E↓ ≠ H2O↓ : The Energy-Water Nexus in Campuses

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ABSTRACT
Water is a critical index of an organization’s sustainability. Since water reuse consumes energy, water management requires careful analysis of energy implications. To this end, we study the energy-water nexus in a multi-building campus with a water delivery network that spans multiple grades (such as potable, reclaimed sewage, etc). Using data collected over several months, we answer these questions: (i) What are the trade-offs between the external water footprint of a campus and its internal energy footprint of water? (ii) Are improvements in either footprint realizable in practice? (iii) Does reducing the consumption of one water grade have more impact on the energy consumption than other water grades? (iv) Does rainwater harvesting help reduce a facility’s energy footprint?

We construct a multi-grade logical flow network with a per-link cost model for energy derived from the measured data. Under the constraint that demands are always met using the existing supplies, we optimize this flow-network for individually minimizing internal energy consumption of water and external water intake. Our study reveals the following: (i) minimizing external water footprint does not correspond to minimizing the internal energy footprint of water; (ii) demand reduction of different water grades impact the energy and water footprints differently; Contrary to intuition, reduction in second grade water demand yields highest reduction in water footprint while reduction in first grade water demand yields higher reduction in energy; (iii) Rainwater harvesting (RWH) can significantly reduce the energy footprint of a campus water network with sewage re-use. Our results show a potential for improving the operating condition of the campus’s water network that can reduce the energy consumption by nearly 56 MWh (10.5%) and 99.6 MWh (18%) annually without and with RWH respectively.

Categories and Subject Descriptors
G.1.4 [Optimization]: Constrained optimization; J.7 [Computer applications]: Computers in other systems

Keywords
Building energy management, Water management, Optimization, Flow network.

1. INTRODUCTION

Energy and water are the two vital indices of any organization’s sustainability. While people have worked on managing their energy and carbon footprints for several years now, water is just beginning to get noticed. In the last century, while the global population has tripled, the demand for water has increased by more than five times. The demand is expected to further increase by 40% over the next decade. Studies show that, by 2025, two-thirds of the world’s population will live under conditions of water scarcity [1]. This projected shortage across various geographies and its economic implications are important motivations for organizations to manage their water footprints.

Increasingly, water and energy are referred to as two sides of the same coin – termed watergy [4]. This is due to two facts: (i) energy is required to treat and transport water from sources to consumers; and (ii) water is required in many processes of electricity generation (e.g., thermoelectric, nuclear power, etc.). A comparable energy-water nexus exists at the relatively smaller scale of a campus\(^1\) too. In a campus, water gets consumed in captive power generation (e.g., for cooling back-up diesel generators). Water is both an energy

\(^1\)By campus, we refer to a reasonably large landscaped industrial, commercial, or academic site with several buildings and/or plants. Campuses manage their own internal utility networks (water, electricity, gas, and telephone) which are ultimately supplied by their corresponding external counterparts to meet some or all of the demands.
carrier (as chilled water being circulated in a HVAC (Heating, Ventilation and Air Conditioning) loop) and most importantly, a significant energy consumer (for treatment and pumping). We refer to this energy spent to treat and supply water within a campus as the \textbf{internal energy footprint} of the campus water network. In addition, any campus that is not self-sufficient in water, has an \textbf{external water footprint} that it draws from the outside utility. An environment-friendly campus needs to holistically address both footprints.

Many campuses (both university and industrial) in developed countries have multi-grade water supplies. Modern campuses in developing countries, including many Tata Consultancy Services (TCS) facilities, have \textbf{multiple sources of multiple grades} of water including utility, ground-water, harvested rainwater, and reclaimed sewage. Water-consuming activities too have varying quality requirements. For instance, water for gardening need not be of high quality; sewage subjected to primary and secondary treatment would suffice. On the other hand, water used in water-cooled chillers requires further tertiary treatment to prevent the formation of bio-films or scales. Typically, a demand for a quality of water can be met from supplies of a higher grade (e.g., demand for reclaimed sewage can be met by utility water but not vice-versa). Each supply has its own (bio-chemical) quality and results in different energy and carbon footprints.

Given these observations, a natural question arises: what are the energy-water trade-offs of a typical campus with supply and demand of multiple grades of water? A campus that reuses sewage may be termed greener from a public relations perspective than another which does not. However, treating and reclaiming sewage is energy and cost intensive. Therefore, there is a need to systematically analyse the interactions between the two dimensions, viz. water and energy, to understand the coherence (or the lack of it) between them. This is important because the internal energy footprint associated with the campus water can be quite high. For instance, in the campus that we study, the annual energy footprint of water alone is nearly 541 MWh which roughly corresponds to the annual energy consumption of 610 residences in South Asia.

