DYNAMIC SIMULATION OF NEIGHBORHOOD WATER USE

A case study of Emirati neighborhoods in Abu Dhabi, UAE

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Abstract. Being located in a hot, humid, and arid bioregion, as well as having a unique religious and social context, the Gulf Cooperation Council cities pose significant challenges to the achievement of sustainable urban development. Using native neighborhoods in Abu Dhabi as a case study, this ongoing research aims to develop a design methodology which utilizes both qualitative and quantitative analysis towards the holistic, feedback driven design of new neighborhood typologies for the native population. This paper focuses on the methodology and application of a water use module which measures neighborhood scale indoor and outdoor water use, an area of simulation critical to developing sustainable neighborhoods for Arab cities, yet underrepresented within the literature. The water module comprises one part of a larger toolkit that aims to measure both environmental sustainability as well as social and cultural factors unique to context of Abu Dhabi and the gulf region.

1. Introduction

This paper introduces a computational module for measuring and simulating neighborhood scale water use and management in hot arid climates. This module is being developed in Python and C# as part of a larger toolkit for the

Rhinoceros and Grasshopper software platforms, and is co-developed with similar modules that address land-use, infrastructure, building energy, mobility, as well as economic and socio-cultural factors. When combined, the entire toolkit will provide a comprehensive and integrated analysis of holistic sustainability. This research uses Emirati villa neighborhoods in Abu Dhabi as a case-study to examine the potential effects of new housing and neighborhood typologies on all factors of sustainability.

Abu Dhabi is the capital and largest of the seven emirates that form the UAE. It covers an area of 67,340 sq.km. and has population of 2.65 million, 19% of whom are native Emiratis.(Abu Dhabi e-Government, 2016) However, despite forming such a small proportion of the total population, Emirati neighborhoods comprise roughly 55% of the total urban landscape (per GIS spatial data calculations). Neighborhoods are constructed and houses allocated to Emirati families at no or minimal cost through a government program facilitated by the Abu Dhabi Housing Authority (ADHA). Being based on the villa housing type, these neighborhoods are low-rise and low-density. Many have claimed these neighborhoods are environmentally unsustainable due to the high volumes of water demanded by their residents, demand driven in large part by the use of non-native vegetation and turf grasses as well as the low cost of water which the government subsidizes.(Bahaman, 1998) Studies have shown that many villa based neighborhoods in Abu Dhabi consume three to nine times more water per capita than other neighborhoods with similar climatic and socio-economic conditions. (Chowdhury and Rajput, 2015; Melbourne Water, 2015; *United Arab Emirates Water Conservation Strategy*, 2010; Waterwise, 2016)

Furthermore, the UAE is burdened with the second lowest supply of renewable freshwater in the world. As a result, the Abu Dhabi government must desalinate 99% of the municipal water supply, which it acquires from eight independent desalination plants.(Degnan, 2010; Paul et al., 2016; Randall Hackley, n.d.) These plants are energy and capital intensive, (Dubreuil et al., 2013; Yu et al., 2015) and their operation results in multiple environmental externalities such as carbon emissions and high-salinity discharge.(Assaf and Nour, 2014; Dawoud, 2012; Miller et al., 2015) Additionally, because these plants predominantly use multi-stage thermal co-generation, they are vulnerable to natural gas shortages, oil spills, and algae blooms, the latter two event occurring in 1998 and 2008 respectively.(Lowell, 1998; McDonnell, 2014; Villacorte et al., 2015) Because Abu Dhabi currently only has three days of potable water storage, any such disruptions to the desalinated water supply becomes an immediate health hazard to the general population, a hazard made more acute during the increasingly frequent and severe summer heat waves.(Lelieveld et al., 2016; Pal and Eltahir, 2016) The potential crisis from a supply shortage, current strain on existing capacity by increasing populations, and environmental externalities of desalination, all emphasize the urgent need for the more efficient use of limited and costly water supplies in Abu Dhabi.

2. Water Algorithm: Introduction

In order to increase water use efficiency in arid regions, both academics and government officials have begun looking more intensely at domestic water use and the potential reuse of treated wastewater flows.(Bazza, 2003; Dawoud et al., 2012; Murad et al., 2006; Shanableh et al., 2012) These studies have demonstrated that both treated graywater and treated blackwater offer financial and environmental benefits relative to using desalinated water alone, and that larger graywater systems perform up to three times better than smaller, household scale, systems.(Gurung et al., 2016; Jabornig, 2014; Malinowski et al., 2015; Memon et al., 2005; Stec and Kordana, 2015; Yu et al., 2015) Within the Emirate of Abu Dhabi specifically, a study in the city of Al Ain showed there is considerable potential for graywater reuse as roughly 70% of potable water use in the houses observed resulted in light graywater, which requires only minimal treatment before being reused.(Chowdhury et al., 2015) Currently, however, all domestic outflows in Al Ain and Abu Dhabi in general are combined and treated together in wastewater plants. Therefore, when considering the development of a water measurement toolkit for this region, accurately measuring the potential for recycled water use is crucial.

