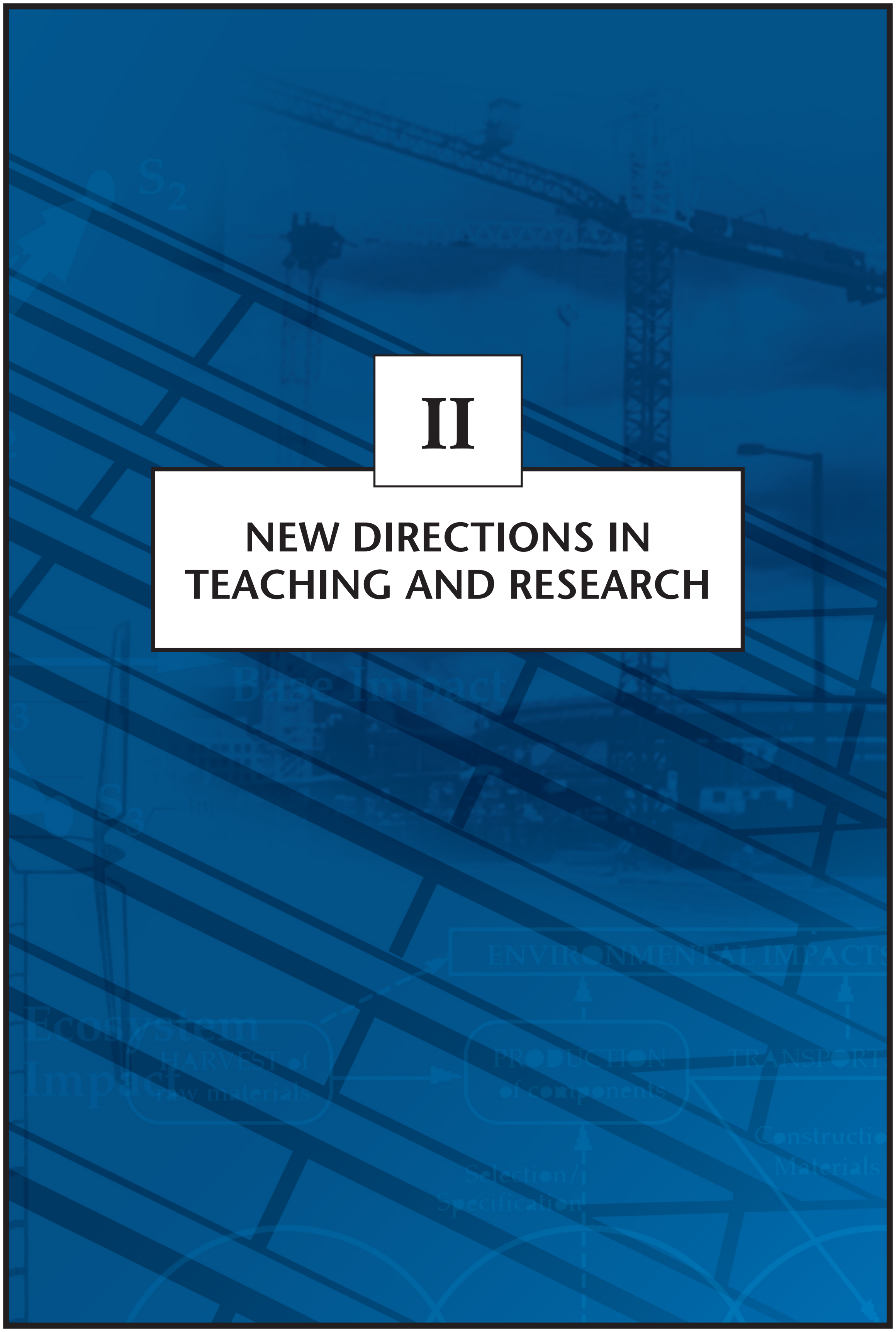
II

NEW DIRECTIONS IN TEACHING AND RESEARCH



SIMULATING THE IMPACTS OF INDOOR VERTICAL FLOW CONSTRUCTED WETLANDS ON HVAC PERFORMANCE USING eQUEST AT HAMPSHIRE COLLEGE'S R. W. KERN CENTER

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INTRODUCTION

Hampshire College, in Amherst, Massachusetts, is taking part in the green building movement with the construction of the R. W. Kern Center, which opened in the spring of 2016. The building was certified to meet the Living Building Challenge in spring 2018 and has satisfied building standards such as Net Zero energy and water. To meet these standards, the design of the building employs solar photovoltaic panels, a rain water catchment and purification system, a greywater treatment system, storm water infiltration rain gardens, composting toilets, and control monitoring systems to make the building more efficient and decrease its harmful impacts on the environment. The greywater treatment system utilizes both indoor vertical flow constructed wetlands (VFCW) and an outdoor horizontal flow constructed wetland (HFCW) to filter greywater effluent from sinks and a coffee bar, meeting the requirement to treat and handle all wastewater generated on site. Although the VFCW system performance has been shown to be effective in exterior environments (Sklarz et al., 2009), its use inside a building requires scrutiny to verify that the adoption of this system does not affect the operation of essential building systems.

The green systems that the Kern Center and others like it are employing may have impacts on the building's environment, construction and operation. These modifications must be monitored, and their effects quantified. The alteration of the thermal and air quality characteristics of the interior building has a significant effect on occupant health and the heating, ventilation and air conditioning (HVAC) energy on consumption. Several studies have investigated the benefits of indoor plants for air filtration or for exterior greywater filtration.

KEYWORDS

Vertical Flow Constructed Wetlands, Greywater Treatment, Relative Humidity, eQUEST, Latent Heat, Sensible Heat, Heating Ventilating and Air Quality and Cooling

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However, due to the evapotranspiration of plants, the addition of plants to a building will alter the interior climate (Zotarelli et al., 2010). The release of water from plants has been well documented and equations to model this process have been developed (Zotarelli et al., 2010). The volume and rate of evapotranspiration from plants is dependent on the solar radiation, air temperature, relative humidity and wind speed. The transpiration rate is also influenced by crop type, development, climate and management. By using the Penman-Monteith equations (Appendix E), which are energy and volume balance equations, the rate of evapotranspiration from a crop over a period of time can be calculated (Zotarelli et al., 2010).

These calculations are simplified by using a reference evapotranspiration and a crop coefficient. The reference evapotranspiration (ET_o) is the rate of vaporization of soil water for a specific vegetated surface given climate conditions (Zotarelli et al., 2010). Based on the atmospheric conditions and a low vegetated reference crop, the atmospheric potential for evaporation can be calculated (Allen et al., 1998). The crop coefficient or crop factor (K_c) is a crop specific ratio that defines the crop's stage of growth and its transpiration potential. The crop coefficient can be used with ET_o to determine the evapotranspiration from a crop over a specific coverage and time (Zotarelli et al., 2010).

By utilizing energy modeling, these calculations can be used to determine the effect of indoor plants on the relative humidity in a building. When the relative humidity inside a building increases, the energy required to change the temperature of a specific volume of air increases due to the high specific heat of water. An HVAC must also maintain a constant humidity; if a building has plants that are increasing the humidity, the HVAC must compensate, potentially increasing the energy consumption.

