Modeling water use for sustainable urban design

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Abstract. Achieving sustainability on an urban scale is an overwhelming problem. We can address this by dividing the problem into manageable proportions. Environmental impacts of urban design fall into measurable categories, for example, air quality, biodiversity, solid wastes, water and wastewater, hazardous materials, and impacts of nonrenewable energy use. Such measures are incorporated into building rating systems as a way of codifying sustainability. In this chapter, to illustrate such codification, we examine water use as well as generated wastewater according to the requirements of a specific sustainable building rating system. Conventional calculations are coupled with building information modeling to illustrate the overall effects of parametrically selecting fixtures, systems and materials to control the use of potable water. We further demonstrate how this approach of combining parametric building information modeling with measures of their environmental impacts can be employed on an urban scale, thereby, guiding the design of sustainable urban spaces.

Keywords: Sustainability, Sustainable Building Rating System, Building Information Modeling, Parametric Modeling.

1 Introduction

In 2008 the number of urban dwellers surpassed those living in rural areas [1]. Cities and their residents occupy 2% of the terrestrial surface and consume large amounts (75%) of the world's natural resources. While these resources are becoming scarcer, the nature of the use and waste of resources contribute to environmental degradation. Among the resources to run our cities—energy, water, building materials—are some that can be reasonably quantified. Water consumption reduction, water recycling, and wastewater minimization are supported by almost all sustainability principles that are codified by sustainable building rating systems.

Urbanization is growing at a staggering scale, according to census 2000 population statistics, almost 80% of the total world's population live in urban areas today [2], and approximately 44.2 bgal/day of water withdrawals are used for public supply [3]. Rise in urban population shows an increase in the use of potable water from public supply from 62% in 1950 to 86% in 2005. Increase of population further complicates, with the geographical shift of population requiring rapid increase in water supply demand and maintenance of aging systems in areas of diminishing populations. In the last twenty years, communities have spent $1 trillion in 2001 dollars on drinking water

THE DEFINITIVE, PEER-REVIEWED AND EDITED VERSION OF THIS ARTICLE CAN BE FOUND IN:
Digital Urban Modeling and Simulation (Eds Stefan Müller Arisona, Gideon Aschwanden, Jan Halatsch and Peter Wonka) CCIS 242, Springer-Verlag, Berline Heidelberg, 2012, pp. 138-155

treatment and supply, and wastewater treatment; although this is an staggering amount, it may not be sufficient for future needs [4].

Water conservation is more widely followed in the arid areas of the United States. However, using water efficiently is increasingly becoming an essential part of creating sustainable buildings and environment [5]. Ezel [6]cites a recent study by McGraw Hill's Construction [7], which indicates that after energy efficiency, water is treated with the next highest priority.

In order to study the effects of water use in the urban setting, we begin, firstly, by looking at water use in a residential building and then look at typical water use in commercial office buildings. According to Vickers [8], water use reduction in residences can be improved by efficiencies in water use, that is, by a combination of using less water with water efficient fixtures, and reusing wastewater generated by water use activities such as showers, baths, and laundry. Wastewater generated from bathtubs, wash basins, dishwashers and laundry is defined as *graywater* by the Uniform Plumbing Code (UPI) in its Appendix G [9]. Although graywater reuse strategies are being used for reducing overall water requirements, our focus in this chapter is to study water savings as a result of using water efficient fixtures and the possibilities for rainwater collection and reuse.

According to Mayer et. al. [10], toilets use 29% of total indoor water consumption. Water used for showering/bathing, dishwashing and laundry respectively account for about 36%, 14% and 21% of total indoor water consumption. In the case of the urban scenario, where we consider commercial office buildings, according to Dziegielewski [11], indoor water use falls into mainly three categories. These are: indoor use for toilets and wash basins, and cooling systems; and outdoor use for irrigation based on the landscape and types of plants.