To this end, we focus on the following \textbf{specific questions} in the context of a campus:

- What are the trade-offs between the external water footprint and the internal energy footprint of water?
- Are improvements identified by studying the trade-offs realizable in practice?
- Does reducing the consumption of one water grade have more impact on the energy footprint than other water grades?
- Does rainwater harvesting help reduce the energy footprint?

We answer these by a \textbf{measurement-based case-study of a state-of-the-art office campus that produces and uses multiple water grades} (described in Section 2). We model the campus water network across multiple grades as a flow network with a per-link cost model for energy. The cost figures were derived from data measured at the campus over several months. Under the constraints that the demands are always met using the existing supplies, we optimize this flow-network for objectives that separately minimize internal energy and external water. We use our model to explore trade-offs between these two dimensions.

Our \textbf{findings} indicate the following: (i) minimizing external water footprint does not correspond to minimizing the internal energy footprint of water; (ii) demand reduction of different water grades impact the energy and water footprints differently; Contrary to intuition, reduction of second grade water demand yields highest reduction in water footprint while reduction of first grade water demand yields higher reduction in energy; (iii) Rainwater harvesting can significantly reduce the energy footprint of a campus water network with sewage re-use. Our results show a potential for improving the operating condition of the campus’s water network that can reduce the energy consumption by nearly 56 MWh (10.5\%) and 99.6 MWh (18\%) annually without and with RWH respectively. These identified operating regimes are now being implemented by the campus manager.

The results of our study reveal that the energy or water optimal operating point of a campus water network is affected by several parameters: quality of water supplied, water demand across various grades, performance of the treatment units, intake constraints placed by the utility, and regulatory requirements on the discharge. Since almost all of these parameters can vary with time, the optimal operating point will continuously vary. It is quite challenging, if not impossible, to manually track the parameter changes and maintain network optimality. There is a need for an automated campus water management system that can integrate with the various sensors and appropriately orchestrate the network elements to achieve optimality. Our study takes the first step in this direction by identifying the parameters to capture and the trade-offs to model.

Specific contributions of our work include:

- We collect data from a campus water infrastructure over several months to quantify the total campus demand, supply, and operational costs of treatment units.
- We model analytically the energy costs of operating a campus water network by assigning to individual links, weights that are derived from the collected data.
- We explore the trade-offs between energy and water for various optimization objectives; and identify feasible operating regimes of the network that reduce the energy consumption and input utility water supply. Our model can be extended to optimize other metrics such as monetary costs and carbon footprint as well. Due to lack of space, we do not discuss them in this paper.
<table>
<thead>
<tr>
<th>Flow</th>
<th>pH</th>
<th>TDS(ppm)</th>
<th>Hardness (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inflow</td>
<td>7.61</td>
<td>1395.03</td>
<td>453.71</td>
</tr>
<tr>
<td>Outflow</td>
<td>7.52</td>
<td>1235.27</td>
<td>264.1</td>
</tr>
</tbody>
</table>

Table 2: Summary of WTPs inflow and outflow quality

Earlier works have studied water consumption at end devices in residential homes [10, 17, 9, 18], and saving the energy spent on hot water [14]. To the best of our knowledge, very few works have holistically analyzed the energy-water nexus in campuses across multiple water grades.

The rest of the paper is organized as follows. We describe the case study facility, its water network, and the collected data in Section 2. In Section 3, we model the campus water network and formulate the optimization problem. In Section 4, we study the energy-water nexus in our case study campus under various scenarios by appropriately defining the objective function and constraints. We discuss related work in Section 5 and conclude in Section 6.

2. FACILITY DESCRIPTION

The campus that we study is a LEED-certified landmark facility located in Southern India. The campus is spread over an area of 70 acres with 18 buildings. It houses 24000 employees in a built-up area of roughly 4.34 million sq.ft.

2.1 Demand and Supply

The campus water demand is for five grades of bio-chemical quality. These are shown in decreasing grade quality in Table 1. Each table row gives the demand for a particular grade and the possible supply sources. In some sense, the choice of supplies for the various demands gives the degrees of freedom for optimization. The total demand of the campus across all grades is about 997 kilo-liters per day (KLD). As mentioned before, demand of a grade can be met from a supply of higher grade. The campus is from the utility, which amounts to 703.8 KLD. The only external supply of water to the campus is from the utility (both pipe supply and tankers), which is stored in tanks at the campus entrance. From these tanks, the daily supply of 703.8 KLD is pumped for campus uses. The internal supply to the campus includes its own sewage to the tune of 418 KLD which is treated to various grades and re-used. By regulation, this campus is prohibited from tapping into the underground aquifers. Therefore, local generation or well water is not an option here. Note that the total supply (1121.8 KLD) is slightly more than the demand (997 KLD) to account for losses. A rainwater treatment unit will become operational shortly which will allow harvested rainwater to be another internal supply source. The flows of various grades of water in the campus across the various units is illustrated in Figure 1. Each edge in this graph represents a flow value and the network is color-coded to identify flows of various grades.

