildingArea} = 0.9 \times \text{Total\_Roof\_Area\_XY} \times \text{Stories}$$

$$\text{Stories} = \frac{\text{RelativeHeight(m)}}{4.5\text{m}}$$

Several assumptions area made to conduct the calculation. 4.5m is the average height of one story and 0.9 is the coefficient of real usable area over roof area.

For example, for the building with objectID = 1, EGID = cc00000011 as shown in Figure 6, monthly toilet water needs can be calculated as:

$$\text{MonthlyToiletFlushWaterNeeds}(\frac{\text{m}^3}{\text{month}}) = \text{CapitainBuilding} \times 30(\frac{\text{L}}{\text{cap} \cdot \text{d}}) \times 23(\frac{\text{d}}{\text{month}}) \times 0.001(\frac{\text{L}}{\text{m}^3})$$

$$\text{Capita in Building} = \frac{\text{Int}(\frac{6.72\text{m}}{4.5\text{m}}) \times 109.19\text{m}^2 \times 0.9}{25\text{m}^2/\text{cap}} = 4$$

$$\text{Monthly Toilet Flush Water Needs} = 4 \times 0.03 \times 23 = 2.712\text{m}^3/\text{month}$$

Based on the similar calculation, monthly toilet water needs for all 237 buildings can be computed. However, zooming into each building we will find for some buildings, the Surface_Area_Total_XY greatly exceeds total roof area, which might lead to greatly overestimation of capita in the buildings. For some buildings, not all building areas are designed for people to stay in. Areas of gardens, garage or machine room also contribute to Surface_Area_Total_XY and these areas should be excluded when doing our calculation to get capita value. In another case, for some buildings, not all buildings areas enjoy the same relative height. It is possible that part of the building is 60 meter tall while some other part of the same building is only 30 meter tall. Under these cases, multiply total building area with the same story value is incorrect and thus we need to remeasure the areas corresponding to different stories. Two cases below which represent the two cases illustrated above respectively are shown below.

For example, the building with object ID=12 and UGID=cc00000072 is Omni Corpus Christi Hotel. While the field of Surface_Area_Total_XY accounts for all its footprint on XY plane, actually only the two towers in the right has a relative height of 123.41m and the left part is a 8 floor garage. Obviously, we should not take area of garage into account when computing office or room areas. Then, we need to use the measure tool of ArcGIS to measure the Surface_Area_XY of the two towers. After measuring, we ge this value of the two towers to be 988 m^2 each, and here we use 1000m^2. Then, capita in this building is $\frac{1000 \times 2 \times \frac{123.41}{4.5}}{25} = 2160$, monthly toilet flush water use is then to be 2160×0.03×23=1490.4 m^3.

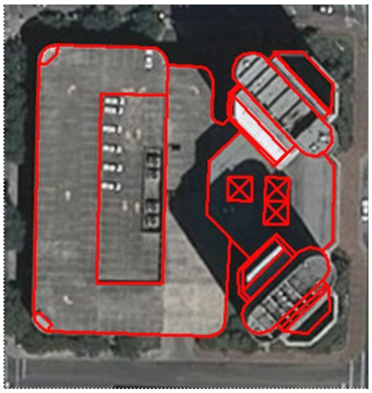

Figure 8 Building with ObjectID=12

Figure 9 Building with ObjectID=211

Likewise, for the building with ID=211 and UGID=cc00000038 as shown in Figure 9, the relative height of 9.09 m only account for the right part of the building and the left part is only one story high. Thus for this building. We need to remeasure its area too. By using the measure tool in ArcGIS, we could get the Surface_Area_Total_XY for the two-story right part to be 723.70m^2 and the Surface_Area_Total_XY for the one-story left part to be 524.48m^2. Then, capita in this building is $\frac{0.9 \times (723.70 \times 2 + 524.48 \times 1)}{25} = 71$, monthly toilet flush water use is then to be 71 × 0.03 × 23=48.981m^3.

After examining all 237 buildings and remeasuring all buildings where Surface_Area_Total_XY far exceeds area where people stay or any building that the relative height only accounts for part of its structure. We could get the monthly toilet water needs for each building. By using graduated colors quantities symbology under the layer property in ArcGIS and setting field MonthUse as field value, we could get a map shows the monthly toilet flush water needs for all the buildings in Figure 10.