In this research we focus on water used from the first category, which considers toilets, and wash basins. We construct an urban mass model around an office building by creating a building information model (BIM) and then implement an add-on application, where the effects of using efficient water fixtures can be easily visualized. It is important to point out that our original prototype application was primarily created for individual sustainable building projects—our aim is to expand its capabilities to meet needs at an urban scale.

2 Background

Environmental Aspects. The total water withdrawn for use in buildings for toilets, faucets and showerheads are from rivers, streams and underwater aquifers. Reducing the amount of water for these uses would benefit potable water conservation. Reduction in potable water means that less water would need to be treated at municipal water treatment works. The accumulated effects of water use reductions go as far as allowing municipalities to defer or keep up with high investments in wastewater treatment infrastructure and supply of clean water.

In the case of rainwater harvesting for systems for reduction of potable water use in flushing, local weather conditions as well as local health ordinances should be taken into account. Quality of water supplied from rainwater collection or recycled graywater have to be accounted for in the selection of fixtures to ensure long-term fixture performance.

Economic Aspects. Reduction of water consumption at the source helps to minimize the overall operating costs of a building. According to USGBC, buildings that have been retrofitted with more efficient plumbing fixtures through incentives programs provide a cost effective way of deferring capital costs of water treatment and supply facilities. The EPA estimates that public wastewater and supply infrastructure repair costs for the United States in the next 20 years will be about $745 billion to $1 trillion. Infrastructure repair and replacement costs to an already aging system will increase the cost average for water bills from 0.5% of the average household income to 0.9% [12]. Thus, water efficiency on a large scale will decrease the stress on current water management infrastructure such as water distribution networks, sewer lines, and treatment of both sewage and drinking water supplies.

Policy Aspects. Changing existing water fixtures with more efficient ones makes them more affordable; councils and organizations that promote green building rating systems have mobilized the industry to make efficient fixtures and water saving technologies more readily available in the general market. However, reusing graywater or harvested rainwater still has potential problems. For example, adequate filtration, treatment facilities and water tanks need to be considered during design.

2.2 Rating Systems and Water Efficiency

As a way of codifying sustainability, certain measures are incorporated in the form of green building rating systems. To illustrate, we examine the water use category from the perspective of four different rating systems. The rating systems shown correspond to those chosen by Fowler [13] as providing inherently distinct ways of calculating water as an important resource in the building domain. Although these rating systems set requirements for buildings, there are certain rating systems such as BREEAM that have started to expand their benchmarking to the community scale [14].

In Table 1, the left column captures the broad categories in which water resource use is measured. Water use reduction is considered as an essential measure in all the rating systems, this category is generally measured by the percentage of water use reduction. Two cases are compared: water use in a design, and a baseline water use. The LEED (Leadership in Energy and Environmental Design) rating system, developed by the US Green Building Council, has 4 credits alone dedicated to this criterion. Green Star of Australia awards from up to a maximum of 5 points for water use reduction. BREEAM (Building Research Establishments Environmental Assessment Method) allocates 3 credits, while Green Globes dedicates between 10-40 points depending on the amount of reduction in water use. Although different weights and points are given to this category by the different rating systems, all consider water use reduction as an essential component of green design.

Table 1. Water efficiency requirements in different rating systems

Water Efficiency	**LEED 3.0**	**Green Star**	**BREEAM**	**Green Globes**
Water use reduction	WE pre, WE 3.1-3.3 Water use reduction by 20%, 30%, 40%, 50%	Wat-1 Occupant amenity water (reduction of water use)	Wat-1 Water consumption reduction for sanitary purposes	D1. Water consumption reduction
Water efficient landscaping	WE 2.1- 2.2 Reduce water use for irrigation	Wat-3 Landscape irrigation		D 2.3 Minimal use for irrigation D2.4 Efficient irrigation equipment
Waste water treatment	WE 2 Innovative waste water technologies			D3.1 Reduce offsite water treatment
Water use control		Wat-2 Water meters	Wat-2 Water meter for monitoring consumption Wat-3 Major leak detection Wat-4 Sanitary supply shut off	D2.1 Sub-metering for high use areas
Systems water use		Wat-4 Heat rejection water Wat-5 Fire system water use		D2.2 Minimal use for cooling towers