Building energy performance modeling software is used to assess many different aspects of a building's construction and design. Energy performance modeling clarifies how a building's HVAC system will react to an alteration in the building construction or occupants' lifestyle choices. HVAC simulations can be used to determine appropriate system sizing, pipe fixture sizing, energy analysis and optimization (Trčka & Hensen, 2010). These simulations are widely used, and programs have been developed that allow increased access to non-engineers. Various programs offer performance analysis and predicting annual energy consumption (Trčka & Hensen, 2010). Through the use of these programs and site specifications it is possible to predict energy consumption of an HVAC system, allowing for identification of errors in system operation (Trčka & Hensen, 2010). Performance energy analysis models may then be used to determine when independent variables alter system performance. eQUEST, developed by the Department of Energy (DOE) is a building energy modeling and simulation software which is used to "perform detailed analysis of today's state-of-the-art building design technologies using today's most sophisticated building energy use simulation techniques" (Hirsch, 2016). The physical building, its layout, and its structure is recreated in the program with the correct construction materials and properties. The user has the ability to decide the level of specificity; to define the building and site location, as well as the scheduling of all the equipment and occupancy of the building for each zone for every hour of the year. The simulation results have heating and cooling loads for each zone, relative humidity, temperature, and peak hours for each zone and time of day, as well as many other simulated values.

This study proposes a new strategy to investigate and quantify the effect of indoor VFCW on the energy consumption of the HVAC, testing the ability of energy modeling to be used to quantify effects of system integration. Through this research, the integrated alternative resource management system will be quantitatively analyzed to find the potential effects on energy consumption, allowing for proper application in the future and possible building changes to mitigate this issue. This may push for new developments in energy modeling software more tailored to a systems analysis approach which improves energy modeling to encompass more aspects into whole building analysis.

METHODS

Building Location and Site Specifications

The Kern Center, located on the campus of Hampshire College in Amherst in western Massachusetts, is four stories including an attic and a partial basement. The Kern Center is an academic building mostly used for admissions and financial aid services. It also has several classrooms and a coffee bar. The building covers an area of 16,689 ft^2 with 221,000 ft^3 of conditioned space and is oriented south. Drawings of the floor plan are given in the Appendix B. The surrounding area is cold and humid, designated as ASHRAE climate zone 5A with Heating Degree Days (HDD) between $5400 < (HDD)\ 65°F \leq 7200$. (DeKay & Brown, 2013). It receives an average rainfall of 45.9 inches and snowfall of 36 inches. The area has cold dry conditions during winter months from November through March and hot humid conditions from June to September.

Greywater Filtration System

To sustainably manage the greywater produced by occupants in sinks, water fountains, and the Kern Kafé coffee bar, the Kern Center employs a system of innovative wetland filtration boxes. Greywater generally contains fats, oils, particulate matter and nutrient levels that would be harmful to the environment. All greywater from the building is piped to a collection tank in a dedicated greywater treatment room in the basement of the Kern Center. This effluent is then pumped through the wetland filtration system which includes the indoor VFCW and an outdoor HFCW with ultimate discharge to a leach field. The indoor filtration system consists of three VFCW boxes in parallel with plants that have a high relative transpiration (Figure 3). These constructed wetlands are periodically dosed with greywater on average 1–3 times per day.

FIGURE 1. Location of the building to the surrounding western Massachusetts area and the United States.

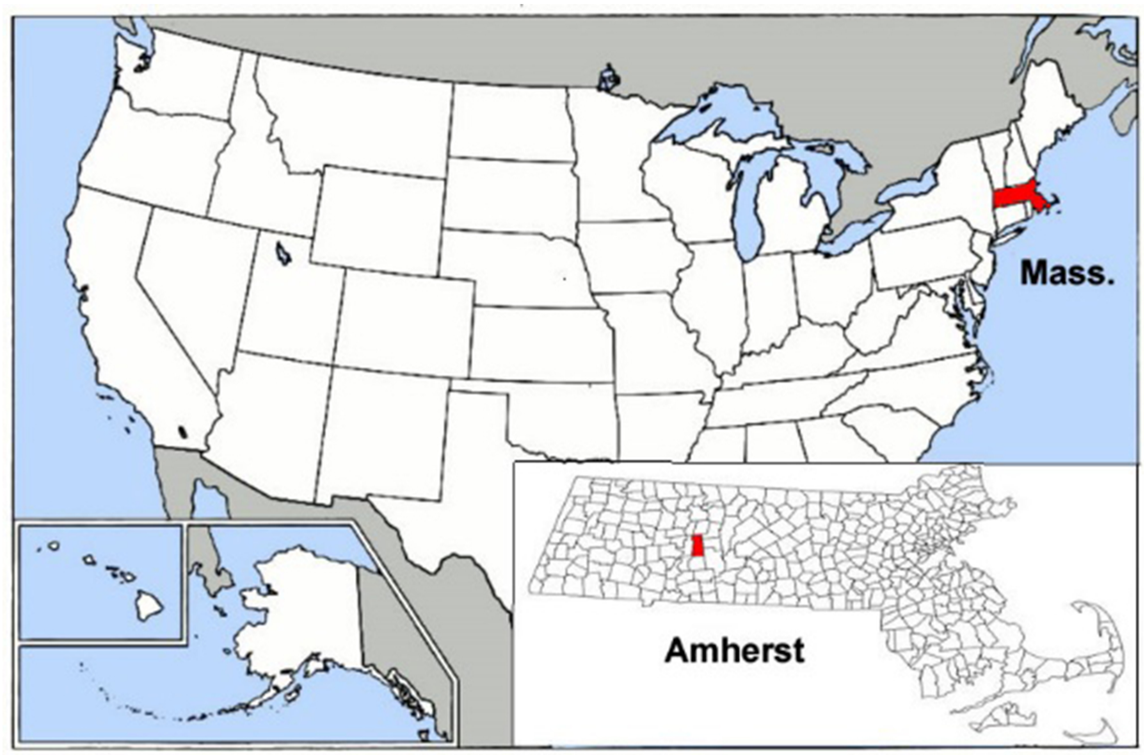


FIGURE 2. Sky view of the Kern Center under construction highlighting the roof top solar panels.

FIGURE 3. Indoor VFCW.

Greywater is treated as it moves vertically through the system. The greywater is then cycled through the system multiple times before being pumped to the outdoor HFCW and the leach field. Figure 4 provides a schematic of each component and the path of the greywater through the system. By using natural processes within the soil and microbial communities, this system provides natural filtration for greywater while also improving indoor air quality and occupant comfort.

eQUEST Model

The model was set up as a three stories high single shell building, excluding the partial basement. The building was broken up into 7 zones for both the first and second floor. The third floor is a conditioned zone closed to public access. Based on the heating and cooling load design documents provided by the architects, every unit in each zone was accounted for and its individual capacity added to the whole building calculation. Appendix C shows each zone, its units and

FIGURE 4. Schematic of greywater treatment system including indoor vertical flow constructed wetland (VFCW) and outdoor horizontal flow constructed wetland (HFCW) with ultimate discharge to an on-site leach field.