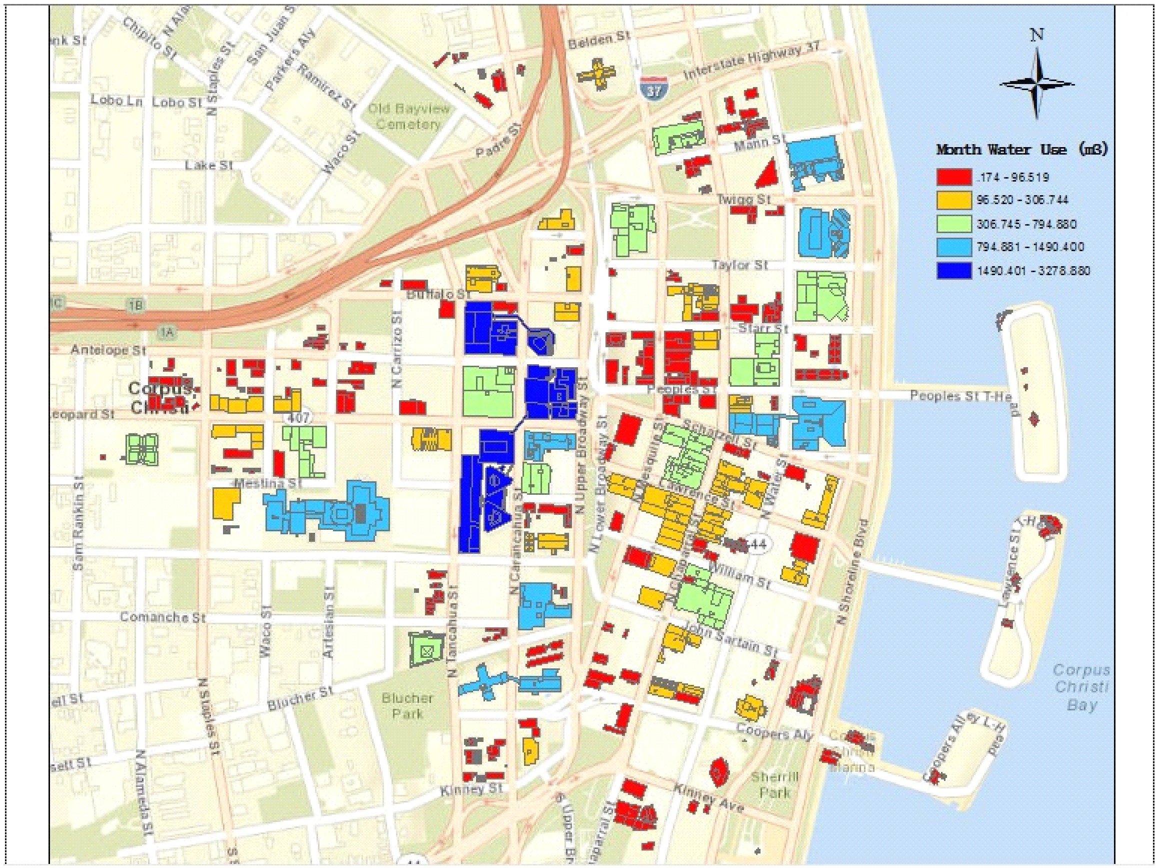

Figure 10 Month Toilet Flush Water Use

According to this map, the bluer the color is, more water is needed for that building, the redder the color is, less water then is required. It is very apparent that skyscrapers like Omni Corpus Christi Hotel, Bayfront Tower, Bank of American and Wells Fargo Bank have a large monthly toilet water needs(as shown in the color of blue), while monthly toilet water needs for one or two story building is quite low(as shown in the color of red).

Month Balance Calculation

One method of determining the feasibility of a proposed rainwater harvesting system is the monthly water balance method(TWDB, 2005). This method of calculation is similar to maintaining a monthly checkbook balance. By giving an assumed volume of water already in the tanks, the volume of water captured each month is added to the previous balance and the demand is subtracted as shown in the equation below.

$$\text{End of Month} = \text{End of Previous Month} + \text{Water Captured this Month} - \text{Water Used this Month}$$

In this study, we start our calculation with value of 0 at first, the required initial volume would then be

1.5×|Min(End of Month Storage)| to make sure that there's water supplied from the cistern for every month. The value 1.5 is the safety factor.

Three cases of month balance calculation is shown below to check the cistern volume of rainwater harvesting system for the given buildings.

First of all, look into the example of the building with objectID = 13, EGID = cc00000086(shown in Figure 11), water balance calculation is shown in Table 3.