2.3 Urban Water Use in Commercial Buildings

Reducing water use by installing efficient fixtures is a relatively simple criteria to follow in order to earn credits, for example, from a sample of LEED 2.1 Silver certified buildings in Pennsylvania, we found that 88% of the buildings achieved credits for water use reduction, and 56% of the same set achieved 4 out of 5 possible credits [15]. Figure 1 shows the samples, numbered from 1 to 25 on the x-axis, with the water efficiency credits on the y-axis, numbered from 1 to 5.

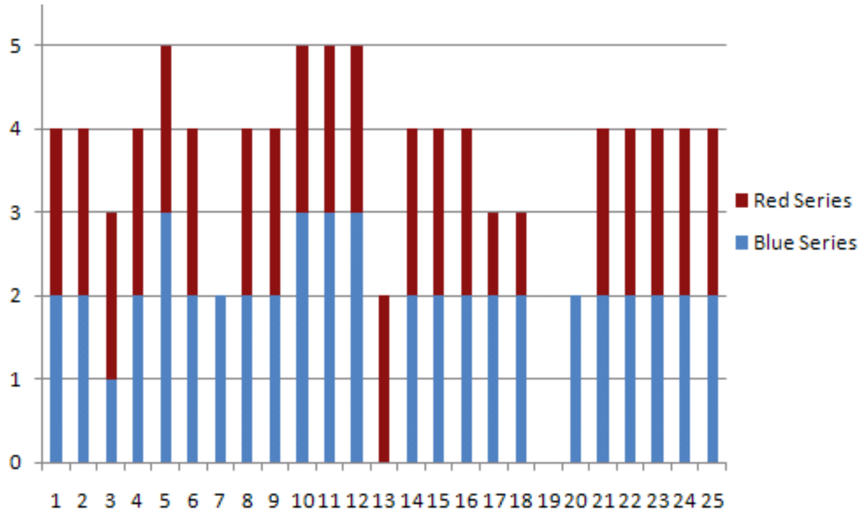

Fig. 1. Distribution of LEED water credits earned by certified buildings. The blue series represents credits WE 1.1, WE 1.2 and WE 2, while the red series represents credits WE 3.1 and WE 3.2. These two kinds of credits essentially cover fixtures, uses and calculations for water use loads for a building.

Taking a close look at LEED certified buildings on the campus of Carnegie Mellon University, we found that all but one had acquired water reduction credits (Table 2). According to facilities management, the benefits can be seen not only in the use of less water but also in the overall operation and maintenance costs of the facilities. It should be noted that although there are different types of buildings certified under LEED New Construction, calculations generally differ only in the allocation of types of fixtures, number of users and number of days in a year the buildings are used. The reason for the one building where LEED water credits were not achieved can be attributed to small area of the building. Water use reduction is reflected in the deployment of available efficient fixtures at the time.

Table 2. Water Efficiency credits achieved for LEED certified buildings on the campus of Carnegie Mellon University

Project Name	Certification	LEED version	LEED water credits achieved
New House	Silver	LEED NC 2.0	WE 1.1, WE 1.2
Henderson House	Silver	LEED NC 2.0	WE1.1, WE 1.2, WE3.1, WE3.2
407 S Craig St	Silver	LEED NC 2.1	None
300 S Craig St	Silver	LEED NC 2.1	WE1.1, WE 1.2, WE 3.1
Collaborative Information Center	Gold	LEED CS	WE1.1, WE 1.2, WE2, WE 3.1, WE 3.2

3 Modeling Water Use

We employ two different methods to model water use in buildings. The first considers individual buildings to determine their water use. It is assumed that the number of occupants is known. Further, there is an urban information model containing the floor areas and numbers of floors in each building. Urban water use is then, an aggregation of water use by the occupants in each the selected buildings. The second approach works from 2D drawing of an urban area with known building heights. Numbers of occupants, fixtures and fixture flow rates are assigned and maintained in an external database. Figure 2 illustrates the test case, modeled in Revit® Architecture 2010 [16].