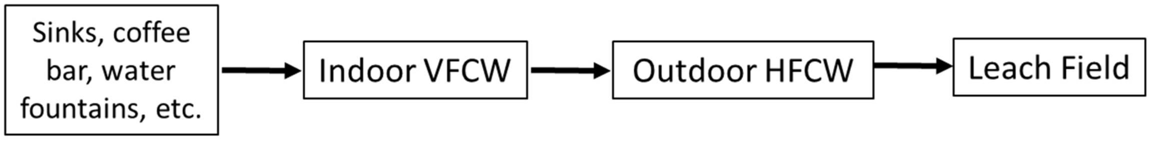
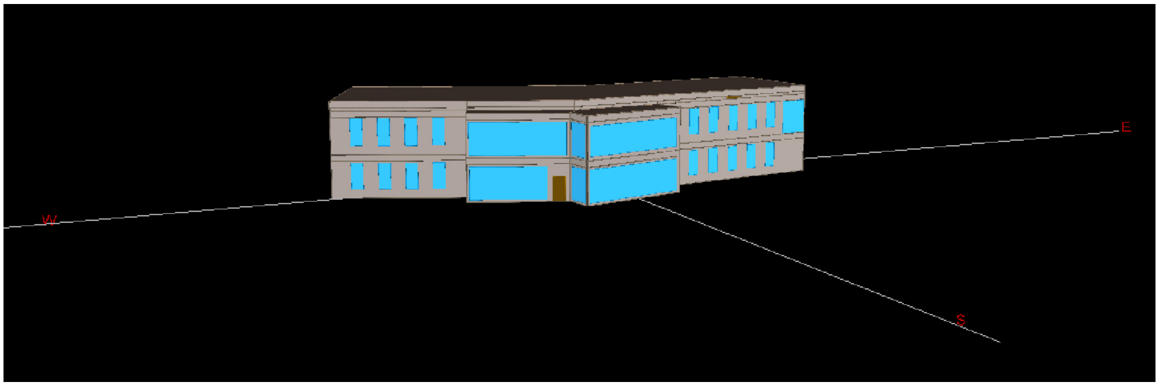


FIGURE 5. The south facing view of the Kern Center in the eQUEST software.

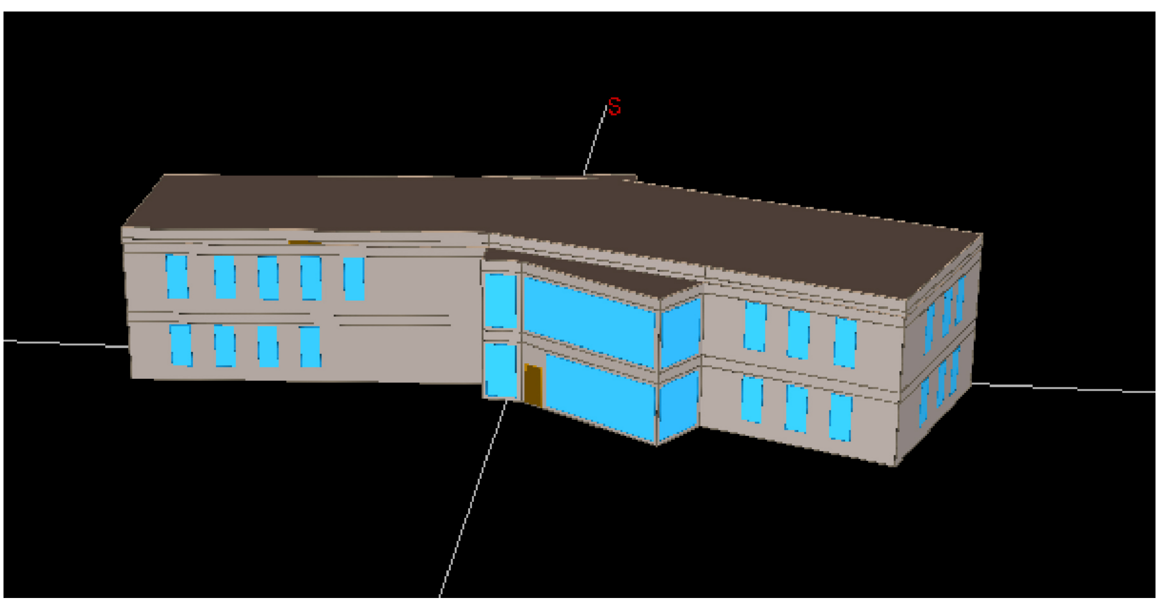


their load. The occupancy schedule was taken from the school operation days as well as the preliminary class and program schedule provided by the building management. The lighting and equipment schedules were taken from the building design documents.

Weather Files

Energy modeling requires a weather file to accurately simulate the operation and energy use of a building's HVAC. To run location accurate simulations, all the variables in Table 1 must be provided. The most recent edition of the Typical Meteorological Year weather files, TMY3, was used for this research and spans from 1991 to 2005. This data was taken from the NREL National Solar Radiation Data Base and was recorded at Chicopee Falls Westover Air Reserve 744910 weather station. The weather station is 10 miles from the building site and is in an area

FIGURE 6. The north-facing view of the model in eQUEST.



that has similar meteorological conditions to the building site and has all the required information for the simulation.

Evapotranspiration Calculation

The energy performance analysis program eQUEST was used to model the annual energy use of the HVAC under two scenarios: the building constructed with the VFCW and the building without VFCW. Using this outline the two simulations were run using the same baseline model of the building accounting for its physical characteristics. The baseline model assesses the building as it was constructed without any load to account for the VFCW. The baseline with planters assesses the building's energy use accounting for the changes to indoor air characteristics due to the VFCW.

eQUEST does not provide a way to directly incorporate undefined, scheduled latent or sensible internal loads to the building model, but does allow for changes in occupancy. Therefore, we used occupancy as a surrogate load to account for the effect plants in indoor

TABLE 1. Weather variables used in eQUEST simulation; these variables are measured and recorded in a weather file and then used to simulate weather conditions in the model. Each variable is denoted with an acronym, description and its units. (NREL Website - http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/).

VARIABLE NAME	DESCRIPTION	UNITS
Kmon	Month	1–12
Kday	Day Of Month	1–31
Kh	Hour Of Day	1–24
Wbt	Wet Bulb Temp	DEG F
Dbt	Dry Bulb Temp	DEG F
Patm	Pressure	INCHES OF HG
Cldamt	Cloud Amount	0–10
Isnow	Snow Flag	1=SNOWFALL
Irain	Rain Flag	1=RAINFALL
Iwinddr	Wind Direction	0–15; 0=N, 1=NNE, ECT
Humrat	Humidity Ratio	LB H2O/LB AIR
Density	Density Of Air	LB/CU FT
Enthal	Specific Enthalpy	BTU/LB
Solrad	Total Hor. Solar	BTU/HR-SQFT
Dirsol	Dir Nomal Solar	BTU/HR-SQFT
Icldty	Cloud Type	0–2
Wndspd	Wind Speed	KNOTS

VFCW have on humidity. The evapotranspiration volume was determined using the Penman-Monteith equations and the equivalent number of people per hour that would have to occupy a zone in the building to release the same volume of water vapor as the VFCW was calculated.

