2018 Building Performance Analysis Conference and
SimBuild co-organized by ASHRAE and IBPSA-USA
Chicago, IL
September 26-28, 2018

CHALLENGES AND OPPORTUNITIES IN WHOLE BUILDING WATER MODELING

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ABSTRACT

Whole building water modeling continues to gain traction in the building industry with the public release of *ASHRAE 191P Standard for the Efficient Use of Water in Building Mechanical Systems* and *LEED Pilot Credit: Whole Project Water Use Reduction*. As this new field develops, technical challenges and opportunities arise that highlight the growing need for accurate whole building water modeling tools and procedures. This paper will explore the current challenges in defining plumbing fixture usage, irrigation calculations, and rainfall patterns as well as current methods and data sources for each section.

While energy modelers have many diversity schedules to use -- such as the ASHRAE handbooks, ASHRAE 90.1 reference guide, and the Labs21 schedules – water modelers don't have a comparable set of resources for fixture usage.

There are numerous methods for calculating evapotranspiration to determine irrigation water demand. Many methods such as Penman-Monteith and SLIDE have been adapted for use in landscape calculations, but this has limitations such as use for non-turf grass plants.

Finally, rainfall data sources are varied and inconsistent across data sets. This inconsistency creates repeatability challenges for irrigation and water storage calculations.

INTRODUCTION

ASHRAE 191P Standard for the Efficient Use of Water in Building Mechanical Systems is made up of three major sections; mechanical systems, process systems, and water balance. The mechanical and process chapters address water efficiency in systems such as cooling towers, ground source heat pump systems, sterilizers, and animal watering systems to name a few. It does not regulate plumbing fixtures or irrigation systems as those are covered under existing regulations. However, Chapter 5 aggregates all water usages including plumbing fixtures and irrigation into a water balance. A water balance is defined as an accounting of all water crossing a project boundary and the form of that water.

Most water balances are developed on a weekly or a monthly basis as this is sufficient for many scenarios, and is the method applied in Appendix A of ASHRAE 191P. However, when finer grain analyses are desired, an hourly model may be prudent. Hourly models are beneficial for a variety of reasons such as aligning with hourly energy models and calculating the water usage associated with cooling towers. Hourly models can be used to determine diversified peak electric demand for pumping, which is needed for properly accounting electric utility costs. The hourly models can also be used to calculate peak water consumption as peak gallons per day values are often requested by water and sewer utilities. Often these daily demands are estimated from monthly or weekly water balances but likely don't include the correct diversification to capture the peaks accurately.

Perhaps the most valuable purpose of hourly water models is to right size water storage tanks. Storage tanks are often required for more significant water savings and include cost and space impacts. These systems are more likely to be included if the tanks are not oversized. The authors have directly observed and heard anecdotal evidence of storage tanks being oversized for actual use, which discourages future investments as the systems do not operate properly. As water storage and reuse become more common, and in some states, may become mandatory [NCSL 2018] right-sizing storage will become an imperative. In aggregate this can lead to significant costs and may well disappoint the owners of these systems. If a cistern is never more than half full, an owner may feel like they spent too much money. Conversely, if a cistern is always overflowing, an owner may feel like they aren't getting all their potential water cost savings. Of course, it's impossible to achieve perfection as one year may be dry and the next very wet, but on average engineers should strive to right size storage systems.

A simple storage example is capturing cooling coil condensate and reusing the water in a cooling tower. In a month or week, a building may generate hundreds of thousands of gallons condensate depending on the size, climate, and program. However, as the water is simultaneously needed in the cooling tower and evaporated, a small buffer tank of a few hundred gallons can capture and pump all the condensate.

