[Kak-tos]: A tool for optimizing conceptual mass design and orientation for rain water harvesting facades

Introduction

MIT researchers "expect 5 billion (52 percent) of the world's projected 9.7 billion people to live in water-stressed areas by 2050" (Roberts 2014). Each year globally water becomes a more valuable resource. This is as much a social problem as it is an environmental problem. Impervious surfaces can make up a significant portion of the surface area in highly developed areas, causing water to quickly shed away from where it is most needed. As the urban runoff flows over the impervious surfaces, it collects pollutants – dirt, oils, fertilizers, bacteria, etc. These pollutants end up in our stormwater systems, or worse – our soil, ponds, streams, and oceans. This kind of pollution can kill wildlife, vegetation, and contaminate drinking water. The hardscape of urban areas also causes storm runoff, which travels too rapidly to absorb into soils. As a result, wells are drying up and needing to be lowered to access new lower water levels.

With the expected increase in urban density, improvements in global construction methods and design standards, highrise buildings are becoming much more ubiquitous. Currently, the best practices for rainwater harvesting considers only the rainfall resource available to the horizontal surfaces of a site: the roof and surrounding land. However, these buildings have the potential to collect and use rainwater not just on their roofs or from excesses of their mechanical systems, but also with their facades. Typical gray water consumption in a highrise office building is well beyond that which can be collected through conventional means. For example, a toilet uses about 3 gallons of water per flush. If an average employee flushes the toilet 2-3 times a day, conservatively, he or she uses 7.8 gallons per day in just toilet flushing. In a 500,000 sf office highrise with 4,000 employees, and 200 work days in a year, this would equate to 6.2M gallons a year of gray water consumption. The collection of rainwater from high rise facades could help mitigate the amount of water that is being flushed down the drain, allowing users to be more conscientious about the sources of our gray water.

Wind-Driven Rain (WDR) is rain which is propelled horizontally by wind, therefore falling at an oblique angle. There is an extensive amount of previous research into the impact of WDR in a myriad of fields. In their paper "A review of wind-driven rain research in building science", Blocken and Carmeliet note that "The large number of parameters and their variability make the quantification of WDR a highly complex problem. It is not surprising that despite research efforts spanning over almost a century, WDR is still an active research subject in building science and a lot of work remains to be done." While current Computational Fluid Dynamics (CFD) research is incredibly complex, ongoing real world testing by a variety of methods still proves that computational solutions about WDR are at best estimations.

Given this we can presume that while still an estimation the changes that could occur in those estimates with better models are simply proportional, therefore we have based our models on a simple formula based on Blocken and Carmeliet conclusions:

> Measurements of both free WDR and WDR on buildings have indicated that the intensity of WDR increases approximately proportionally with wind speed and horizontal rainfall intensity. Measurements of WDR on buildings have revealed part of the complex wetting pattern of a facade: top corners, top and side edges are most exposed to WDR.

As far back as 1955, WDR research has presumed this proportional relationship. Hoppestad established a WDR index based on proportional calculations and the weather data which is collected in each location: Wind direction, wind velocity and rainfall amounts. Based on this he determined:

> ‘‘The annual mean WDR index gives, it is believed, a reasonably precise method of comparing different sites with respect to total amounts of WDR on walls. It enables a designer to compare the exposure of a place with that at another with which he is already familiar.’’

We can therefore presume for this study that Hoppestad's semi-empirical method and equation provides a proportional method for understanding the potential changes of WDR on building facades:

$$R_{\mathrm{wdr}} = R_{\mathrm{h}} \cdot \frac{U}{V_{\mathrm{t}}}$$

Equation 1: Hoppestad's equation where R.wdr is total WDR and R.h is the rainfall rate, U is the wind speed (m/s) and Vt is the raindrop terminal velocity of fall (m/s)

This *semi- empirical* equation serves as a basis for our evaluation and though other factors clearly contribute and can change the impact of those changes in the equation would be relatively uniform given the evaluation criteria established for the tool. Each of the variables would consistently alter the evaluation of WDR amounts which could potentially be collected.

In this paper, we will examine the impacts and potential for WDR to be harvested on the facades of buildings, and will describe a plug-in tool for schematic design for *Autodesk Revit*, which can assist in the definition of optimal geometries and orientation for a building to harvest water in its particular location and site. The tool described here is intended to create comparisons between building masses and their orientation based on conditions in particular locations and sites. These base calculations presumably would adjust uniformly as the science around WDR adjusts or as other factors complicate models.