The characteristics of the plants and the physical conditions of each planter box were used to determine the expected evapotranspiration. There are three boxes: two with Philodendron (*Philodendron xanadu*) and one with Peace Lily (*Spathiphyllum wallisii*). The crop factor was assumed to be the same for all the planter boxes. There are two south facing planter boxes and one north-facing box. The two south facing boxes receive sunlight throughout the day except when the outside shades are down. The indoor temperature, dew point and relative humidity were recorded using HOBO UX100-003 Temperature/Relative Humidity Data logger (Onset Computer Corporation, Bourne, MA). The average recorded indoor temperature and dew point, recorded for two months, were used and the wind speed was assumed to be zero since the boxes were indoors. For the two south-facing boxes the average daily solar radiation for the town of Amherst, MA, was used and a reduction of 0.5 was used to account for the reduced transmittance through the triple pane glazed windows (Appendix D). The north-facing box does not receive direct solar radiation, so it was set to receive no solar radiation for the evapotranspiration calculation.

Using the Basic Irrigation Scheduling (BISe) excel calculation workbook, the ET_o for each month of the year was determined based on solar radiation, wind speed, average monthly high and low temperature, dew point temperature and precipitation (Snyder et al., 2013). The

TABLE 2. This gives the ETo for each month the gal/per day determined by the equation sqft * Kc * ET. This value was converted to people/hour (ppl/hr) for use in eQUEST assuming an insensible loss of 700 ml/person per day (Box South West B.SW, Box North East B.NE, Box South East B.SE).

	B. SW			B.NE			B.SE		
Months	ET o	gal/day	ppl/hr	ET o	gal/day	ppl/hr	ET o	gal/day	ppl/hr
Jan	0.03	0.63	3	0.03	0.68	4	0.03	0.64	3
Feb	0.04	0.88	5	0.03	0.68	4	0.04	0.89	5
Mar	0.06	1.30	7	0.03	0.68	4	0.06	1.32	7
Apr	0.07	1.54	8	0.03	0.68	4	0.07	1.57	9
May	0.08	1.85	10	0.03	0.68	4	0.08	1.88	10
Jun	0.08	1.77	10	0.03	0.68	4	0.08	1.81	10
Jul	0.08	1.77	10	0.03	0.68	4	0.08	1.80	10
Aug	0.07	1.60	9	0.03	0.68	4	0.07	1.63	9
Sep	0.06	1.34	7	0.03	0.68	4	0.06	1.37	7
Oct	0.04	1.01	5	0.03	0.68	4	0.04	1.03	6
Nov	0.03	0.68	4	0.03	0.68	4	0.03	0.70	4
Dec	0.03	0.59	3	0.03	0.68	4	0.03	0.60	3

calculated ET_o per month for each box was multiplied by the area of the box and the crop factor held at a constant 0.436 to give the evapotranspiration in gallons per day. The calculated evapotranspiration per month and per hour is given in Table 2 as well as the equivalent number of humans given a standard insensible loss of 0.185 gallons per day.

Occupancy Scheduling

Due to eQUEST's inability to model an undefined hourly latent or sensible heat load, humans were used as a substitute to model the behavior and effect of the indoor VFCW on the Kern Center's environment. Building occupancy scheduling allows for the addition of hourly latent and sensible loads to specific zones throughout the building and allows for multiple schedules. The latent heat gain is the increased load due to the insensible loss or water loss into the air per person. The sensible heat gain is the load due to the release of heat from occupants. The additional increase in occupancy for zones on the first floor, SE NE and SW, was calculated based on the hourly equivalent number of people needed to account for each box (Table 2). Taking the original baseline occupancy schedule and adding an additional occupant load to the affected zones, the plants can be simulated in the model. The equivalent number of humans that would release the same amount of water as the plants per hour was calculated (Table 2). With this value and the room maximum occupancy, a new zone occupancy ratio was calculated (Table 3) To account for the increase in sensible heat gain with the increase in occupancy, a new sensible heat gain per person was calculated. Since the new occupancy relies on the standard insensible latent heat loss from humans, this value was kept constant.

TABLE 3. The calculated additional hourly occupancy ratio for each affected zone for every month of the year. These values are added to the original normal occupancy ratio to give the adjusted occupancy zone ratios.

Months	B.NE ADD RATIO	B. SW ADD RATIO	B.SE ADD RATIO
Jan	0.29	0.36	0.45
Feb	0.29	0.50	0.63
Mar	0.29	0.74	0.93
Apr	0.29	0.88	1.10
May	0.29	1.06	1.32
Jun	0.29	1.01	1.27
Jul	0.29	1.01	1.26
Aug	0.29	0.92	1.14
Sep	0.29	0.77	0.96
Oct	0.29	0.58	0.72
Nov	0.29	0.39	0.49
Dec	0.29	0.33	0.42

The model accounts for humans' impact on the occupant load section, giving a latent heat gain and a sensible heat gain per person. This increase in occupancy ratio, based on the individual box and the month of the year, was added to the original occupancy for each hour of the zone's day schedules. New day schedules for each effected zone were created with 36 new day schedules to account for 3 boxes and zones over 12 months. New week schedules and annual schedules were made following the same original schedule. The new sensible heat gain per person was calculated for each zone to adjust for the increased occupancy, allowing for increased occupancy and net latent heat load, without increasing net annual human sensible heat load. The new sensible heat gain per person was determined by multiplying the sensible heat gain per person by the net occupancy without VFCW divided by the net occupancy with VFCW.

Sensitivity Analysis

To determine the significance of the energy usage impacts related with VFCW in a building environment, a sensitivity analysis was completed to compare the model's reaction to varied set point and occupancy parameters. The model's sensitivity to latent load, in the form of humans, compared to its sensitivity in relation to the building's heating & cooling set point and occupancy schedules was quantified. Numerous methods for sensitivity analysis have been proposed: Lomas J & Eppel, 1992, developed differential sensitivity analysis; Loonen & Hensen, 2013, looked at dynamic sensitivity analysis as compared to traditional methods; Pang, Wetter, Bhattacharya, & Haves, 2012, quantified the sensitivity of weather variables; Nguyen & Reiter, 2015, compared sensitivity analysis strategies; and Azar & Menassa, 2012, investigated building variable occupancy. In this study, due to the desire for a simplified model dependent approach for replication in building energy modeling software, a differential sensitivity analysis was performed.

TABLE 4 Below are the equations used to determine the new sensible heat gain per person to be used in eQUEST for the three affected zones. The first two equations calculate the net annual sensible heat gain for the zone given occupancy without and with VFCW respectively.