Like energy performance modeling where architects, engineers, contractors, etc. vary greatly in skill and purpose, water performance modelers suffers from similar inconsistency. One major challenge in water modeling is there is no single dominant user of water on a building-by-building basis. Many urban buildings have little to no irrigation, smaller buildings tend to use air-cooled equipment, and some facilities are so dominated by process equipment or heat rejection that the other end-uses can make up less than 5% of the total water usage such as a data center. Therefore, each project must be examined on a case-by-case basis and goals set according to a whole building water balance. This case-by-case approach means that a passionate piping engineer may need to encourage the mechanical engineer and/or landscape architect to care about water efficiency or vice versa.

To elaborate on this point, in certain parts of the United States irrigation is a top consumer of potable water as shown in Figure 1 and is, therefore, a critical factor to accurately account for in water balances. In practice, the authors have observed varying levels of sophistication among landscape architects (LA's) regarding estimating water consumption for irrigation. Some LA's rely on old rules of thumb whereas other deploy sophisticated algorithms to determine an accurate water consumption estimate. Some LA's include rainfall data whereas others do not as they are sizing the system for a drought rather than typical operation. The level of sophistication has been independent of the location, ie. water stressed regions do not necessarily have more sophisticated practices nor higher water costs.

Ulitmately water performance should be the entire project team's responsibility. Having standards and reliable metrics on which to base methods and calculations is of paramount importance.

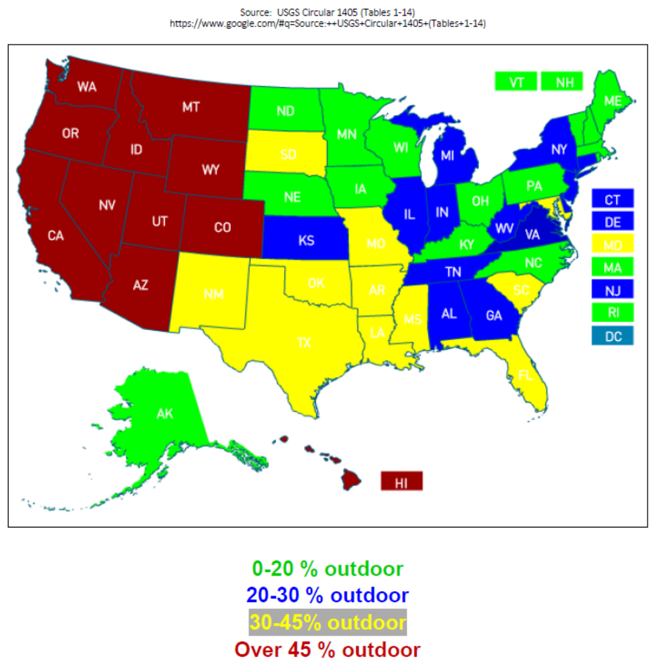

Figure 1: Percentage of Domestic (Residential) Estimated Water Use for Outdoor Use [USGS 2010].

FIXTURE SCHEDULES

Plumbing systems are designed using a variety of methods but ultimately are designed for an instantaneous peak flow rather than a diversified hourly flow rate that would be used in a whole building water model. For example, a building's fixtures and drain requirements are added together to determine peak flow, and then Hunter's curve is applied to determine a diversified peak flow [Cole 2017]. Compare this peak flow with the data shown in Figure 2 for a typical week in a 50,000 ft^2 (4,645 m^2) office building with a six-inch (152 mm) supply pipe. The peak flow of such a pipe is approximately 500 gal/min (31.5 lit/sec) assuming a maximum supply velocity of six ft/sec (1.82 m/sec). The peak consumption in an hour is 120 gallons (454 liter). A diversity of 0.4% would need to be assumed to achieve an accurate peak consumption value, and a schedule with most fraction values well below 0.004, which is not what most modelers would assume as a diversity. This doesn't imply that plumbing system design should change as there are other considerations when sizing plumbing systems such as supplying water to sprinkler systems but illustrates the challenge of aligning peak flow rates and water models. An alternative approach is needed to determine water consumption rather than estimating the water consumption on system capacity.