2.2 Treatment Facilities

The campus has two Water Treatment Plants (WTP1, WTP2), two Drinking Water Reverse Osmosis units (WRO1, WRO2), one Sewage Treatment Plant (STP) and one STP Reverse Osmosis unit (STPRO). The WTP and WRO units treat the incoming utility water supply to even higher standards. The STP and STPRO provide secondary and tertiary treatments to reclaim sewage.

Utility water treatment: Both WTP1 and WTP2 have a treatment design capacity of 550 KLD. Utility water coming into the campus is collected in two raw water tanks. From the tanks, water is pumped to the WTPs where it goes through pressure sand-filters and water softeners. In the pressure sand-filters, water under pressure will be passed through a layer of small sand particles. The filtered water is then passed through an ion-exchange resin which replaces Calcium (Ca\(^{2+}\)) and Magnesium (Mg\(^{2+}\)) ions with Sodium (Na\(^{+}\)) ions thereby reducing its hardness. The ion-exchange resin needs to be regenerated (cleaned) with Na\(^+\) ions periodically, and this regeneration water is used for gardening in the campus. Water quality parameters of the inflows and outflows to each of the WTP are given in Table 2. The softened water gets collected in treated water tanks. One part of the treated water is pumped to garden, faucets and dish-washers in the campus. The other part is sent to two reverse osmosis plants (WRO1 and WRO2) to produce potable water. The capacities of WRO1 and WRO2 are respectively 50 and 150 KLD. WROs reduce the TDS level of incoming water considerably. On an average, the TDS level of incoming water will be around 1235 ppm and WROs reduces it to around 65 ppm.

Sewage: The waste from all water usages goes to the STP. The STP has a design capacity of 700 KLD and produces pH-neutral water. The main unit of STP is the Membrane Bioreactor (MBR). MBR is a combination of microfiltration with a suspended growth bioreactor. In the campus STP, the MLSS (Mixed Liquid Suspended Solids, i.e., the concentration of suspended solids in the aeration tank) is maintained at around 3 kg/m\(^3\). The treated water has a pH of 7.5 and TDS around 1700 ppm. A portion of the STP treated water is used for flushing and gardening directly. Another portion is fed to the STPRO unit, which further treats it using an RO process. This RO treated STP water is used for replenishing the water lost due to evaporation in water cooled chillers. The STPRO has a capacity of 250 KLD. It brings down the TDS level of incoming water from around 1700 ppm to 250 ppm and pH to 6.5.

Rainwater: The facility has a rainwater harvesting pond of capacity 24000 KLD, which collects rainwater from rooftops of buildings. Harvested water can be directly used for gardening or sent for treatment. A rainwater treatment unit with a capacity of 500 KLD is scheduled to be commissioned.

In addition to the above, drain water from the Air Handling Units(AHUs) of the campus HVAC system is mixed with the STP treated water and used for flushing.
Table 1: Demands and associated supply options for the campus. Quality decreases from potable grade through third grade. The various supply options provide the degrees of freedom for optimization. The supplies are paths in the water flow network shown in Figure 1.

<table>
<thead>
<tr>
<th>Grade</th>
<th>Demand</th>
<th>Supply</th>
<th>Flow (KLD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potable</td>
<td>Drinking, Cooking</td>
<td>Utility + Softening + RO</td>
<td>51</td>
</tr>
<tr>
<td>First</td>
<td>Faucets, Dish-washing</td>
<td>Utility + Softening</td>
<td>300</td>
</tr>
<tr>
<td>Second</td>
<td>Fire-fighting, Chillers</td>
<td>Utility + Softening, Recycling + Tertiary</td>
<td>250</td>
</tr>
<tr>
<td>Third</td>
<td>Flushing, Gardening</td>
<td>Recycling Utility + Softening + RO - Reject</td>
<td>396</td>
</tr>
</tbody>
</table>

Table 3: Summary of data measured at the various campus treatment units. Note that outflow = yield + reject and inflow = loss + outflow.

<table>
<thead>
<tr>
<th>Entity</th>
<th>Avg. monthly inflow (KL)</th>
<th>Avg. monthly energy (KWh)</th>
<th>Avg loss (% of inflow)</th>
<th>Avg reject (% of outflow)</th>
<th>Avg yield (% of outflow)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WTP1</td>
<td>5912</td>
<td>1301</td>
<td>5</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>WTP2</td>
<td>3961</td>
<td>871</td>
<td>5</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>WRO1</td>
<td>455</td>
<td>755</td>
<td>0</td>
<td>62</td>
<td>38</td>
</tr>
<tr>
<td>WRO2</td>
<td>4570</td>
<td>7586</td>
<td>0</td>
<td>70</td>
<td>30</td>
</tr>
<tr>
<td>STP</td>
<td>12481</td>
<td>26749</td>
<td>10</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>STPRO</td>
<td>5208</td>
<td>7521</td>
<td>0</td>
<td>50</td>
<td>50</td>
</tr>
</tbody>
</table>

2.3 Data Collection

For each of the treatment units, we collected the following data over several months: From these data cost associated with per unit flow is arrived at.