Equation for New Sensible Heat Gain per Person	
TSn = A/P * S1 * Rn TSn = A/P * S2 * Rp S2 = S1 * Rn/Rp	
TSn	Annual Sensible gain with normal occupancy
TSp	Annual Sensible gain with normal and plant occupancy
A	Area of the zone (sqft)
Rn	Total occupancy ratio with normal occupancy
Rp	Total occupancy ratio with normal and plant occupancy
S1	Sensible heat gains per person with Rn
S2	Sensible heat gains per person with Rp
P	Number of people per zone

From the sensitivity analysis, the relationship between the annual energy usage and three parameters: occupancy, set point, and VFCW were compared. Four models were created with varying levels of VFCW as follows: Model 1 with no VFCW; Model 2 with VFCW in three zones consistent with the buildings construction; Model 3 with VFCW in three zones on the first and second floor for 6 total effected zones; and Model 4 with VFCW in 8 zones, evenly distributed between the first and second floor. Nine simulations were run for each model, using the parametric simulation function in eQUEST. These simulations varied the building's set points based on a reasonable thermal comfort range ASHRAE Standard 55-2013 and varied the occupancy using square feet (sq.ft.) per person. These parameters were chosen as they affect internal building loads and the range of acceptable building loads and are therefore comparable and important to the impacts of VFCWs. The occupancy parameter has low confidence in its assumptions and variation should be accounted for in a building energy model. The effects of variation in occupancy gives an understanding of the model's sensitivity to errors in assumptions of a highly variable parameter. The set point parameter is also a common parameter to alter in energy savings initiatives and comparison to this parameter could allow for determination of prioritized energy savings retrofit options. These simulations were then compared to the baseline run of each model with altered VFCW but without altered parameters to determine percent change from the baseline. These results were then used to find the average percent change in annual energy usage for a 1% change in the selected parameter. This gives the locally linear derivative of the parameter's impact on energy usage. The correlation of this relationship was calculated with R^2 value and the standard deviation was also determined. The R^2 value gives the linear correlation between the percent change in annual energy usage with the percent change in the parameter; this demonstrates that the relationship between the parameter and annual energy usage is linear. This sensitivity analysis allows for the comparison of each parameter's influence on the model and was used to determine if the percent variation in annual energy usage due to varied VFCW is within the model's range of uncertainty, established by comparison to the derivative impact of other parameters.

RESULTS

From the comparative simulations of the building, with the original occupancy and with the adjusted occupancy to account for the VFCW, the effect of the VFCW on the energy consumption of the HVAC was quantified. The VFCW, represented by increased human occupancy caused an increase in the load on the HVAC system by 2.5%. The breakdown of this effect into each component of the building is shown in Table 5. Based on the sensitivity analysis, the percent change in parameters was compared to the percent change in end use energy consumption. From this analysis, it is demonstrated that a 2.5% increase in annual heating load is within the model's range of uncertainty. The 36 simulations were run and the annual energy usage for each is given in Table 6. These simulations were separated by parameter to compare the baseline of each model with varied VFCW to the variation in the parameters. Table 7 shows the baseline of the four models with varied VFCW and the percent change from the baseline simulation with no VFCW. Tables 8 and 9 display the set point and occupancy adjustments with their respective annual energy usage separated by each model. The percent change in the simulations with varied parameters was calculated in relation to the respective baseline model (Table 10). The R^2 value was calculated based on the percent change in parameter and the calculated percent change from the varied VFCCW baseline models. The set point had a slope of –0.97

TABLE 5. The percent change from the baseline design is calculated with a 2.5% increase in combined heating and cooling load, a negative value represents a decrease in energy usage.

Baseline	Energy Used (kWh (x000))	Baseline + VFCW
Space Cool	31.22	1.0%
Space Heat	17.22	1.4%
HP Supp.	7.48	0.1%
Vent. Fans	35.38	0.0%
Pumps & Aux.	2.86	0.0%
Misc. Equip.	13.26	0.0%
Area Lights	9.5	0.0%

TABLE 6. The annual end usage in kWh x10^3 for each run under each scenario is given below.

	Building Annual Energy Usage (kWh 10^3)			
	Without Plants	VFCW	VFCW (6 Zones)	VFCW (8 Zones)
Baseline	116.92	117.7	118.25	119.71
Set Point – 5%	122.31	123.05	123.72	125.61
Set point – 2.5%	121.12	121.88	122.52	124.33
Set Point + 2.5%	116.03	116.63	117.07	118.31
Set Point + 5%	114.54	115.1	115.48	116.57
Sq.ft./Person 20%	116.01	116.69	117.13	118.26
Sq.ft./Person 10%	116.4	117.14	117.62	118.9
Sq.ft./Person – 10%	117.24	118.09	118.73	120.39
Sq.ft./Person – 20%	118.1	119.03	119.74	121.69

TABLE 7. The annual energy usage for the baseline runs with varied levels of VFCW with the percent change in annual energy usage for each run based on the simulation without VFCW is given below.

	Building Annual Energy Usage (kWh 10^3)			
	Without Plants	VFCW	VFCW (6 Zones)	VFCW (8 Zones)
Baseline	116.92	117.7 (0.7%)	118.25 (1.1%)	119.71 (2.4%)

TABLE 8. The annual energy usage of the building with adjusted set point parameter and with varied levels of VFCW in the building.

	Building Annual Energy Usage (kWh 10^3)			
	Without Plants	VFCW	VFCW (6 Zones)	VFCW (8 Zones)
Set Point – 5%	122.31	123.05	123.72	125.61
Set point – 2.5%	121.12	121.88	122.52	124.33
Set Point + 2.5%	116.03	116.63	117.07	118.31
Set Point + 5%	114.54	115.1	115.48	116.57

TABLE 9. The annual energy usage of the building with adjusted occupancy using varied SqFt. per person and with vaired VFCW levels.

	Building Annual Energy Usage (kWh 10^3)			
	Without Plants	VFCW	VFCW (6 Zones)	VFCW (8 Zones)
Sq.ft./Person 20%	116.01	116.69	117.13	118.26
Sq.ft./Person 10%	116.4	117.14	117.62	118.9
Sq.ft./Person – 10%	117.24	118.09	118.73	120.39
Sq.ft./Person – 20%	118.1	119.03	119.74	121.69

TABLE 10. From the parametric runs, the percent change from the baseline is given in relation to the percent change in each adjusted parameter. The correlation between the %Δ in parameter to the %Δ in annual energy usage is determined using R^2.

			% Δ from Baseline				
% Δ parameter			0	0.5%	0.7%	0.6%	R^2
	Set Point	–5%	3.06%	3.29%	3.66%	4.05%	0.62
		–2.5%	3.36%	3.56%	3.84%	4.09%	0.67
		2.5%	–1.82%	–2.01%	–2.22%	–2.38%	0.75
		5%	–3.77%	–4.09%	–4.49%	–4.80%	0.73
			0	1%	1%	1%	R^2
	Sq.Ft. / Person	20%	0.43%	0.30%	0.23%	0.09%	0.69
		10%	0.20%	0.12%	0.09%	0.04%	0.79
		–10%	–0.23%	–0.16%	–0.05%	–0.04%	0.83
		–20%	–0.36%	–0.21%	–0.04%	0.07%	0.77

with a standard deviation of 0.325 (Table 11). As set point increases by 1%, the annual energy usage decreases by 0.97%. The Sq.Ft. per person had a slope of 0.01 with a standard deviation of 0.008 (Table 12). As Sq.Ft. per person increases by 1%, the annual energy usage increases by 0.01%. As the level of VFCW increases by 1%, there is a 0.008 % increase in annual energy usage; this is correlated with an R^2 value of 0.9 (Table 13).

TABLE 11. The ratio between the percent change in the parameter to the percent change in the building annual energy end use is calculated. The average of these ratios is –0.972 with a standard deviation of 0.448. As set point increases by 1%, the annual energy usage decreases by 0.972%.