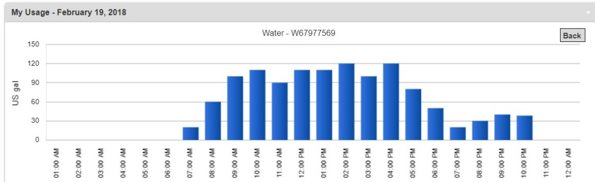

Figure 2: Office Building Hourly Water Usage [MWU 2018].

To develop effective load profiles and water usage schedules for building plumbing systems, a statistically significant amount of water consumption data will be required. Numerous studies have been conducted that provide benchmarks [Wilkes 2005], but measurement methods, building types, and boundary conditions have hampered creating a solid basis for load profiles.

ASHRAE Applications 2015 Figure 24 provides typical and peak hourly domestic hot water flow characteristics for 11 building types. In comparing the 2015 and 2007 handbooks the data used in these profiles have not been updated since at least 2007. Based on observed changes in fixture flow rates over the last 10 years, this data is potentially out of date, especially since total water consumption per capita has declined over the last several decades. Furthermore, this reference looks at domestic hot water flow which in certain applications is well correlated to total potable water use, but in many others such as fixture flushing, there is no value and thus is of limited use for developing a whole building water balance.

A 2015 CALMAC study was conducted to determine the impact of peak water demand on electric utilities in California. In California treating and conveying water consumes approximately 20% of the total electricity in the state [Aquacraft 2011]. The U.S. average is 4% of total electricity consumed. With better water usage schedules, a peak demand study can be conducted demonstrating electric utility savings, which can in turn be used to justify utility incentives [EPRI 2002]. This study also provides a good sample set of building profiles for whole building water models and a variety of end-uses as shown in Figure 3.

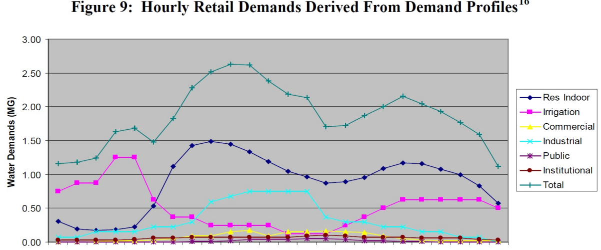

Figure 3: Hourly Demand Profiles [Aquacraft 2011]

In the absence of an hourly profile for water usage, a modeler may use a combination of whole building water use benchmarks and the building's occupancy and equipment schedules to determine a reasonable approximation of an hourly profile. For example, the EnergyStar© benchmark for an office building uses 20 gallons per square foot per year (814.5 L/m^2-year) [ref EPA]. End-use breakdowns show that 40% of the total water usage is applied to domestic fixtures or eight gallons per square foot per year (325.8 L/m^2-year). Assuming a project size of 50,000 ft^2 (4,645 m^2) and 250 days of operation per year about 1,600 gallons per day (6,057 L/day) is consumed in fixtures. Additional refinement can be achieved by applying the building's occupancy schedule, which will further narrow the range; for this example 7 am to 7 pm. Finally, the modeler may now want to apply profiles to this window of time that would yield 1,600 gallons per day (6,057 L/day) and provide a realistic diversity. This approach will minimize the likely error within the water model.

Process equipment that uses potable water such as sterilizers, washing machines, etc. may require a unique schedule for each project. Again, it is recommended to bound the total water usage with a benchmark. Furthermore, aligning the water usage of the equipment with the energy usage will ensure consistency between the models. Finally, don't forget about standby water usage for certain process equipment. Sterilizers in a hospital, for example, will continue to consume a minimal amount of steam and quench water during idle mode day and night.

In recent years several cities such as Madison, WI, have implemented automated meter reading programs that have placed thousands of real-time water meters throughout dozens of building types. This data could be collected as shown in Figure 2 and anonymized to provide a large data set of hourly whole building water usage data. One limitation of this approach is that most buildings have a single water meter so there will be limited granularity.