- **Input and Output flow values**: Inflow and outflow data in a treatment unit was collected using the flow meters attached to the unit. The average value of the samples obtained over a day is used as the daily flow rate. Since each grade of water is covered either at the inflow or outflow of one of the treatment units, we have a complete picture of the water flow in the entire campus. Further, monitoring at inlet as well as outlet allows us to calculate the water loss and recovery percentage associated with each treatment unit.

- **Energy consumption**: From the monthly energy meter logs, we obtained the energy consumption corresponding to different treatment units and water pumps.

- **Sundry costs**: From the monthly operational logs, we obtained the other monetary costs associated with the treatment and pumping units such as chemicals, labor, and maintenance. Some of these costs are dependent on the flow rate while others are not. The monetary cost of operating a treatment unit would be the sum of these sundry costs and the monetary cost of the consumed energy.

A brief summary of the data measured at the various treatment units is given in Table 3. We also collected data about the operation of various pumps. For the sake of brevity, we do not present the pump data and the monetary costs.

3. MODELING THE WATER NETWORK

We need a framework that can model multiple grades of water and the associated energy costs. Inherently, the campus water network is a flow network. While flows vary with time, we are interested in characterizing the macro behavior. A natural analytical model for this would be a logical flow network with the flows of each link being the average flow over the period of study. Specifically, if an active entity (viz. treatment plant, pump) is on for some duration and has an associated cost/volume with that duration, we assume that the entity is switched on throughout the day with the actual cost/volume being amortized over the day.

3.1 Logical Flow Network Construction

The logical flow network is a directed multi-graph $G = (E, V, Q)$, where $E$ is the set of edges, $V$ is the set of nodes, and $Q$ is a set of water qualities (grades). The set of nodes $V$ in the graph include the following: (i) supply points which include utility supply and rain water pond; (ii) storage units that include tanks; (iii) intermediate points that neither supply nor consume but only treat water such as treatment units. (iv) demand points that include office buildings, garden, and the discharge point.

A directed edge $e \in E$ represents the pipe between two nodes; the edge’s direction is that of the flow. The magnitude of flow is $f_q(e)$ where $q \in Q$ represents the water grade. As in the real world, an edge $e \in E$ carries flow of only one quality. Therefore, multiple directed edges are
possible between two nodes if multiple water grades flow across the corresponding physical entities. A node \( v \in V \) may have demands of various grades \( q \) denoted \( d_q(v) \). Intermediate nodes have zero demands and the supply points have negative demands.

3.2 Network Constraints

Flow: As in any flow network, we assume that the total flow across all water grades entering a node in the flow graph is equal to the outflow across all water grades. We note that losses at active treatment elements are accounted for as additional demands. We have:

\[
\forall v \in V, \sum_{q \in Q} \sum_{u \in V} f_q(u, v) = \sum_{q \in Q} d_q(v) + \sum_{q \in Q} \sum_{w \in V} f_q(v, w) + \text{Losses}
\]

(1)

Demand: We assume that all demands across all grades are always met. Therefore our analysis is demand-driven, i.e., demands are constraints in the optimization problem. However, there is some flexibility in terms of the grade of water used to meet the demand, as can be observed from practice. For instance, first-grade water can be used for flushing but not vice-versa. In other words, we assume that the demand at a node for a given quality \( q \) can be met not only by water grade \( q \) but also by any water grade higher than \( q \). Note that higher grades are denoted by lower numerical values (i.e., grade 1 is higher than grade 2). Formally, this constraint along with the grade flexibility can be stated as:

\[
\forall v \mid d_q(v) > 0 \left( \sum_{p, p \leq q} \sum_{u} f_p(u, v) - \left( \sum_{p, p \leq q} \sum_{w} f_p(v, w) \right) \right) \geq d_q(v)
\]

(2)

This flexibility in meeting a given demand with better grades gives rise to different energy-water trade-offs. The ordering of different water grades by quality is given in Table 1.