Set Point Parameter					
% End Use / % Parameter				Average Ratio	Standard Deviation
–0.61	–0.66	–0.73	–0.81	–0.972	0.325
–1.34	–1.42	–1.53	–1.63		
–0.73	–0.80	–0.89	–0.95		
–0.75	–0.82	–0.90	–0.96		

TABLE 12. The ratio between the percent change in the parameter to the percent change in the building annual energy end use is calculated. The average of these ratios is 0.011 with a standard deviation of 0.008. As sq.ft. per person increases by 1%, the annual energy usage increases by 0.011%.

Sq.Ft. / Person Parameter Ratio					
% End Use / % Parameter				Average Ratio	Standard Deviation
0.021	0.015	0.012	0.004	0.011	0.008
0.020	0.012	0.009	0.004		
0.023	0.016	0.005	0.004		
0.018	0.011	0.002	-0.004		

TABLE 13. The percent change in annual occupancy is calculated and the ratio to the percent change in annual energy usage determined. The R^2 is 0.46 and on average a 1% increase in the parameter is equal to a 0.008 % increase in annual energy usage.

Indoor VFCW Parameter					
		% End Use	% End Use / % Parameter	Average Ratio	Standard Deviation
% Δ parameter	48%	0.5%	0.011	0.008	0.003
	96%	0.7%	0.007		
	135%	0.6%	0.005		

DISCUSSION

The results demonstrate the ability to use energy modeling software to model latent loads associated with plants inside buildings as well as their effects on HVAC operation. However, the limitations of the energy modeling software impacted the simulation and accuracy of the VFCW representation. The modeling of the plants in eQUEST is a tedious, time consuming process. The occupancy schedules are only an hourly adjustment for three of the building's zones and do not perfectly demonstrate the processes that are taking place. It is understood that the building occupant schedule is used to calculate more than just the increased latent loads and that humans are not a perfect fit to the behavior of plants as they also release heat. The resultant end net calculation of the sensible heat gain is a way to eliminate the annual net impact when adding more people to the occupancy schedules. On days when the plants have a limited impact, the hourly sensible heat gain will be less than on the original schedule. This has the effect of giving a lower sensible heat gain than the original schedule for days below the average occupancy ratio and greater for those above the average. This decreases the standard deviation in the sensible gain per hour; this decrease could affect the peak days and impact the heating and cooling load. If the model allowed for the ability to add an undefined latent or sensible load on a schedule basis for any zone, the accuracy of the simulation would be greatly improved. Energy modeling software needs to update its tools to adapt to the changing world of energy efficient buildings allowing for increased ability to model the interaction between multiple new systems.

From the simulation, an increase in heating energy usage of 2.5% was demonstrated. This energy usage, while small in relation to cost, does not consider the other potential effects on building materials that the increased latent heat gain may have (e.g. mold, material degradation). The model also does not analyze the effect of location on the interaction between the VFCW and HVAC. The effects and optimization of these systems in the building environment may be dependent on building location and use. Due to the humid climate in the northeast the use of this type of system has HVAC design risks, as introducing an internal latent heat gain in an already humid climate increases the enthalpy removal during the cooling season. Using indoor wetland filtration systems in dry and hot climates would serve as a benefit, humidifying the air and making for a more pleasant interior environment. Future studies should investigate the operation of these systems in various climates. The optimization of these alternative resource management systems needs to be improved and there must be a building and site-specific design process that relies on system analysis.

Based on the sensitivity analysis, the relationship between the number of VFCW inside the building and the annual energy usage was determined with high correlation and a slope of 0.01 (Table 13). This slope compared to the slope of the other parameters, set point and sq.ft./person (Table 11 and 12), demonstrates that it will take a large percent change in the annual occupancy latent heat gain to have a significant impact on the building's energy usage. From this comparison, it is concluded that the model is much more sensitive to building set points; an addition of VFCW has a negligible impact on energy usage and could be offset with occupant thermal comfort range adjustment.

These simulations have made steps to demonstrate the effect of the indoor VFCW planter boxes on the energy consumption of the HVAC. The simulations demonstrate that there is not a significant impact from indoor VFCW for this building in this climate. These results support the continued development of indoor VFCW and these methods give a platform to begin to understand the dynamic relationships that are taking place between these systems. These results highlight the ability to investigate the interaction of various systems in the building environment with the limited options that now exist. Exploring integrated systems is an important new field of energy modeling that must be expanded as more buildings integrate alternative resource management systems.

CONCLUSIONS

Integrated alternative resource management systems for buildings, such as energy production, water treatment, and building management practices are being implemented to achieve higher standards of efficiency, design and construction. These systems have been measured and researched in the lab and in the field to determine their range of operation. It is essential to pair these operation specifications with investigation of whole building performance analysis to establish nuanced impacts of adopting these alternative resource management systems. Investigating the effects of VFCW employs this approach to assess the integration VFCW and assure the continuance of the environmentally minded, energy efficient, net zero pursuit that the Kern Center represents. The introduction of VFCW was investigated using eQuest energy modeling to determine the potential impacts on the HVAC due to increased latent heat gain in the building. The results of this research do not show a significant change in the Kern Center's end use energy consumption; however, analysis should be completed on other buildings in contrasting locations to determine the impact of climate conditions on the relationship between VFCW and HVAC performance. This research demonstrates the ability of energy modeling to provide a platform for numerical evidence of negative and positive effects of combining separate alternative energy systems together. Continued investigation of VFCW systems will provide design practices and procedures that will consider the varied performance of the HVAC system when used in an integrated environment. Assessment of alternative resource management systems has widespread effects on green building strategies and certifications, by allowing greater ability to customize buildings and system combinations, improving efficiency and decreasing environmental impact. If the green building movement is going to continue to improve a systems analysis approach to building science should be applied to determine potential reductions in energy consumption and cost, allowing for improved building quality and housing accessibility.

REFERENCES

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). Crop evapotranspiration—Guidelines for computing crop water requirements—FAO Irrigation and drainage paper 56. *FAO—Food and Agriculture Organization of the United Nations*.

[Amherst Massachusetts location]. (n.d.). Retrieved from https://www.cityofbreckenridgehills.com/amherst-massachusetts-map.html

Azar, E., & Menassa, C. C. (2012). A Comprehensive Analysis of the Impact of Occupancy Parameters in Energy Simulation of Office Buildings. *Energy and Buildings, 55*, 841–853. https://doi.org/10.1016/j.enbuild.2012.10.002