Figure 11 Building with ObjectID=13

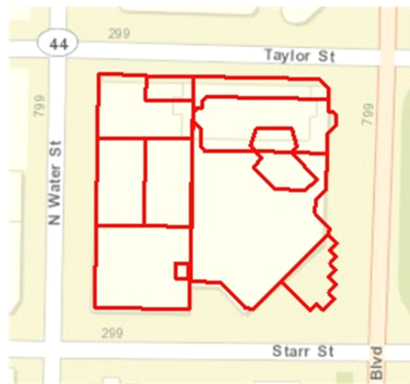

Figure 12 Building with ObjectID=15

Table 3 Month Balance Calculation for ObjectID=13 Building

Month	Median Rainfall (inches)	Rainfall Collected (m3)	Toilet Water Used (m3)	End of Month Storage(m3)
Jan	0.99	22.514	26.164	6.644
Feb	1.36	30.928	26.164	11.407
Mar	0.78	17.738	26.164	2.981
Apr	1.39	31.610	26.164	8.426
May	2.70	61.401	26.164	43.663
Jun	2.43	55.260	26.164	72.759
Jul	1.04	23.651	26.164	70.246
Aug	2.64	60.036	26.164	104.117
Sept	4.00	90.964	26.164	168.917
Oct	2.60	59.126	26.164	201.879
Nov	1.34	30.473	26.164	206.188
Dec	0.90	20.467	26.164	200.491

Apparently, for this building, there would always be enough water in the cistern to be supplied as toilet flush water. Initial volume of water in the cistern is then needed to supply for the first few days when there's no rain. Here, we give the value of $1.5 \times 2.981 = 4.5$ m^3 for the required cistern volume. For those months when end of month storage value exceeds this cistern volume, the exceeded volume is then discharged as overflow since we do not need to collect all the rainwater if the required needs is satisfied. Of course, for buildings like this where a small volume cistern is enough for toilet flush use, cisterns of larger volume are welcomed if rainwater is intended for additional use. However, under those scenarios, additional treatment requirement would have to be met and more complicated disinfection or pipeline system will be implemented.

For the building with ObjectID = 1, EGID = cc00000011(shown in Figure 6), water balance calculation is shown in Table 4.

Table 4 Month Balance Calculation for ObjectID=1 Building

Month	Median Rainfall (inches)	Rainfall Collected (m^3)	Toilet Water Used (m^3)	End of Month Storage(m^3)
Jan	0.99	2.334	2.71228	-0.378
Feb	1.36	3.206	2.71228	0.115
Mar	0.78	1.839	2.71228	-0.758
Apr	1.39	3.277	2.71228	-0.194
May	2.70	6.365	2.71228	3.459
Jun	2.43	5.729	2.71228	6.475
Jul	1.04	2.452	2.71228	6.215
Aug	2.64	6.224	2.71228	9.726
Sept	4.00	9.430	2.71228	16.443
Oct	2.60	6.129	2.71228	19.860
Nov	1.34	3.159	2.71228	20.307
Dec	0.90	2.122	2.71228	19.716

If there’s no water in the cistern at first, for this building, there would not be enough water supplied as toilet flush water from January to April, which means that the initial volume of water in the cistern is required to make sure no end of month storage value is less than zero. Here, we give the value of $1.5 \times |-0.758| = 1.137$ m^3 for the required cistern volume. For those months when end of month storage value exceeds this cistern volume, the exceeded volume is then discharged as overflow since we do not need to collect all the rainwater if the required needs is satisfied. Such cistern volume is very reasonable and for this building, rainwater harvesting is of great potential.

Finally, look into the third example, the Omni Corpus Christi Hotel(Figure 12). For this skyscraper with objectID = 15, EGID = cc00000106, water balance calculation is shown in Table 5.

Table 5 Month Balance Calculation for ObjectID=15 Building

Month	Median Rainfall (inches)	Rainfall Collected (m^3)	Toilet Water Used (m^3)	End of Month Storage(m^3)
Jan	0.99	150.644	452.088	-131.566
Feb	1.36	206.945	452.088	-376.709
Mar	0.78	118.689	452.088	-710.108
Apr	1.39	211.510	452.088	-950.686
May	2.70	410.846	452.088	-991.928
Jun	2.43	369.762	452.088	-1074.254
Jul	1.04	158.252	452.088	-1368.090
Aug	2.64	401.716	452.088	-1418.462
Sept	4.00	608.661	452.088	-1261.889
Oct	2.60	395.63	452.088	-1318.347
Nov	1.34	203.901	452.088	-1566.534
Dec	0.90	136.949	452.088	-1881.673

If there's no water in the cistern at first, for this building, there would not be enough water supplied as toilet flush water for the whole year, which means that the initial volume of water in the cistern is required to make sure no end of month storage value is less than zero. Here, we give the value of $1.5 \times |-1881.673| = 2822.510\ m^3$ for the required cistern volume. Such cistern volume is extremely large and unacceptable. So for skyscrapers like this, collecting rainwater for toilet flush is not feasible. We could look into its potential for irrigation of gardens or some other use if rainwater harvesting system is hoped to be built as a demonstration project.