If the data could be combined with other building metadata such as if the building has food service, a cooling tower, or irrigates, then it may be possible to make an educated guess on hourly profiles. For example, if a building has domestic uses and a cooling tower, then it is likely that the domestic usage will stay relatively steady year-round; whereas the cooling tower will have seasonal water usage. An example of this is for a university research park in Indiana shown in Figure 4.

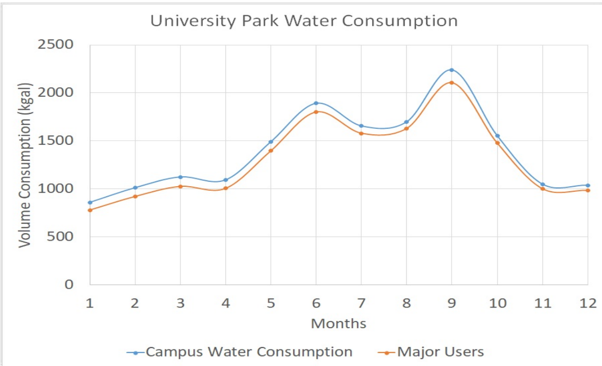

Figure 4: 2016 University Park Monthly Water Consumption

Figure 4 shows a relatively constant winter water demand, whereas it shows a significant increase in consumption in the warmer months as cooling and irrigation demands increase. The relatively constant wintertime demand enables the modeler to determine a reasonable estimate for fixture and process water consumption.

Recommendation

There is likely sufficient data being generated by numerous sources to create a statistically significant benchmark dataset. The collection and processing of this data from water utilities would be a worthwhile project that would benefit the modeling industry and more importantly, help building owners make more informed investments in water efficiency.

IRRIGATION

A key first step is to identify the purpose of the irrigation calculation. Purposes may include; code compliance, peak demand calculation, water budgeting, and design analysis. To date, most tools have focused on code compliance and peak demand calculation to support the design of irrigation systems and appear to achieve this adequately. However, as water becomes more scarce and valuable, water budgeting and detailed design analysis will gain importance. When a full water balance is desired the calculation, especially with non-potable water uses, becomes interdisciplinary and more complex.

The two key challenges identified related to incorporating irrigation calculations into a broader water balance is a consistency and quality of plant demand data, and coordination among different consultants to assemble a complete water balance. There are several plant databases that landscape architects (LA) have access to for determining design conditions for irrigation. Furthermore, the LA has access to irrigation equipment specifications to understand the performance of irrigation systems. However, evapotranspiration (Et) data sources are not available everywhere [ET Connection 2018]. Finally, Et equations such as Penman-Montieth and SLIDE do not provide accurate results under all conditions [Kjelgren et al 2016].

Energy modelers have had access to broad weather data sets that are meant for energy models but can be adapted to calculate Et [Betz and Kuh 2016], although this is not common practice. Furthermore, the measurement height of TMY measurement stations is inconsistent with the heights used in the Et calculations [Wilcox and Marion 2008, Zotarelli et al, 2015]. A wind speed correlation would be needed to align these calculations. A research project utilizing computational fluid dynamics would determine the impact of the measurement inconsistency.

Furthermore, some non-potable water such as cooling coil condensate would come from an energy model that an LA may not always be able to access as not every building has an energy model. Further complexity is introduced with the potential reuse of gray water in irrigation, which comes from the piping/plumbing consultant. Finally, all the calculations might be done at different time increments making alignment of water sources and demands a challenging accounting exercise.

To demonstrate desired water balance results, Figure 5 shows the weekly water balance calculated from hourly data from April through October for a hospital in Wisconsin where available includes rainfall and cooling coil condensate that is combined and is available for reuse in irrigation and cooling tower makeup.