Tool Logic

Based on our calculations, we approximate that the roof of a 100’ x 200’ vertical high rise 400’ in height would collect 12,400 gallons with 1 inch of precipitation. However, when we add in the quantities of rainwater that can be collected on the facades of the same tower the total collection increases significantly. We calculate that a 5 mph wind drives rain to fall at a 21 degree angle, and 10 mph wind drives it at a 36 degree angle onto the facade. The rainfall that can be collected on the four facades of the building we approximate to be 28,800 gallons per year or 152% more than the roof alone if the wind is blowing on average at 5 mph, and 46,628 gallons per year or 276% more than the roof alone if blown at an average of 10 mph during rainfall. According to the National Oceanic and Atmospheric Administration, the City of (Name), receives an average of 43 inches of annual precipitation. Based on our calculations, we approximate that the roof of the same high rise would collect 71,667 cubic feet, or 536,104 gallons per year on its 20,000 sf roof surface. With 5 mph winds, we can calculate that approximately 814,878 gallons per year to be collected on the four facades, and 1,479,647 gallons with an average of 10 mph winds annually.

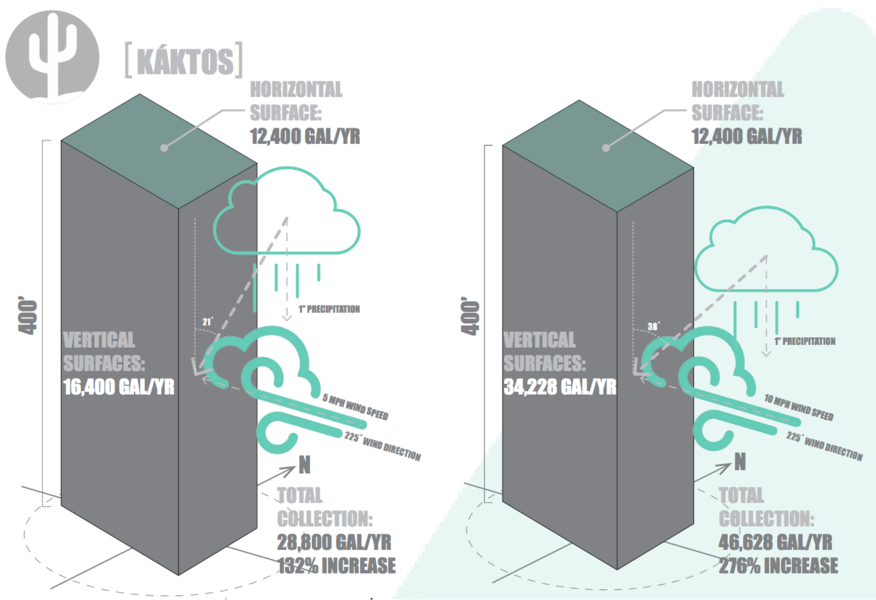


Figure 1: Kaktos tool diagram

The tool outlined here works by importing the weather data for a given location from the National Oceanic and Atmospheric Administration (in our initial studies we used a five-year window). This data is first simplified to include only days where measurable rainfall occurred. The data is then further stripped to only include the measurement of precipitation, wind direction and velocity, presuming a median rain drop size. The tool functions by projecting rays onto the building mass following the angle calculated that the WDR would fall during that given day, and calculates how much of the WDR would hit each of the sides of the mass.