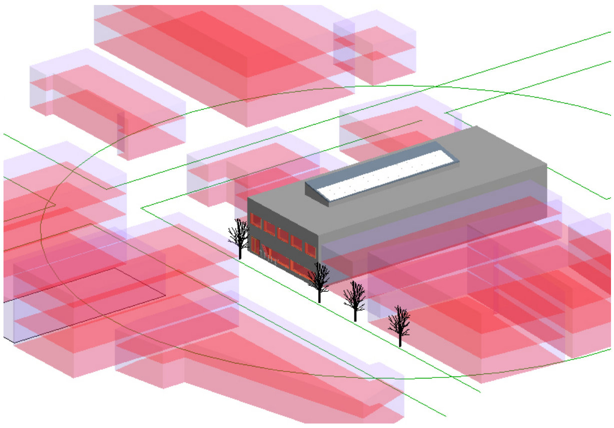

Fig. 2. Test case for modeling water efficiency for LEED

We employ criteria from LEED NCv2.2 for water use requirements and a building information model (BIM) to make informed decisions on using certain fixtures for achieving sustainability goals set by LEED. The advantage in creating and using a building information model is its intrinsic characteristic of holding project information for all team members. This includes designers, planners, facility managers, and on a larger scale, policy and decision makers. To demonstrate the approach of designing towards specific LEED goals, we use Revit Architecture 2010 as the building information model. As a commercial BIM, Revit offers capabilities for ready documentation and calculation that can be, ultimately, submitted for certification. Figure 3 shows a family of fixtures with essential information pertaining to water use calculation such as flow rate.

Calculations principally follow the LEED method for water use calculation outlined below. Water use reduction for a building/project corresponds to the difference between the *design* case and a *baseline* case. In this methodology water use is calculated by estimating occupant usage and fixture flow rates. Occupants are determined by calculating full time equivalent (FTE) occupancy of a building, which is based on a standard 8-hour occupancy period, thus, resulting in a value based on the hours per day divided by 8. In the case of transient building populations such as students, visitors, or customers, hours are estimated for a representative daily average.

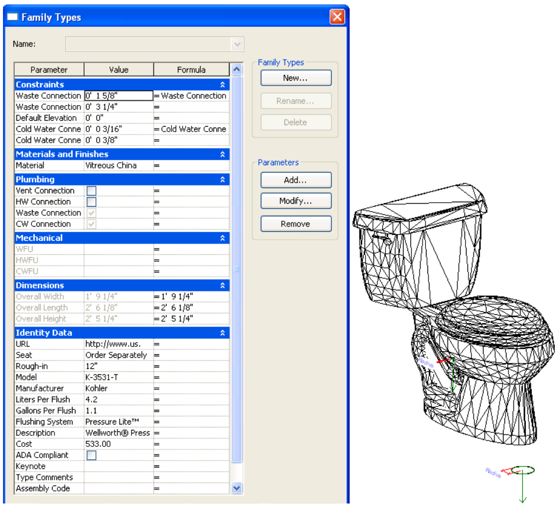

Fig. 3. Fixture information related to water use

Design Case. Annual water use is obtained by totaling the annual volume of water use by each fixture type and then, subtracting rainwater or graywater reuse. Actual flow rates and flush volumes for the installed fixtures are used in the calculation. For consistency, a balanced one-to-one ratio of male and female is assumed. Table 3 shows an example of a design case study for water usage from interior fixtures.