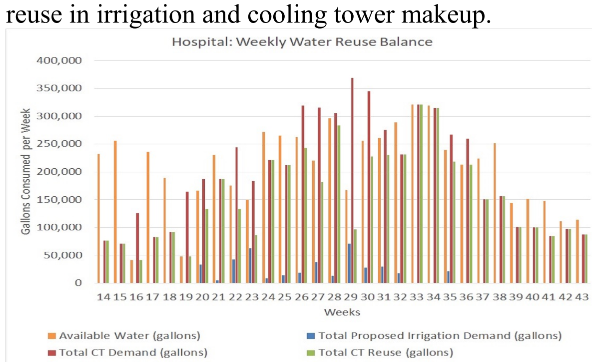

Figure 5: Weekly water reuse balance for a Wisconsin hospital [Betz 2017].

Another value of hourly irrigation models is on a broader community scale. As shown in Figure 1, irrigation can be a significant water consumer and in turn a significant electricity user for municipal water pumps. Understanding how irrigation demand reacts to weather patterns would enable cities to plan for peak water demands as well as electric utilities providing electricity to the supplying pumps [Mayer 2017].

Irrigation Tools

A survey of several irrigation water calculators that are available for download was conducted. The tools achieve a wide variety of purposes. Most are simple tools used for compliance purposes focusing on plant types and perhaps irrigation technology (drip vs. sprinklers, etc.). Sophistication increases in other tools that calculate seasonal demand, and include precipitation estimates [EPA, Florida Water Star© Tool, California Department of Water Resources Water Budget Calculator]. There are several other tools used for sizing irrigation systems [RainBird, Gaia, and WSU http://irrigation.wsu.edu/Content/Select-Calculators.php]. None of these tools offer an input for variable amounts of non-potable water available for reuse, which limits their utility for whole building water balances.

Et References

There are no less than 42 Et databases that are broken out geographically [ET Connection 2018]. Mostly this data is collected for agriculture purposes, however, some states have weather stations in urban areas. Furthermore, not all of these databases use the same Et equations, and the time increment of the data can vary from hourly to monthly. This inconsistency makes it challenging to develop a repeatable calculation method.

Plant Databases

There are numerous types of plants some of which have detailed measurements on transpiration whereas others don't. On a recent 701,095 ft2 (65,134 m2) landscape project with three hydrozones contained 17 distinct plant types. This included five different types of grass some requiring irrigation and others not requiring irrigation after plant establishment. Within each grass type was a mixture of seeds in order to create an aesthetic that is green for much of the year. A spreadsheet tool was developed that used an hourly reference Et rate based on the local TMY file, and then applied that value to each species factor throughout the year to determine an irrigation rate.

Soil Factors

Soil properties vary greatly in both their ability to hold moisture and the hydrozone being investigated. Some irrigation design tools require specification of the soil type to properly account for water infiltration [Rainbird].

The depth of the soil is also a factor when considering urban landscapes. For example, it is known that extensive green roofs (tray systems, etc.) require more frequent irrigation than intensive green roofs. This is primarily due to the minimal amount of soil contained in the green roof to minimize weight, which in turn stores less moisture. Essentially, soil acts as a cistern storing some rainfall and infiltrating others. If the soil has a low storage capacity, then gaps between rain events need to be filled by irrigation. Characterization of rainwater infiltration is also a factor in determining foundation drain water which is increasingly being investigated as a source of non-potable water.

Landscape Aesthetics

High-quality landscapes are defined as landscapes that are maintained and irrigated for a specific purpose such as an athletic field or golf course. The aesthetic and consistency of the plants have a noteworthy value beyond the general aesthetic of landscape found around many homes and businesses. High maintenance turf grass (athletic fields, golf course fairways, etc.) require more irrigation and may have multiple types of grasses to maintain aesthetics over time [Brown 2003]. High maintenance turf grass may have longer irrigation seasons to maximize operational time and increase revenue.