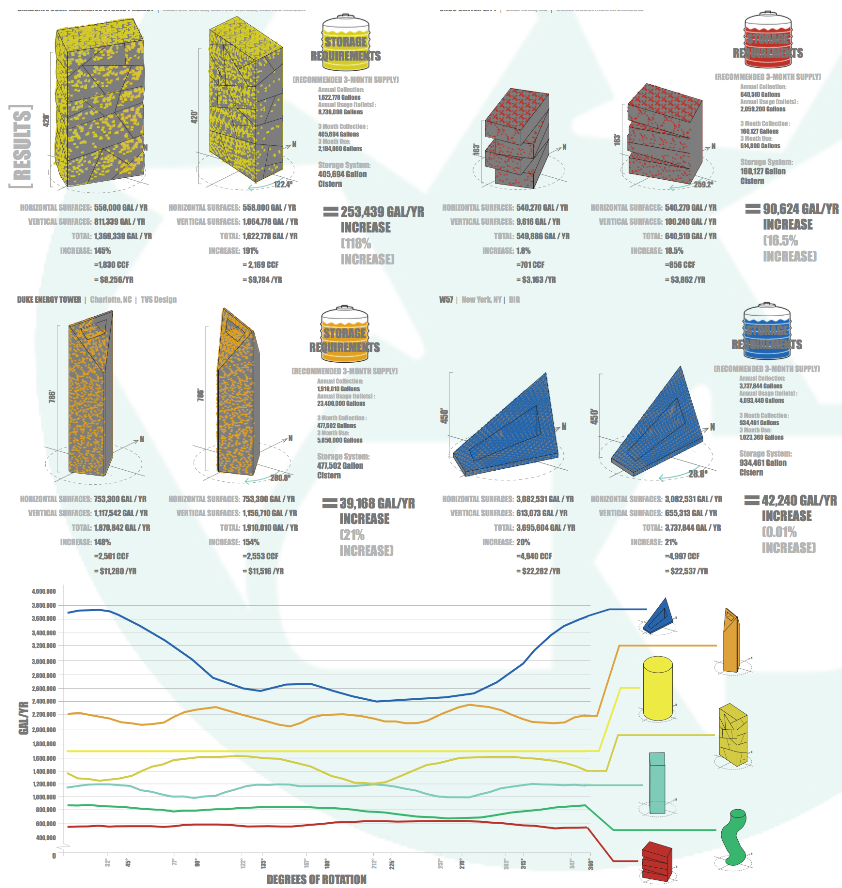


Figure 2: Testing a variety of building masses

Based on these calculations the tool can then provide a total annual calculation for WDR on each facade or can rotate the mass based on a user specification to test for the optimal orientation of the given shape. Predictably, the optimal orientation being that in which the greatest surface area of the mass is facing the median windward direction on rainy days, which will allow the most amount of WDR to hit the largest surface area. The user can specify the amount of variation in the rotations to determine how computationally intensive the testing is.

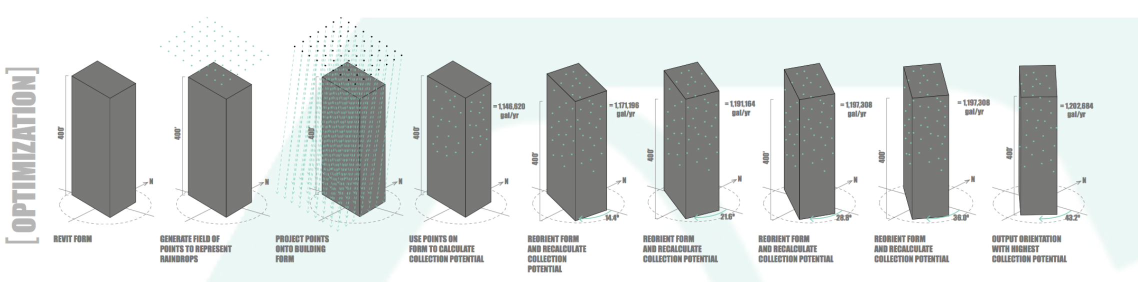


Figure 3: Mass orientation testing

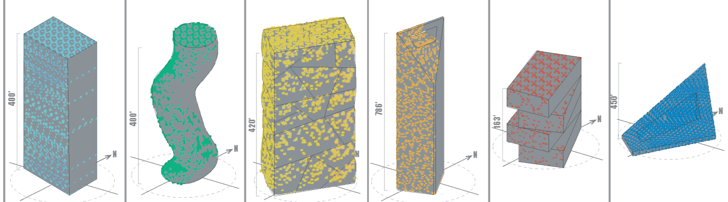
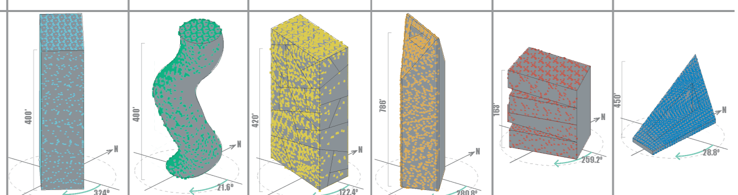
	1	2	3	4	5	6
						