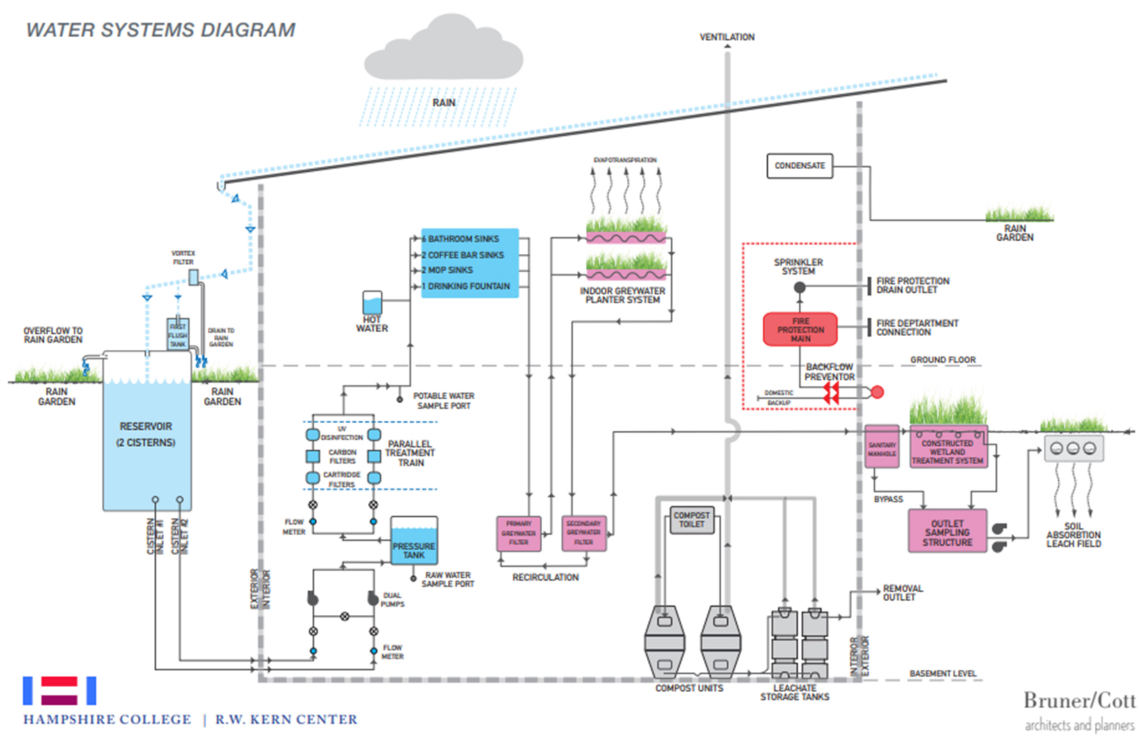
DeKay, M., & Brown, G. Z. (2013). *Sun, wind, and light: Architectural design strategies*. John Wiley & Sons. Retrieved from http://books.google.com/books?hl=en&lr=&id=vMVFp_7zlaIC&oi=fnd&pg=PR3&dq=%22Warmest+month+mean+%3C+72%C2%B0F%22+%22times+as+much+precipitation+as+the+month+with+the+least+precipitation+in+the+rest+of+the%22+%22Dry+season+in+summer.+The+month+with+the+heaviest+precipitation+in+the+cold+season+has+at%22+&ots=NBV7Bjwc6R&sig=sTgSMthR9fkY5l37xQbl53JnDDY

Hirsch, J. J. (2016). eQUEST. Retrieved August 16, 2016, from http://www.doe2.com/equest/

Lomas J, & Eppel, H. (1992). Sensitivity Analysis Techniques for Building Thermal Simulation Programs. *Energy and Buildings, 19*, 21–44.
Loonen, R., & Hensen, J. L. M. (2013). Dynamic Sensitivity Analysis for Performance-Based Building Design and Operation. In *Proceedings of BS2013: 13th Conference of International Building Performance Simulation Association* (Vol. 26, p. 28). Retrieved from https://pure.tue.nl/ws/files/3927151/686740143608400.pdf
Pang, X., Wetter, M., Bhattacharya, P., & Haves, P. (2012). A Framework for Simulation-Based Real-Time Whole Building Performance Assessment. *Building and Environment, 54*, 100–108.
[R. W. Kern Center Arial View]. (n.d.). Retrieved from http://onlyintherepublicofamherst.blogspot.com/2016/03/sunday-construction-update.html
Sklarz, M. Y., Gross, A., Yakirevich, A., & Soares, M. I. M. (2009). A Recirculating Vertical Flow Constructed Wetland for the Treatment of Domestic Wastewater. *Desalination, 246*(1–3), 617–624. https://doi.org/10.1016/j.desal.2008.09.002
Snyder, R. L., Orang, M., Bali, K., & Eching, S. (2013). BISe Basic Irrigation Scheduling Excel Program (English units). *ResearchGate*. Retrieved from https://www.researchgate.net/publication/257409541_BISe_Basic_Irrigation_Scheduling_Excel_Program_English_units
Trčka, M., & Hensen, J. L. M. (2010). Overview of HVAC System Simulation. *Automation in Construction, 19*(2), 93–99. https://doi.org/10.1016/j.autcon.2009.11.019
Zotarelli, L., Dukes, M. D., Romero, C. C., Migliaccio, K. W., & Morgan, K. T. (2010). Step by step Calculation of the Penman-Monteith Evapotranspiration (FAO-56 Method). *Institute of Food and Agricultural Sciences. University of Florida*. Retrieved from http://storm.okstate.edu/bae3313/fall%202013/lecture/5)%20ET/Penman-Monteith.pdf