Capacity: We need to model the capacity constraints of the various active nodes in the network. Specifically, we need to add the constraint that the total inflow to any treatment plant does not exceed the design capacity of the plant. In addition for storage elements such as tanks, we need to ensure that

Figure 1: The multi-grade campus water network. Nodes and edges are colored based on the water grade(s) they handle. The \( x \)’s are the edge labels used to represent the flows of the edges. Links x26 and x27 are complimentary, only one of them will be active at a time. If regulations of the region do not permit direct discharge of sewage into the discharge canal, x26 will be active or else x27 will be active. Link x26 will help to model the treated sewage discharged into the discharge canal in the event of heavy rainfall or others, when the demand for third grade water comes down drastically. (this figure is best viewed in color.)
the tank does not overflow, i.e., the average net flow into the tank over the time-period of analysis should not exceed its capacity.

$$\sum_u f(u,v) \leq \text{Capacity}(v) \tag{3}$$

### 3.3 Cost Models

Intuitively, the water in the campus network can be thought of as moving across qualities (via treatment units) and locations (via pipes). Thus the total cost\(^3\) of operating the campus water network across the entire water cycle can be categorized into two components: (i) treatment cost \(C_T\) of moving water across qualities (e.g., sewage to flushing grade) and (ii) pumping cost \(C_P\) across locations (e.g., from treatment unit to building). Note that we do not consider capital costs as the network is already operational.

Water enters a treatment unit (e.g., STP) at a certain grade and leaves the unit at a higher grade. We associate the treatment/pumping energy cost with the edge that brings the inflow into a treatment unit. The total cost of a flow \(f(e)\) through an edge \(e\) is \(C_P(f(e)) + C_T(f(e))\). If an edge is gravity fed (as in the case of sewers), \(C_T(e)\) would be zero. In cases where an edge leaves an office building, \(C_T(e)\) would be zero as an office building converts water from higher quality to a lower quality at no cost. Based on the data collected for this campus, we fit linear models to \(C_T(f(e))\) and \(C_P(f(e))\).

Mathematically, improving the as-is condition would correspond to minimizing total cost (across all edges) of the network over the set \(F\) of all feasible flow values of the network subject to the above three constraints:

$$\text{Objective: } \min_{F} \sum_{e \in E} C(f(e)) \tag{4}$$

subject to Equations 1, 2, and 3.

where \(C(f(e)) : f(e) \rightarrow \mathbb{R}^+\) is a linear cost function defined on the flow through a subset of edges \(E \subseteq E\).

### 3.4 Solution

The objective function and the constraints are linear and so standard approaches for linear programming can be used. For larger scale networks with several nodes and multiple grades of water, the number of constraints can be significant. However, as the network constraints are from a flow network, this optimization problem can be solved by using a network simplex [15] approach to minimize the cost of operation either in energy, or water terms. While standard solutions to the linear program can also be used, the network simplex is likely to be more efficient for larger scale flow networks as it exploits the network structure. For each objective, we obtain the flow values that would generate that

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**Table 5:** The campus water network’s performance under different objectives is shown. The average daily values are given. The link-wise flow values for these optimization objectives are given in Table 4.

<table>
<thead>
<tr>
<th>Objective</th>
<th>Energy (KWh)</th>
<th>Water Intake (KLD)</th>
<th>Discharge (KLD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>As-is</td>
<td>1484</td>
<td>703.8</td>
<td>105</td>
</tr>
<tr>
<td>Water</td>
<td>1431</td>
<td>688</td>
<td>92</td>
</tr>
<tr>
<td>Energy</td>
<td>1328</td>
<td>703.8</td>
<td>111</td>
</tr>
</tbody>
</table>

Optimal operating condition using the \(\mathbb{R}\) language optimization libraries.

### 4. ANALYSIS

For this analysis, the daily supply and demand values observed during the winter & early spring months were used. We find that the daily values do not vary significantly over these months. During this period, the campus’s average utility water intake is 703.8 KLD. In addition to this, the campus recycles 418 KLD of sewage. These two sources feed a demand of 997 KLD across various grades, the treatment unit losses, and the campus discharge. The demand break-up across various grades is given in Table 1. The campus discharges nearly 105.1 KLD of water in the sewers as waste. The average monthly operational costs (in Indian Rupees) and the energy consumption associated with the present state are respectively ₹1.14 M and 44.5 MWh. The "as-is" state is summarized in the first row of Table 5.

#### 4.1 Energy-Water Trade-off

We now consider the trade-off between minimizing water’s internal energy footprint and minimizing external water footprint. This is subject to the constraints that demands of all grades are met in both quantity and quality.

**Minimizing external water footprint:** By external water footprint, we refer to the total amount of fresh water procured by the campus from outside sources such as the utility. To minimize external water footprint, we instantiate the cost function \(\mathcal{C}\) and edge set \(E\) in Equation 4 as follows:

- \(E = \{x_2\}\), i.e., the edge set is a singleton set containing just the utility supply line \(x_2\) marked in Figure 1.
- \(\mathcal{C}(f(e)) = f(e)\), i.e., the cost function equals the average flow through the utility supply line.
- Equations 1, 2, and 3 are the constraints.