Table 3. Water use calculation based on flush and flow fixtures from a sample case study

Fixtures	**Daily use**	**Flowrate**	**Duration**	**Occupant**	**H_2O use**
Flush Fixture		*GPF*	*(flushes)*	**(gal)**	
Ultra Low Flow WC (m)	0	0.8	1	80	0
Ultra Low Flow WC (f)	3	0.8	1	80	192
Composting Toilet (m)	1	0	1	80	0
Composting Toilet (f)	0	0	1	80	0
Waterless Urinal (m)	2	0	1	80	0
Waterless Urinal (f)	0	0	1	80	0
Flow Fixture		*GPM*	*(minutes)*		
Conventional Lavatory	3	2.5	0.20	160	240
Kitchen sink	1	2.5	0.2	160	80
Shower	0.1	2.5	5	160	200
				Total Volume (gal)	712
				Work days	260
				Annual volume	185120
				Rain water or graywater reuse	0
				Annual water use (gal)	185,120

Baseline Case. According to LEED methods, to create a baseline case, the design case table is used to provide the number of male and female occupants, with fixture flush and flow rate values adjusted as per EPAct default specifications [9]. Table 4 shows the baseline case for the same design case study.

Table 4. Baseline calculations for the same case study

Fixtures	**Daily use**	**Flowrate**	**Duration**	**Occupant**	**H_2O use**
Flush Fixture		*GPF*	(*flushes*)	**(gal)**	
Conventional WC (m)	1	1.6	1	80	128
Conventional WC (f)	3	1.6	1	80	384
Conventional Urinal (m)	2	1	1	80	160
Conventional Urinal (f)	0	0	1	80	0
Flow Fixture		*GPM*	(*minutes*)		
Conventional Lavatory	3	2.5	0.25	160	300
Kitchen sink	1	2.5	0.25	160	100
Shower	0.1	2.5	5	160	200
				Total Volume (gal)	1272
				Work days	260
				Annual volume	330720
				Rain water or graywater reuse	0
				Annual water use (gal)	330,720

Water use calculations are straightforward. However, this can be problematical, because of missing data as a result of integrating requirements from a rating system with a particular building information model. A model is only as complete as the information entered. Pertinent information for water use calculations include occupant numbers, fixture costs and materials, which a designer must enter. Other required information external to any project in any building information model include rainfall data, plant water use data, etc. Such information is not expected to fall directly into the designer's purview, yet these factors have to be accounted for. Table 5 shows the required objects for calculating LEED NC 3.0 water related credits.

Water fixtures are components stored in the Revit library. As stored, when queried, only dimensions of instances are returned. Dimensions are incorporated into the object names; there is no other way of getting at object parameters, or other needed material properties from the objects, unless the information from manufactures specifications has been filled as shown in Figure 3.

To calculate Water Efficiency credits, we implemented external databases for fixtures and landscapes. In the prototype shown in Figure 4 there are two tabs under the Water Efficiency category. These contain the necessary tasks to be fulfilled when evaluating water efficiency credits.

Table 5. LEED credit requirements for water efficiency calculations

Credit Name	Description	Existing objects in Revit™	Required Properties	New objects and required properties	Associated info	External info
WE pre	Water use reduction	Plumbing fixtures	Low flow fixtures, male and female; Kitchen, sink, shower		Number of male and female users	
WE 1.1	Water Efficient Landscaping Reduce by 50%	Plant	1. Species factor 2. Density factor 3. Landscape coefficient 4. Irrigation efficiency	Site area covered by specific plant		
WE 1.2	Water Efficient Landscaping No potable water use or no irrigation	Plant	1. Species factor 2. Density factor 3. Landscape coefficient 4. Irrigation efficiency	Site area covered by specific plan	Water harvested	ET rate database; CE value
WE 2	Innovative Wastewater Technologies	Plumbing fixtures	Water usage properties: flow rate, frequency used	Water treatment facilities and properties	Number of male and female users	
WE 3.1	Water Use Reduction 20% Reduction	Plumbing fixtures	Low flow fixtures, male and female; Kitchen, sink, shower		Number of male and female users	
WE 3.2	Water Use Reduction 30% Reduction	Plumbing fixtures	Low flow fixtures, male and female; Kitchen, sink, shower		Number of male and female users	