In Phoenix, AZ, measured turf grass Et varies from ~0.05 in/day (1.27 mm/day) in winter months to 0.25 in/day (6.35 mm/day) in summer months for high quality landscapes whereas an acceptable quality landscape may vary from ~0.04 in/day (1.02 mm/day) in winter months to 0.22 in/day (5.56 mm/day) in summer months or approximately 10-20% less water [Brown 2003]. In other words, design Et values are for maximum growth and productivity which makes sense for crops and certain landscapes but is likely excessive for most landscapes around the built environment.

New or Established Plantings

It is known that the new plantings require more water than established plants as the root systems of established plants are more extensive and hardy. However, none of the surveyed modeling tools identified this factor. Long-term operation of irrigation should trend towards less water as plants become established. To the best of the author's knowledge, no guidance has been identified at the time of this writing as a target reduction. For soil moisture sensors, likely a variable setting is required for new plants that are reduced over time once the plants are established.

Rainfall Offset

The last challenge for proper irrigation modeling is how to best account for the impact of precipitation. Evapotranspiration effectively determines the demand side, but the supply side will be a combination of rain and irrigation. Water runoff and direct loses from evaporation need to be accounted for especially when substantial rainfall occurs in a short period of time. The model might consider a maximum soil saturation before the water runs off. Rainfall in short bursts is another reason hourly models are beneficial rather than monthly models. A landscape may require 4 inches (0.1 m) of water per month, and 4 inches (0.1 m) of rain may fall that month. However, if all if it falls within a few hours likely a significant fraction will run off. Consequently, irrigation will be required to maintain the landscape aesthetic.

Recommendation

More sophisticated tools to fully account for all the water use factors in irrigation are desired by the water modeling industry. The current tools have been developed by government, non-profit, and for-profit entities. However, the tools need to be more holistic in their scope and flexible to enable working with a larger water balance including water reuse from fixtures, processes, and mechanical systems.

PRECIPITATION

The most common use of rainfall data in the built environment is to size stormwater management systems. This data is typically broken down into 1-hr and 2-hr rain events. These represent reasonable peak values for sizing storm systems to handle most rain storms although higher rainfall amounts occur with some frequency. However, this peak design data is less useful for determining how building systems that make use of that rainfall on-site should be designed and operated.

Historical annual, monthly, and even hourly rainfall data is available through resources such as NOAA, ARCSA, and Weather Underground. Many of these resources reference the same historical NCDC dataset although inconsistency is frequently observed for the same city if not comparing the exact same weather station and date range. Some weather stations that are short distances apart show a significant difference between peak and average values. Anomalies and periods of uncertain measurement or recording are frequent as well.

The lack of a standard or reliable source of rainfall data requires water modelers to obtain and parse these inconsistent data sets on their own. Parsing these data sets can be difficult and time-consuming. Without industry accepted practices for analyzing this data for water modeling, the same raw data can end up looking very different depending on the methods used to translate this data into a form that is useful for water modeling. A water modeler could end up making dramatically different conclusions on rainwater catchment system design depending on the data source and method of parsing the data for water modeling and analysis.

For years energy modelers have utilized typical meteorological year (TMY) weather files that provide all the necessary inputs to the energy model. The liquid precipitation field was added to the TMY3 data set, although many TMY3 files do not include any values because a statistically significant data set was not collected [Wilcox and Marion 2008]. Water modelers are then required to merge different sets of TMY weather data and rainfall data together which can lead to unrealistic conditions and unreliable analysis outcomes. The alignment of rainfall data with TMY, extreme, and forecasted weather data used in energy models is frequently uncertain.

A final challenge is that the TMY files used from location to location are relatively consistent although microclimates do exist in certain parts of the country; rainfall can vary dramatically over a short distance.