HORIZONTAL SURFACES: (GAL / YR)	558,000	219,015	558,000	753,300	540,270	3,082,531
VERTICAL SURFACES: (GAL / YR)	558,620	636,534	811,339	1,117,542	9,616	613,073
TOTAL:	1,146,620	855,549	1,369,339	1,870,842	549,886	3,695,604
INCREASE:	100%	290%	145%	148%	1.8%	20%
						
ROTATION ANGLE: (DEGREES)	324°	21.6°	122.4°	280.8°	259.2°	28.8°
HORIZONTAL SURFACES: (GAL / YR)	558,000	219,015	558,000	753,300	540,270	3,082,531
VERTICAL SURFACES: (GAL / YR)	644,684	638,070	1,064,778	1,156,710	100,240	655,313
TOTAL:	1,202,684	857,085	1,622,778	1,910,010	640,510	3,737,844
INCREASE:	115%	291%	191%	154%	18.5%	21%
INCREASE:	56,064 GAL/YR	1,536 GAL/YR	253,439 GAL/YR	39,168 GAL/YR	90,624 GAL/YR	42,240 GAL/YR
INCREASE:	115%	0.2%	118%	21%	16.5%	0.01%

Table 1: Mass Comparison/Orientation Comparison

As seen in Table 1, both form and orientation play significant roles in the amount of WDR that hits each facade. By adding the facades of the mass into the calculations for rainwater harvesting, the percentage of WDR that interacts with the form at least doubles for each instance, except for forms 5 and 6 - both of which contain larger horizontal surfaces and shorter facades than forms 1-4. The increase in WDR on the facades through optimal orientation on the site differs for each form. Re-orienting forms 1 and 3 from their original test position once again doubles the amount of WDR on the facades, whereas re-orienting forms 2 and 6 has minimal effect on the amount of WDR. The intent of this tool is to aid designers in massing and orientation studies. Using Revit's conceptual mass tool allows designers to study iterations quickly, analyze them using Kaktos, and make changes accordingly.

Lastly, the tool can be used to calculate the optimal locations for rainwater collection to minimize the frequency of large quantities flowing along the surface of the building. This aspect of the tool works by tracing the gravitational flow of the water along the facade using a sphere-mapping method (Beorkrem 2013). Sphere-mapping uses a technique of intersecting spheres with a complex mass to find the approximate circular shaped intersection between the mass and the sphere. The shortest line between the center of the sphere and this circular intersection represents the likely path for the water. Using the endpoint of the shortest line, another sphere is placed and this process continues iteratively while a total water amount is tallied to indicate when a total reaches a user defined amount at which point the water can be collected. Placing intermediate collection points on the facade of a building removes the water before it reaches the ground, reducing the amount of urban runoff and preventing the unnecessary use of energy to pump the water back up through the building.

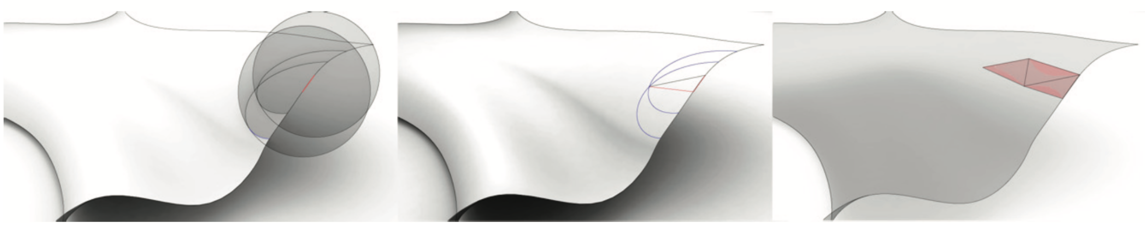


Figure 4. Sphere-mapping process. Sphere intersecting with surface (left). Resulting lines projected on surface (center). Resulting mapped triangles (right).