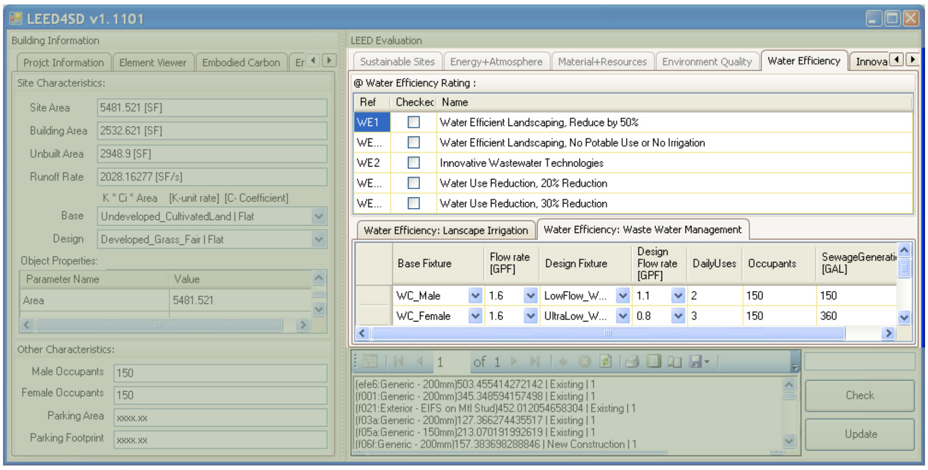

Fig. 4. Water efficiency tabs for rating credits, and various water related calculations

The overall workflow for wastewater management, firstly, retrieves information about the numbers of male and female occupants, which are specified in the building information section of the building information model (Revit). Differences between the baseline and design cases are then compared to determine the number of credits that are earned at this stage.

Most building information models, including Revit, usually offer capabilities for calculating the area covered by buildings, site area, but ground cover type typically has to be manually specified. Although the model can be detailed with material type, information retrieved mostly relates to size and graphics. Additional materials and object parameters such as porosity for materials and flow rates for fixtures are needed. Cost values for fixtures from manufacturers are used for comparison in water use and ultimate cost savings.

The prototype was implemented as an add-on to Revit Architecture 2010. It collects information from the fixtures placed in the model and calculates credits according to methods set out by LEED and the other standards. The application has the potential to be extended to accumulate information from multiple buildings and aggregate total water use. This approach, however, would work only when all pertinent information is available.

3.1 Modeling Urban Water Use

Size matters when there is a shift in scale from the unit to a community. At the urban scale, we face the challenge of propagating results from one building to many. In this study we assume that the buildings are commercial office buildings.

Assumptions and Challenges. In modeling for water use on a larger scale, we have far less information. Here, we adopt a slightly different approach, and employ a combination of different commercial software. The parameters that affect water use are similar to those seen in Tables 3 and 4. At this stage, graywater quantity and rainwater harvesting is not accounted for in the calculation.

As there are many buildings, assigning users to each individual building is difficult owing to lack of information; in this case, we have adopted the method of assigning occupants used by Green Star's method for space allocation [17].

Urban Case Study. The sample case study covers an area of 17346.85 m^2. Of this total area, 11706.56 m^2 covers the building footprint; the remainder comprises roads, pavements and parking areas, which are assumed to have an impervious ground cover. There are also open spaces, which have potential for planning for rainwater catchments and water management. The model is generated from a 2D CAD drawing, and converted into a mass model for the purpose of calculating the total floor areas of buildings. Figure 5 shows the CAD drawing of a portion of the urban area modeled.