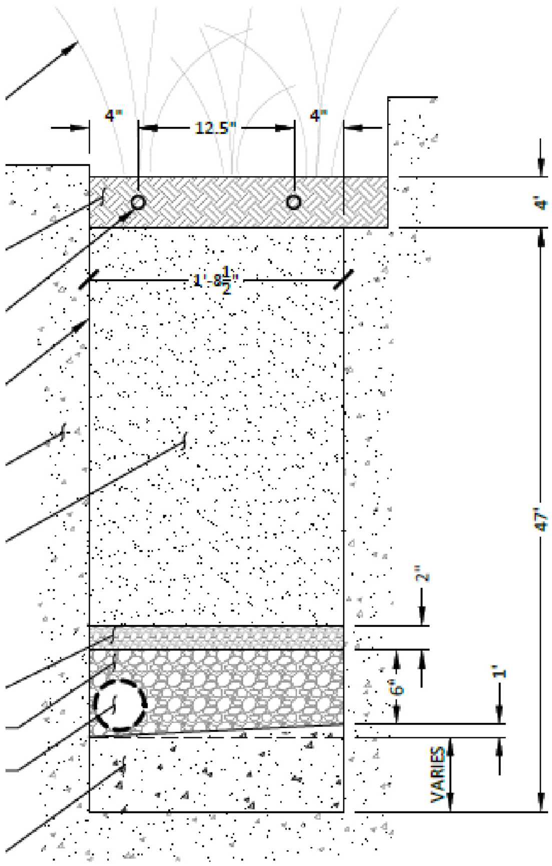
APPENDIX A

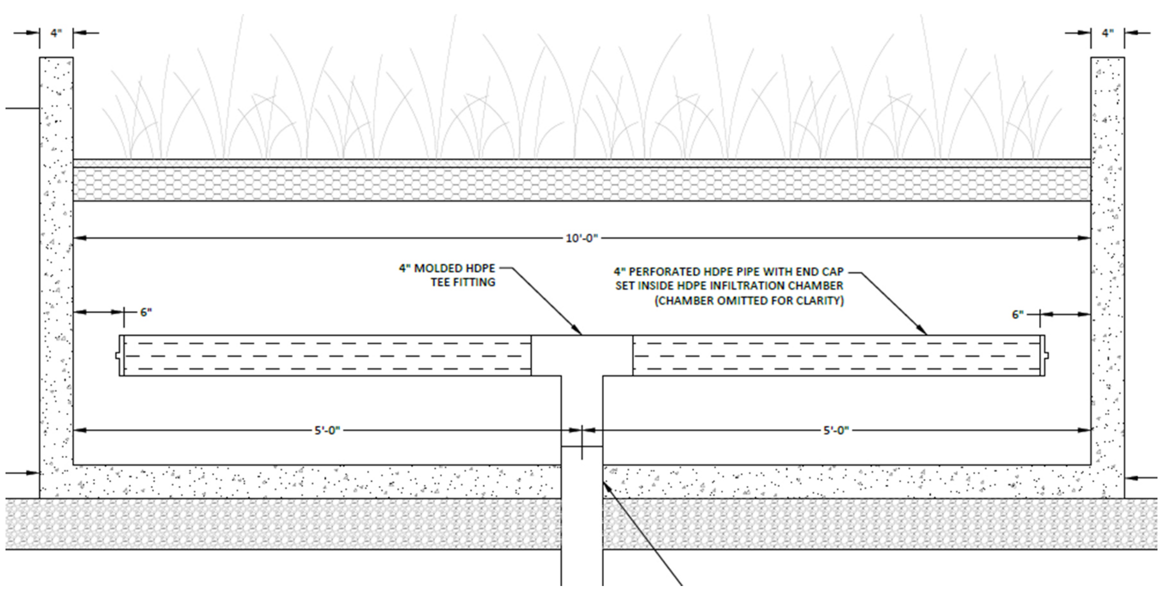
Building water systems diagram detailing the water catchment, treatment, and greywater filtrations systems.



APPENDIX B

The section and cross section view of one of the VFCW showing the gradients of soil gravel types and size of planter boxes.





APPENDIX C

Denotes each zone, its floor, and each unit in the zone. The heating and cooling load in tons is given, as well as the high and low air flow for each unit.

Floor 1	Zone	Units	Cooling	Heating	AIR FLOW (HIGH/ LOW)
	G.SSE1	HP-A36	36,000.00	40,000.00	1165/812
		ERV-2			
TOTAL			**36,000.00**	**40,000.00**	
	G.N2	HP-A15	15,000.00	17,000.00	494/353
		HP-E240			
TOTAL			**15,000.00**	**17,000.00**	
	G.WNW3	HP-12	12,000.00	13,500.00	371/265
		HP-W18	18,000.00	20,000.00	425/320
		HP-W18	18,000.00	20,000.00	425/321
		ERV-5			
		ERV-4			
		ERRV-1			
TOTAL			**48,000.00**	**53,500.00**	
	G.SE4	HP-W08	8,000.00	9,000.00	200/170
		HP-W06	6,000.00	6,700.00	200/170
		HP-A15	15,000.00	17,000.00	494/353
TOTAL			**29,000.00**	**32,700.00**	
	G.SW5	HP-L12	12,000.00	13,500.00	328/258
		HP-A30	30,000.00	34,000.00	742/512
TOTAL			**42,000.00**	**47,500.00**	
	G.C6	HP-C15	15,000.00	17,000.00	390/320
		HP-A30	30,000.00	34,000.00	742/512
		HP-A15	15,000.00	17,000.00	494/353
TOTAL			**60,000.00**	**68,000.00**	
	G.NNE7	HP-A48	48,000.00	54,000.00	1412/989
		HP-L12	12,000.00	13,500.00	382/258
TOTAL			**60,000.00**	**67,500.00**	

(continues)

Floor 2	Zone	Units	Cooling	Heating	AIR FLOW (HIGH/ LOW)
	T.SSE15	HP-C24	24,000.00	27,000.00	706/530
		HP-C24	24,000.00	27,000.00	706/531
		HP-A18	18,000.00	20,000.00	600/424
		ERV-8			
TOTAL			**66,000.00**	**74,000.00**	
	T.N16	HP-W06	6,000.00	6,700.00	200/170
		HP-A15	15,000.00	17,000.00	494/353
TOTAL			**21,000.00**	**23,700.00**	
	T.WNW17	HP-A08	8,000.00	9,000.00	200/170
		HP-A18	18,000.00	20,000.00	600/424
		HP-W06	6,000.00	6,700.00	200/170
		HP-W06	6,000.00	6,700.00	200/171
		HP-W06	6,000.00	6,700.00	200/172
		HP-W06	6,000.00	6,700.00	200/173
		HP-W06	6,000.00	6,700.00	200/174
TOTAL			**56,000.00**	**62,500.00**	
	T.SE18	HP-W08	8,000.00	9,000.00	200/170
		HP-C18	18,000.00	20,000.00	636/494
		HP-W06	6,000.00	6,700.00	200/173
		HP-W08	8,000.00	9,000.00	200/170
		ERV-7			
TOTAL			**40,000.00**	**44,700.00**	
	T.SW19				
	T.C20	HP-A18	18,000.00	20,000.00	600/424
		ERV-9			
TOTAL			**18,000.00**	**20,000.00**	
	T.NNE21	HP-C18	18,000.00	20,000.00	636/494
TOTAL			**18,000.00**	**20,000.00**	

APPENDIX D

The Solar radiation for each month is converted MJ per m 2 per day, taken from the US Climate data. A reduction of 50% is applied to account for the decreased transmittance through the windows of the Kern Center.

Solar Radiation for Evapotranspiration Calculations				
	Average Kw/ m^2/day	btu/ft^2/hr	MJ m^{-2} d^{-1}	Transmitted Through Windows (MJ m^{-2} d^{-1}) (0.50)
Jan	1.4	18	117	59
Feb	2.5	33	216	108
Mar	3.9	52	340	170
Apr	4.4	58	381	191
May	5.4	71	465	232
Jun	4.9	65	427	214
Jul	5	66	432	216
Aug	4.6	60	395	198
Sep	4	52	342	171
Oct	3.2	42	276	138
Nov	1.8	23	153	77
Dec	0.9	12	77	38

APPENDIX E

Penman Monteith Evapotranspiration equation (Allen et al., 1998)

Equation 1: The Penman energy flux rate equation

$$\lambda E = \frac{\left[\Delta\left(R_n - G\right) + \left(\gamma\lambda E_a\right)\right]}{(\Delta + \lambda)}$$

λE = Evaporative Latent Heat Flux (MJ m^{-2} d^{-1}), Δ = Slope of the saturated vapor pressure curve ($\delta e°/\delta T$), where e° = Saturated vapor pressure (kPa) and Tmean = Daily mean temperature (°C), Rn = Net radiation flux (MJ m^{-12} d^{-1}), G = sensible heat flux into the soil ((MJ m^{-2} d^{-1}), y = Psychrometric constant (kPa °C^{-1}) Ea = Vapor transport of flux (mm d^{-1})

Equation 2: The Monteith volume flow rate equation

$$ET_o = \frac{0.408\Delta\left(R_n - G\right) + \gamma \frac{900}{T + 273} u^2 \left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34u_2\right)}$$

ETo = Reference evapotranspiration rate (mm d^{-1}), T = Mean Air Temperature (°C), U2 = Wind Speed (m s^{-1}) at 2 meters above the ground, Rn and G are expressed as MJ $m^{-2}h^{-1}$.