This part of the tool also challenges designers to factor the way water flows over the facade during early schematic phases of building design, whether that be for aesthetic reasons (using the rainwater to activate the facade), for acoustical reasons (using the rainwater to dilute exterior noise in certain areas of the building), or for thermal reasons (using the rainwater to mitigate heat gain/loss in the facade). Allowing the collection of rainwater to assist in the design of a mass, rather than leaving it as an afterthought the way traditional rainwater collection systems do allows the WDR to become a more integral part of the architecture. As with other passively sustainable systems these criteria need to be evaluated early on in the design process, too often designers use technology to mediate the effects of poor decisions and this tool hopes to help them visualize the impacts of one aspect of massing design. The visual impact of a facade designed to collect rainwater could also create more awareness and afford the client the ability to equate their brand with a desire to minimize their impact on the environment.

The collection and reuse of rainwater could begin to reshape the architectural landscape of our cities. As computational manufacturing and prefabricated building components become more pervasively used, buildings formal typologies are continuing to expand into ever more complex shapes. These complex forms are often driven by arbitrary and stylistic ideas (or lack thereof). We envision a series of tools integrated for evaluation of multivariate performative criteria integrating forms and orientational choices driven by Kaktos with other evaluative tools, based on solar radiation, daylighting and structural performance, amongst others.

The integration of facade based water collection systems with other infrastructure could help create more resilient neighborhoods and cities. Various cities have infrastructure in place which could supplement the performance of such systems, for instance in New York City most buildings already have water towers to create pressure for the water systems in the building, but could also serve as the location for storing greywater. This would require a transfer system for creating pressure in both systems within the same tower, but is a reasonable use for existing technology. New York as well as other cities could respond better to heavy stormwater scenarios by collecting rather than shedding the WDR which hits buildings.

Furthermore, these localized systems could provide backup for disaster scenarios such as the Haitian Earthquake, whose impact was exacerbated by the lack of clean drinking water following the earthquake. If the infrastructure was in place to collect water on buildings which remained through the event, there would have been hyper local sources for relatively safe water following the event.

Additionally, envelope designs and their capabilities continue to evolve becoming ever more complex. They are at the same time more water resistant while still affording for the building to exchange air with the outside. These envelopes could supplement their performance by integrating collected rainwater as a cooling system for the envelope as well as to create light shelves or other daylighting controls with or containing the forms of the WDR collection gutter system. Once collected, there are a multitude of ways to reuse the water: irrigation, fire protection, toilet flushing, and heating/cooling systems. Some uses require the filtration and sanitization of the rainwater. The Center for Architecture, Science, and Ecology (CASE) at Rensselaer Polytechnic Institute (RPI) has developed a facade system of modular glass blocks in which greywater flows through channels that are embedded in the surface of the block. By tilting each module for maximum exposure to solar energy, the grey water is purified for reuse via sunlight. Using one natural resource to purify another creates the potential for an unlimited resource which requires little if any large-scale infrastructure. This hyper local water source could create cities which are much more resilient to the ever changing and intensifying climate in which we live, in the 21st Century.

Conclusion

The design for Kaktos is intended to create an integrated method for designers to analyze and test massing studies based on wind driven rain water collection. Challenging current design standards, we have developed a method and tool to calculate the amount of rainfall that can be collected on all surfaces of a building design. In a typical office building, 90% of the water consumed is for non-potable uses. As the need for water in urban areas predictably increases especially in sensitive areas, over the coming decades, tools like Kaktos will provide the ability for designers to factor rainwater collection in as one of the primary schematic conditions for successful building design.

References

Beorkrem, Chris; Mitchell McGregor, Igor Polyakov, Nicole Desimini. “Sphere Mapping: a method for responsive surface rationalization”. International Journal of Architectural Computing vol. 11 - no. 3, 319-330. 2013.

Blockena, Bert , Jan Carmelieta,b. *On the accuracy of wind-driven rain measurements on buildings*. Building and Environment Vol. 41, Issue 12, December 2006, Pages 1798–1810.

Blockena, Bert , Jan Carmelieta,b. A review of wind-driven rain research in building science. Journal of Wind Engineering and Industrial Aerodynamics Vol. 92 (2004) 1079–1130.

Hoppestad, S., Slagregn i Norge (in Norwegian), Norwegian Building Research Institute, rapport Nr. 13, Oslo, 1955.

Roberts, Alli Gold. *"Predicting the future of global water stress."* MIT News. MIT Joint Program on the Science and Policy of Global Change, 09 Jan. 2014.