Fig. 5. CAD drawing of the test urban area

To generate the three dimensional model we used Rhinocerous® [18] with Grasshopper™ [19]. This offers an easy way to generate a parametric model with the facility to calculate total floor areas for the buildings and specify occupants, fixtures and parameters for calculating water use on a larger scale, with greater flexibility than the Revit environment can currently afford at this juncture. As both Rhino3d and Revit are built on top of the .NET framework [20], communicating specific information between software is fairly straightforward. Figure 6 shows the mass model generated through Grasshopper in Rhino3d. The grasshopper definition file in Figure 7 shows the connection between model geometries to external databases that contain fixture information to generate the water use model for the urban area.

As the scale changes from building to urban, we begin to notice that water use reduction is only a piece of the overall water management scheme. The model reveals potential spaces for artful rainwater catchment areas [21]. Rainwater management, collection and reuse in buildings, and for community activities, rely not only on individual buildings and their storm water collection strategies, but also become part of urban planning, as this is not always cost effective to do so for smaller projects. Information for groundcover type, vegetation, rainfall data for the area are critical to calculating rainwater runoff and collection potential. This is information that is not originally part of the building information model; however, such data needs to be supplied whether calculations are done either in Revit or Rhino3d, or some other combination of commercial building/urban information models.

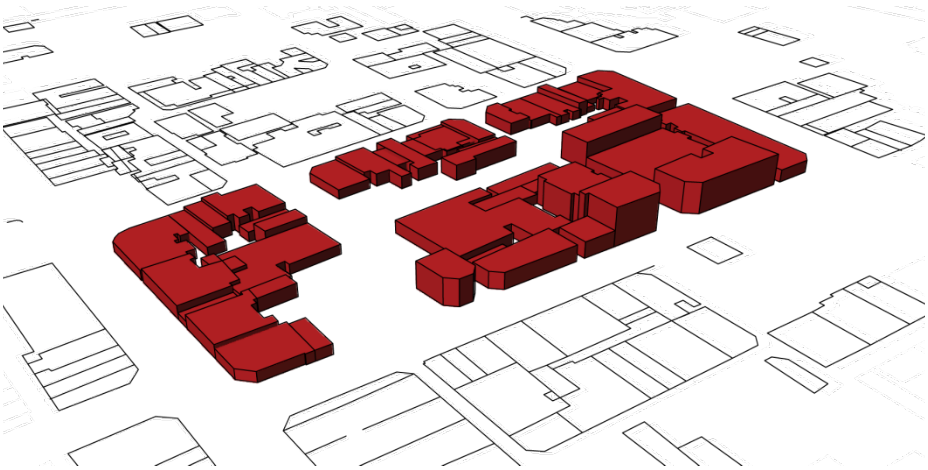

Fig. 6. Modeling the urban area

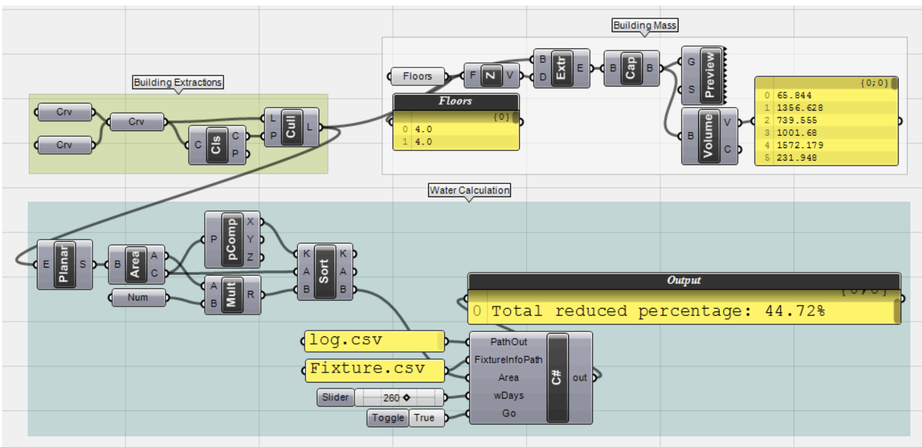

Fig. 7. Grasshopper definition file for water use model generation

4 Analysis

Our sample model for urban water use considered a total building area of 52439m^2 and 3516 occupants. By changing design cases we were able to see explore variations in water use reduction rates. Tables 6 and 7 depict a portion of the sample urban area. For both design cases the number of uses of the fixtures was the same and distribution of male and female were evenly balanced at a ratio of 1:1.