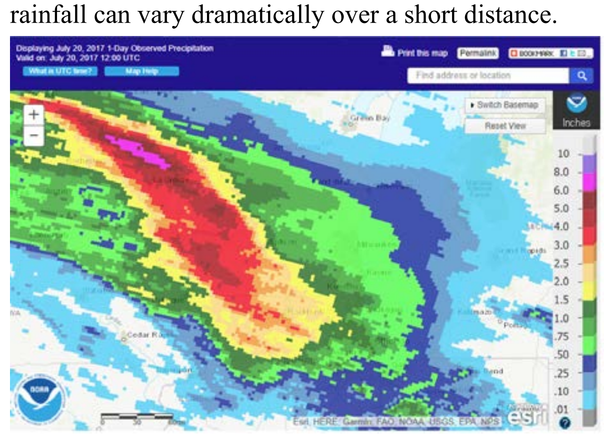

Figure 6. July 20, 2017 Rain Fall Gauge Data

Figure 6 shows rainfall totals for the state of Wisconsin on July 20, 2017. Within 100 miles (162 km) the rain gauges can measure more than a factor of 10 difference.

These differences are significant from West to East even though the relative difference between TMY weather conditions is minor. Droughts can affect areas that are also prone to flooding. Figure 7 shows a screenshot taken from the Gravity Recovery And Climate Experiment [GRACE 2018], a pair of satellites orbiting the Earth that measure groundwater amounts.

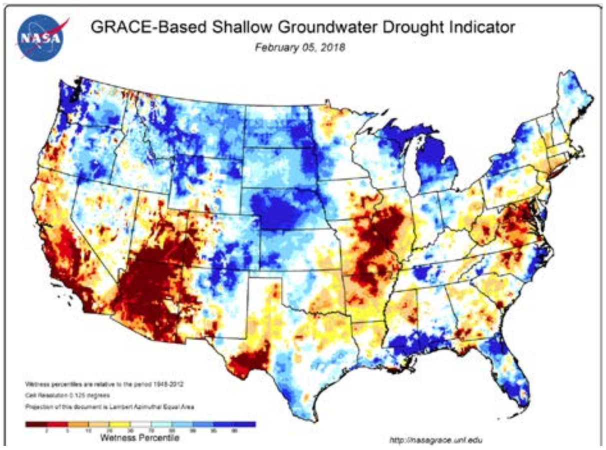

Figure 7: GRACE Data for 5 February 2018.

All of these data demonstrate that precipitation is a highly complex variable to characterize, however, there is an industry need to develop higher quality

Recommendation

Without industry accepted practices on the parsing of rainfall data for water modeling, the only way to address these issues is to conduct sensitivity analyses when determining the optimal design and financial value of rainwater catchment systems. The authors recommend that TMY3 is updated to include better rainfall data as well as the creation of extreme weather files that include better peak demand data. Finally, future weather files would also benefit from better precipitation models as the life of cisterns may be measured in decades.

MODEL ACCURACY

A common criticism of a detailed water modeling approach is the accuracy of the models. The same criticism is leveled against energy models. It is outside the scope of this paper to quantify the value of each modeling approach although that would be a worthwhile endeavor. The scope of this paper is to point out deficiencies and methods to address the deficiencies in water modeling methods and develop best practices. As stated in the introduction there are numerous benefits to more accurate water modeling methods. However, like energy modeling, the results can be skewed by atypical weather and user behavior patterns. The goal is to develop a thorough modeling method that works for most scenarios under typical conditions. The modeling method is not considered a failure if the storage system is oversized because a drought occurs in your project's location. It is a comparison method and the best estimate based on the inputs provided.

CONCLUSION

The demand for whole building water modeling tools and procedures is growing rapidly among industry professionals. Standard methods for these analyses are beginning to take shape, however, there is a lot of refinement that needs to occur in the near future to make it a viable and reputable undertaking. Opportunities include the development of statistically significant benchmark datasets for plumbing system operational diversity, more sophistic and holistic tools for estimating hourly irrigation demand and sources, and finally, industry accepted practices for merging TMY weather data with historical rainfall data for water catchment and reuse systems.

ACKNOWLEDGMENT

The authors would like to thank the ASHRAE 191 committee members and Affiliated Engineers' Water Stewardship Group for providing technical support for the advancement of water modeling techniques.

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