The optimal solution yields the operating point with the lowest external water footprint. All footprints of this operating point are shown in Table 5. The link-wise flow values are given in Table 4. The external water intake reduces by 2.2% and the campus discharge decreases by 12%. The strategies that realize this operating point can be obtained by comparing the flows through the various edges under the "as-is" and water-optimal operating points.

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\(^3\)We use the word ‘cost’ in a generic way in the paper, this term can imply the external water intake, internal energy footprint, or the dollar footprint depending on the optimization objective.
Table 4: The campus water network’s flow through the links are shown. The average daily values in KLD are given.

<table>
<thead>
<tr>
<th>Link IDs</th>
<th>Description</th>
<th>As-Is (KLD)</th>
<th>Min Water (KLD)</th>
<th>Min Energy (KLD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>x1</td>
<td>RWTP-RWSum</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>x2</td>
<td>UW-RWSump</td>
<td>703.86</td>
<td>688.1</td>
<td>703.86</td>
</tr>
<tr>
<td>x3</td>
<td>RWSump-WTP2</td>
<td>550</td>
<td>138.1</td>
<td>550</td>
</tr>
<tr>
<td>x4</td>
<td>RWSump-WTP1</td>
<td>153.86</td>
<td>350</td>
<td>153.86</td>
</tr>
<tr>
<td>x5</td>
<td>WTP1-SWSump</td>
<td>141.78</td>
<td>506.83</td>
<td>141.78</td>
</tr>
<tr>
<td>x6</td>
<td>WTP2-SWSump</td>
<td>506.83</td>
<td>127.26</td>
<td>506.83</td>
</tr>
<tr>
<td>x7</td>
<td>SWSump-WRO2</td>
<td>150</td>
<td>106.18</td>
<td>106.18</td>
</tr>
<tr>
<td>x8</td>
<td>SWSump-WRO1</td>
<td>16.3</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>x9</td>
<td>SWSump-Office</td>
<td>463.47</td>
<td>477.91</td>
<td>492.42</td>
</tr>
<tr>
<td>x10</td>
<td>SWSump-Garden</td>
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</table>

Figure 2: The energy-water trade-off. The first two graphs provide a comparison of the campus water network’s different optimal operating points with respect to the "as-is" state. The third graph shows that as the cap on utility water intake increases, the water network’s energy footprint decreases.
Realization: Figure 2(a) gives the difference in flow values that have changed considerably from the as-is state. The demand point whose supply has changed significantly is the garden. Specifically, the garden’s demand of third grade water is met either through 1) STP output, 2) reject of the WTP and WRO treatments, and 3) softened water. Of these supplies, both options 2 and 3 are fed from utility water directly (as opposed to sewage which is consumed utility water). To meet the same garden demand, the STP output to the garden has gone up by 28 KLD while softened water supply decreases by 18 KLD and the rejects from WRO1 and WRO2 collectively decrease by 10 KLD. The WRO treatment and the water softening treatment are both fed by utility water supply. Therefore, in accordance with the above decreases, the utility supply should decrease by roughly 30 KLD (after accounting for the rejects at WROs). However, the utility supply also increases by 15 KLD to offset the increase in STP-RO’s output. This results in a net decrease of 15 KLD (2.2%).

The reduction achieved in external water footprint is limited for the following reason. Being a state-of-the-art facility, the campus already reuses water to a good degree through its STP and STPRO plants. A significant reduction in water intake cannot be achieved unless (i) the demands themselves are reduced, and/or (ii) the losses in the treatment units are improved by using a different set of treatment technologies, which requires some investment. In sum, the quantum of reduction in external water intake is limited by the reduction in the demands for the first and second grades.

Minimizing the internal energy footprint of water: The cost function $\mathcal{C}$ and edge set $\mathcal{E}$ in equation 4 are instantiated as follows:

- $\mathcal{E} = E$, i.e., the edge set under consideration is the set of all edges in the flow network in Figure 1.
- $\mathcal{C}(f(e)) = \sum_{e \in \mathcal{E}} C_T(f(e)) + C_P(f(e))$, where $C_T(\cdot)$ and $C_P(\cdot)$ are the energy costs of treating and pumping respectively a flow $f(e)$ through an edge $e$.

In addition to Equations 1, 2, and 3, we include one more constraint. As Table 3 shows, the sewage recycling inflow link $x_{x2}$ is quite an energy intensive link. So an unconstrained energy optimization will identify a solution that bypasses this link completely. As a consequence, the campus will use utility water alone for meeting the demands of all grades. While this is feasible theoretically, this will dramatically increase the utility intake and hence may not be viable in terms of water availability. Therefore, we add an additional constraint that restricts the utility water intake to be less than or equal to the utility intake in the as-is condition. In other words, we add the constraint: $f(x_2) \leq 703.8$.