Table 6. Water use reduction: design case 1

Building No.	Case 1	Area (m^2)	Occupant	Water Use
Building_000	BASE	1174.0848	79	617247.540
Building_000	DESIGN	1174.0848	79	340844.868
Building_001	BASE	1356.6284	91	711006.660
Building_001	DESIGN	1356.6284	91	392618.772
Building_002	BASE	153.9494	11	85945.860
Building_002	DESIGN	153.9494	11	47459.412
Building_003	BASE	1001.68	67	523488.420
Building_003	DESIGN	1001.68	67	289070.964
Building_004	BASE	739.5551	50	390663.000
Building_004	DESIGN	739.5551	50	215724.600
Building_005	BASE	65.8443	5	39066.300
Building_005	DESIGN	65.8443	5	21572.460
			Total reduced percentage	44.78%

Table 7. Water use reduction: design case 2

Building No.	Case 1	Area (m^2)	Occupant	Water Use
Building_000	BASE	1174.0848	79	617247.54
Building_000	DESIGN	1174.0848	79	298918.62
Building_001	BASE	1356.6284	91	711006.66
Building_001	DESIGN	1356.6284	91	344323.98
Building_002	BASE	153.9494	11	85945.86
Building_002	DESIGN	153.9494	11	41621.58
Building_003	BASE	1001.68	67	523488.42
Building_003	DESIGN	1001.68	67	253513.26
Building_004	BASE	739.5551	50	390663
Building_004	DESIGN	739.5551	50	189189
Building_005	BASE	65.8443	5	39066.3
Building_005	DESIGN	65.8443	5	18918.9
			Total reduced percentage	51.57%

With the tool it is possible to vary the number and type of fixtures, change the ratio of male and female occupants, and also allocate different design cases to different parts of the urban area in order to parametrically model various scenarios for water use. The two design cases shown have different fixture flow rates; the resulting water reduction savings for design case 1 is 44.78%, and 51.57% for design case 2. Case 1 also has a savings of 12.3 million liters of potable water annually.

5 Conclusions

We have hinted at a fraction of possible calculations that stem from combining a rating system requirement (in this case, LEED) with capabilities provided by a specific commercial building information model (in this case, Revit). We have also given an alternate approach, based on a combination of commercial software, that is, Grasshopper and Rhino3d, external databases and rating system requirements, to illustrate how information (in this case, for modeling water use) can be gathered and processed on a larger scale. These methods can be used to both pre-certify a building for sustainability, and on a larger scale, to project the effects on environmental resources. Through the use of different parameters, generally simple calculations, and by augmenting extant databases of materials and objects, we show how current commercial tools can be used to model environmental resources at both the building and urban scales. There is also no technical reason to suppose that the approach will not work with other green rating system requirements, other commercial building information models and software, or for other environmental resource related calculations. The approach outlined here, to modeling urban water use, prepares the groundwork for implementing other water resource management tools, for example, for graywater and rainwater collection, design of green roofs and water runoff calculation from different surfaces.

The findings described in this chapter lead to the conclusion that strategies, which focus on water use reduction from the scope of the individual building to the urban scale, are among the components required for water management that have to be cohesively integrated to create a 'Green Urbanism' [22].

Acknowledgments. This work reported in this chapter is an extension of a project on integrating building information models and rating systems funded by Autodesk®, which aims to bringing sustainability principles closer to design. However, any opinions, findings, conclusions or recommendations presented in this chapter are those of the authors and do not necessarily reflect the views of Autodesk®. We would like to thank the facilities department at Carnegie Mellon University for their assistance in providing us data and insights on strategies used for achieving credits in the water reduction category though the LEED rating system.

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