After conducting monthly water balance calculation for all 237 buildings, required cistern volume is found for every building as shown in Figure 13. It's quite reasonable that buildings with lower height and large roof area require smaller cistern volume while skyscrapers require extremely large cistern volume to supply enough water for their large capita value.

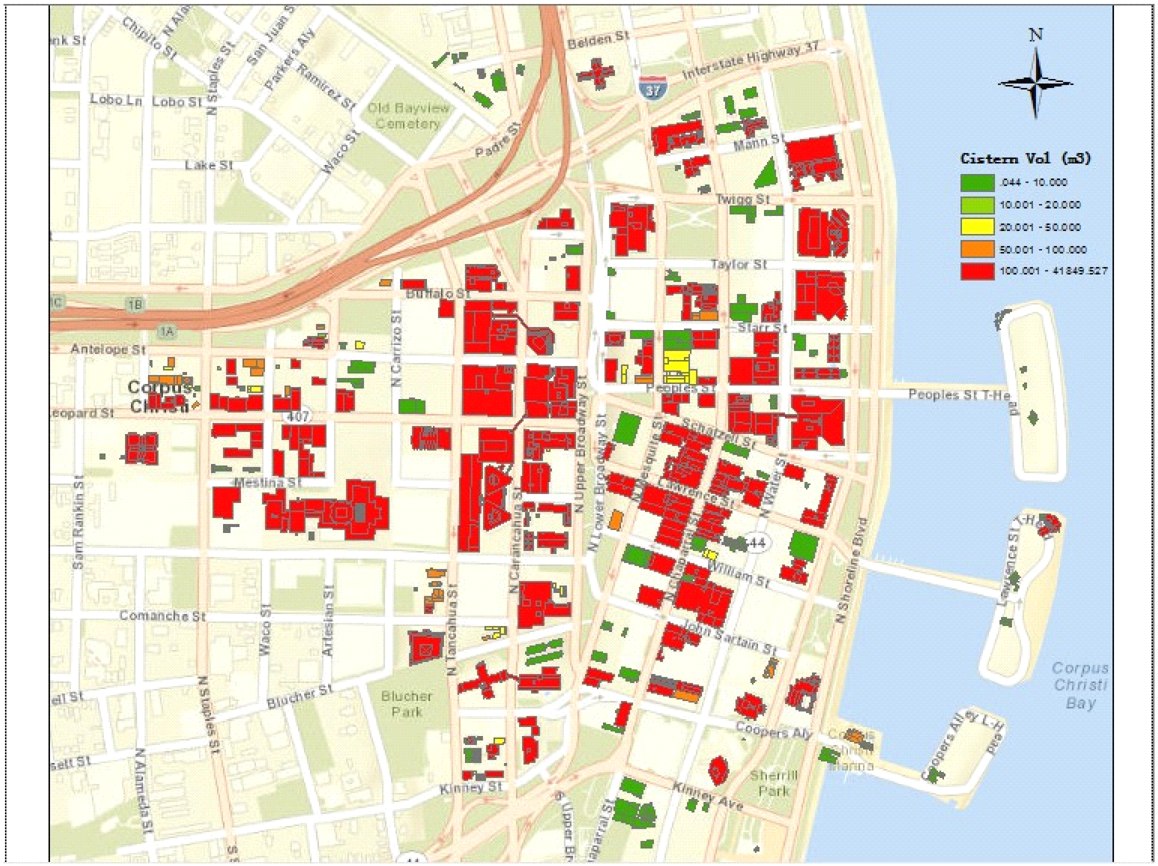

Figure 13 Cistern Volume

Then we could check the feasibility for rainwater harvesting for toilet flush water use. First of all, some threshold value should be set for feasibility examining. For buildings with large Surface_Area_Total_XY(⩾1000 m^2), we set 100 m^3 as threshold cistern volume. For other buildings, we set 50 m^3 as threshold cistern volume. Computed it in ArcGIS and change layer symbology, we could get the map shown as Figure 14 to see the feasibility of rainwater harvesting for toilet flush.