The footprints associated with the minimum energy operating point are shown in Table 5. The optimal flows which minimize energy give a 10.5% reduction in energy consumption and a zero reduction in utility water intake. The discharge from campus increases by 5.4%. The energy saved is 56 MWh/year (10.5%), which is roughly the annual consumption of 60 house-holds in South Asia. Figure 2(b) shows the significant changes in flow values with respect to the “as-is” state.

Realization: The solver has optimized energy by identifying a switch in the operating conditions. Specifically, utility water which was earlier used for supplying the garden (via the softener plant) is now re-directed to supplying water for the chillers in the office buildings. In a complementary fashion, the inflow to STPRO whose outflow was supplying the chillers is reduced and instead redirected to the garden without the tertiary RO treatment. Because the operation of the more energy intensive STPRO is cut down, the net energy has decreased and the flows get redistributed across less energy intensive links.

If the additional constraint on utility water not exceeding 703.8 KLD is relaxed, further reduction in energy consumption is possible. Figure 2(c) shows the variation in the internal energy footprint for varying caps on the utility water intake. As the utility water availability crosses 756 KLD, the STPRO unit can be completely bypassed; potable, first and second grade demands of the campus can still be satisfied without using the STPRO unit.

The operating points identified by the optimization scenarios clearly show that minimizing external water footprint is not equivalent to minimizing water’s energy footprint. The solutions to the optimization problems also help us identify the strategies required to realize the optimal operating points.

4.2 Energy and Reducing Water Demands

Suppose that a budget is available for either waterless urinals or low-flow faucets. The former reduces the campus’s third-grade water demand, whereas the latter reduces first-grade demand. While reducing demand of any grade should help, the benefit in terms of energy or water may differ. If so, the capital budget should be used for the option that offers the maximum benefit.

To this end, we now explore the impact of reducing demand across various water grades. Specifically, we reduce the demand for a selected grade, while keeping the demands of other grades a constant. Under this modified set of demands, we optimize the energy and water footprints of the water network and observe the footprints’ difference from their "as-is” values. As before, the utility water intake is constrained to be less than 703.8 KLD.

We consider the top three grades by volume of demand. These are third grade, first grade, and second grade respectively. We choose three demand side management scenarios (DSM), viz. DSM3, DSM2, and DSM1, in which the demands for third, second, and first grades of water are reduced respectively by the same amount in KLD. As an illustration,
one can achieve DSM3 by deploying waterless urinals. For DSM2, the HVAC cooling towers’ demand can be reduced by efficient blow-down techniques. For DSM1, we can use low-flow faucets. For each value of the quantity of reduction, we quantify the impact of DSM1, DSM2, and DSM3 by obtaining the minimum energy and water footprints as before. Figure 3 shows the results. The X-axis refers to the reduction in the demand and the Y-axis refers to the optimal footprint value for this new demand vector.

Figure 3(a) shows that DSM3 has least reduction in utility water intake, while DSM2 does best. This is because grade-3 demand is met after meeting grade-1 and grade-2 demands and is being recycled. Therefore, a reduction of, say, 20 KLD in DSM3, results in a utility water reduction of only 3.2 KLD. On the other hand in DSM1, the reduction of grade-1 leads to a reduction of sewage also. This in turn increases utility intake due to reduction of treated sewage. The net effect is a reduction of 14.2 KLD. DSM2, which does not have any of these side effects, yields the best reduction of 19.69 KLD in utility water.

Figure 3(b) shows that DSM1 does best on the energy footprint, while DSM3 gives the least reduction in energy. Intuitively, utility water can be traded off for reduced energy due to reduction of STP operation. Therefore, minimizing energy would yield an increase in the utility water consumption. Because we do not want to increase utility water more than the as-is, we choose the as-is as the lower bound for energy. Because there is a minimum supply of utility water required to keep the solution feasible, we choose that as the upper bound of energy. We report the mid-point of these two bounds as the minimum energy for a particular reduction in the demand. With this framework, we expect the strategy for maximum utility water reduction to be most energy intensive and vice versa, and the results agree with this observation.

### 4.3 Impact of Rainwater Harvesting

Using our network flow model, we study the impact of rainwater harvesting on the various footprints of the campus. Since the rainwater treatment plant (RWTP) plant is yet to be commissioned, we use the cost figures of WTP1 for RWTP. The rainwater available for harvesting is estimated by product of the average annual rainfall and the roof-top area, scaled by a loss percentage. The average annual rainfall is obtained from historical rainfall data of the region. For the city where the campus is located, this is about 1250 mm. The roof-top area was calculated from the site plan. The loss percentage was taken as the standard figure of 20% to account for loss due to run-off and evaporation. With this campus specific data, the average harvestable rainwater is 19.6 KLD. The results of using harvested rainwater on the various footprints under the existing set-up is shown in Table 6. There is a potential reduction of 4.8% from the as-is condition when optimizing the utility water footprint. When minimizing for energy, we find that rainwater harvesting can save bring down the energy footprint by nearly 18%. This is because, the STPRO treatment process flow rate is reduced (which is offset by using the harvested rainwater), which results in reduced energy consumption.