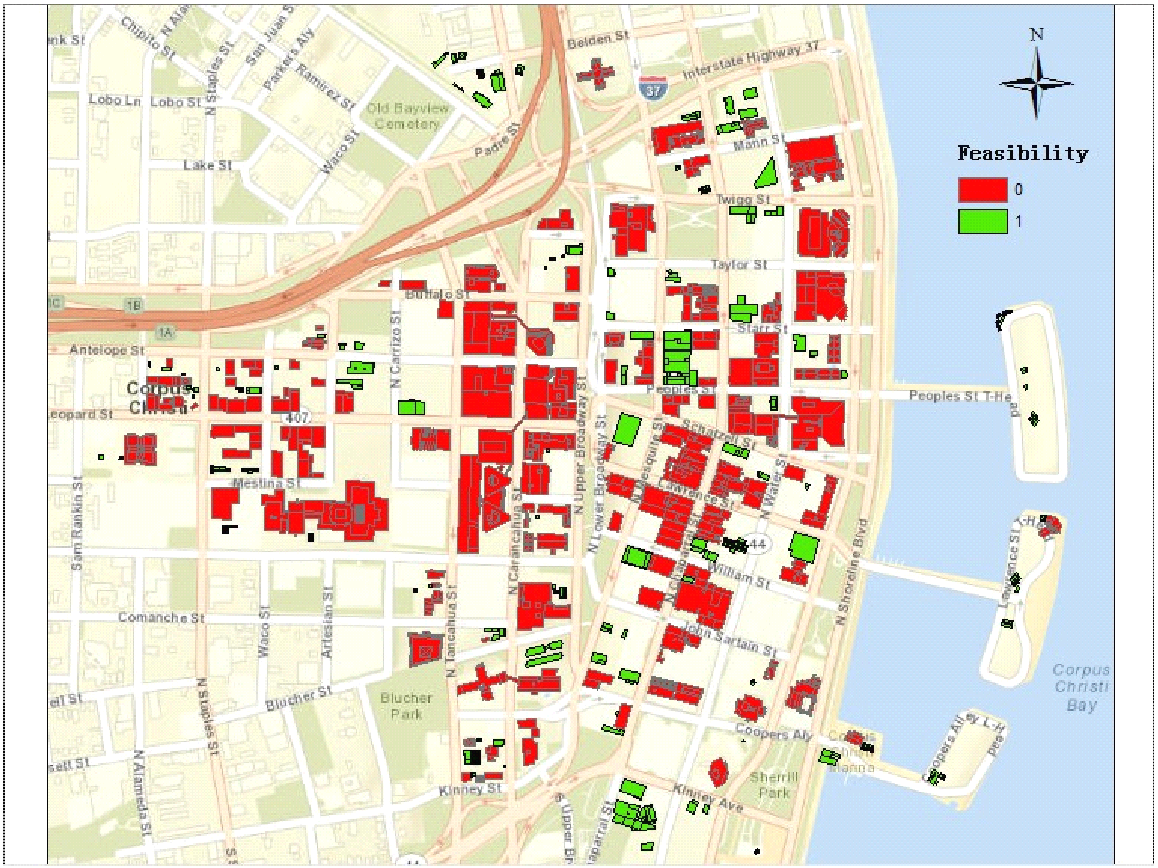

Figure 14 Feasibility

In this map, red color means unfeasible while green color means feasible. 131 of the total 237 buildings is feasible for rainwater harvesting based on the approximate calculation in this study while the other 106 buildings' potential needs to be checked with detailed or additional information. It is clearly that for those skyscrapers with large population, rainwater harvested alone is not enough to supply toilet flush, while for those low buildings with relatively large Surface_Area_XY, rainwater harvesting is of great potential to supply toilet flush use.

Conclusion

The development of Corpus Christi would encounter the problem of water scarcity while projected population growth would not slow down. Rainwater shows great potential in downtown area as a source of toilet flush water for many(131 of the total 237) buildings with comparatively large roof area and modest water needs. However, for skyscrapers and some other tall buildings with comparatively small roof area, rainwater alone is not enough for toilet flush. Thus, when constructing rainwater harvesting system for these buildings, detailed and additional information are needed based on the given project.

For the future work on such study, it would be better to have water needs data for the given buildings rather than estimating values based on some assumption. Meanwhile, when examining rainwater harvesting potential, it is better to base the study on the specific building with more detailed data. Under such scenarios, in addition to cistern, plumbing system and treatment equipment could also be taken into account when checking feasibility. Furthermore, if weekly rainfall data could be used instead of monthly rainfall data, balance calculation could be more precise and makes more sense.

In general, ArcGIS is very useful and powerful to provide maps in explaining a certain problem and month balance calculation helps to get some brief understanding of rainwater harvesting of buildings. The application of 3D roofs helps make the estimation more directly and could exert more power if further works related with rainwater flood control is conducted.

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