### 4.4 Limitations of Our Approach

In focussing on the macro-level tradeoffs between energy and water, we have abstracted the micro-level operational details. In other words, while we focus on network-wide optimum operating conditions, it is not clear if they would result in improvements at the individual element level. Specifically, if a pump or treatment plant operates at some flow in the identified solution, that flow may not be the optimum for that plant’s operation. Instead, it may be better to run that plant at peak efficiency and then switch it off to attain the same average flowrate. Inputs from the facilities managers indicate that most units have some storage element to buffer the input and output. So it may be possible to use the

<table>
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<th>Water Intake (KLD)</th>
<th>Discharge (KLD)</th>
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<td>1211</td>
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</table>

Table 6: RWH improves both energy and external water. It saves energy by 18% and water intake by 4.8%.
Another limitation of our approach is the modeling of cost for each link in the network. While a linear model is what the data suggested, this may not hold if we model the details of peak-vs-average flows accurately. We defer these analyses to future work.

5. RELATED WORK

Related work in the literature can be broadly categorized into three categories:

- Sensor systems that provide visibility into the water footprint of a building or a residential home
- Sustainability efforts in campuses, typically those of universities
- Studies and systems that look at city-scale watershed management across multiple grades

Sensor Systems: Recent research has gone into the design and implementation of sensing infrastructure for water at the building scale [10, 17, 9, 18]. These works while providing visibility into the water footprint also enable the usage to be dis-aggregated at various end device levels. However, the interplay between energy and water is not investigated in these works. The work that studies the energy-water nexus to some measure is Hotwater-DJ [14]. This system intelligently selects water temperature for each water fixture using the previous usage history and also introduces a fixture specific delay in providing hot water to reduce energy loss due to short duration water usage events. Hotwater-DJ focuses on one water grade while we are interested in obtaining a holistic picture of the energy-water nexus across multiple grades at campus scale. There are also works that provide visibility into operations at utility scale [19], but again they focus only on potable water grade. References [5, 20] focus on providing dashboards to manage energy in a building but do not address water.

Sustainability efforts in university campuses: Several campuses have highlighted their approaches to conservation and sustainability. Reference [6] looks at an integrated approach to campus sustainability. However, there is no analysis of the nexus between energy and water at multiple grades. The Association for Advancing Sustainability in Higher Education (AASHE) has a collection [3] of several projects that look at sustainability issues. Again, to the best of our knowledge, there has been no study that looks at the nexus between energy and water holistically at the campus level.

City-scale watershed management: The concept of integrated water management system is not new [7]. This was revived in early 1990s with the setting-up on industrial parks. Several model packages have been developed since then for integrated water management in urban watersheds [12, 8, 11, 2, 16, 13]. However, these systems offer decision management support only when considering water grades at a macroscopic scale of a city or a county. The cost-benefit dynamics of water management at a relatively smaller scale of a campus scale are likely to be different from an urban scale owing to the economies of scale in processing water and sewage. Therefore, these may not be applicable in the context of a campus.

6. CONCLUSION

We analyzed the energy trade-offs involved in managing the water footprint of a multi-building campus through a measurement-based case-study. We modeled the campus water network across multiple grades as a flow network with a per-link cost model for energy. The models were derived from data measured at the campus over several months. Under the constraints that the demands are always met using the existing supplies, we optimized this flow-network for various objectives that separately minimize internal energy and external water intake. Our study reveals the following: (i) minimizing external water footprint does not correspond to minimizing the internal energy footprint of water; (ii) demand reduction of different water grades impact the energy and water footprints differently. Contrary to intuition, reduction of second grade water demand yields highest reduction in water footprint while reduction of first grade water demand yields higher reduction in energy; (iii) Rainwater harvesting can significantly reduce the energy footprint of a campus water network with sewage re-use. Our results show a potential for improving the operating condition of the campus’s water network that can reduce the energy consumption by nearly 56 MWh (10.5%) and 99.6 MWh (18%) annually without and with RWH respectively. Future directions of this work include automatic identification of strategies to realize various analytically obtained optimal operating points and usage of flow-dependent unit cost models for various network elements in the optimizer. We are also working towards deploying this framework as an automatic system in the case study campus to monitor the flow variations and continuously optimize for the water/energy footprints.

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7. REFERENCES