A potential challenge in using recycled graywater and blackwater in this region, however, is the unique socio-cultural and religious context. Islamic society requires stringent regulation of human contact with water-born contaminants based on concerns for human health. In the past, these requirements have slowed the transition towards using recycled water sources. Recent scholars have concluded that when adequately processed the use of recycled water (whether gray or black) is not only safe enough to be permitted by Shari'a law, but in fact aligns with its precepts towards the "reclamation… rehabilitation and purification of the soil, air, and water".(Al-Jayyousi, 2010; Farooq and Ansari, 1981)

Due to the absence of an existing tool[1] which allows urban and architectural designers to measure and understand the complex interdependencies between each water flow type, while parametrically testing

1 To the authors' knowledge no stand-alone software package nor plug-in for the major design software platforms (Revit, Rhinoceros, SketchUp, and Envision Tomorrow) currently exists which offers the necessary combination of neighborhood scale analysis, multiple water type simulation and balancing, detailed parametric control over all demand producing parameters, and multi-factor optimization.

and optimizing the overall water balance within a designated area, this paper proposes a Python based, neighborhood scale water analysis module for the Rhinoceros software platform. This tool will calculate daily average volumes and costs (when possible) for all indoor and outdoor potable water demands, their resulting light and heavy graywater and blackwater waste flows, percentages of graywater and blackwater recycling, all potential demands for recycled water, including toilet flushing, outdoor water cleaning, and vegetation, as well as final over and under supply volumes. The module provides users parametric control over all critical input metrics, including behavioral changes (eg., shorter bathing times), technological advancements (eg., more efficient dishwashers or sprinkler systems), and new system configurations (eg., presence of graywater system). An abstract representation of this model and its linear simulation process is shown in Figure 1.

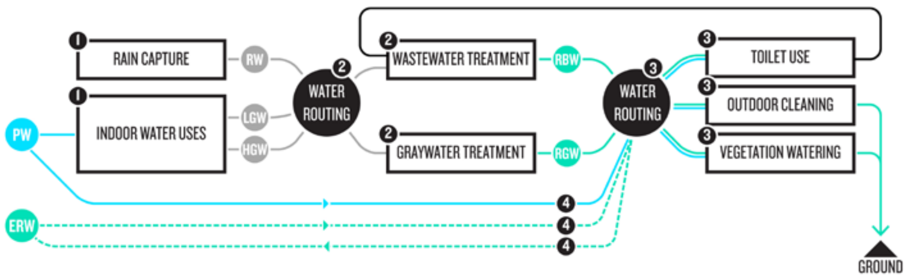

Figure 1. Proposed Simulation Process (ERW = External Recycled Water; PW = Potable Water; LGW = Light Graywater; HGW = Heavy Graywater; RGW = Recycled Graywater; RBW = Recycled Blackwater)

It is important to note that while research shows the potential benefits of recycled water use under many conditions, the water module itself do not assume nor prescribe any one system. All potential factors and water system configurations are open to testing and subject to design decisions or numeric optimizations which may weight various aspects of social, environmental, and economic factors differently. As such, the final optimal water schema will change depending on which factors are weighted most heavily. This capability is driven by a novel water routing functionality (Figure 1: 3, 4) which abstracts and differentiates between water in-flow demands and their resulting out-flow streams.

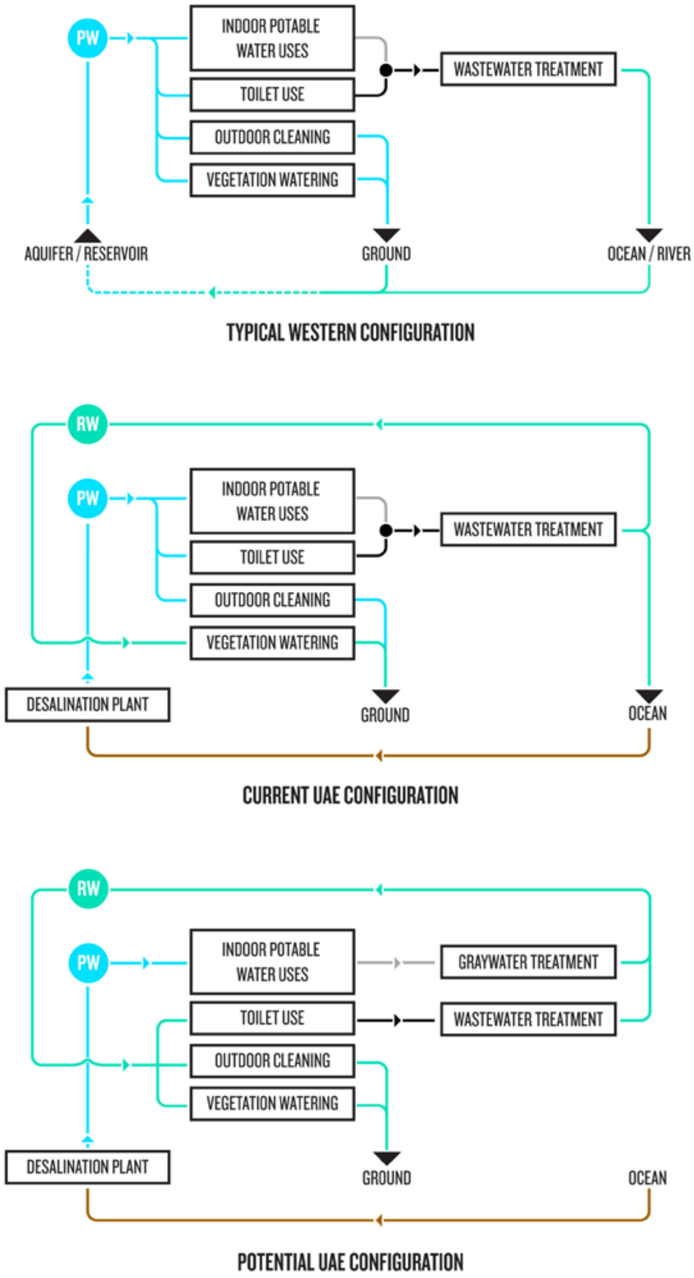

Figure 2. Municipal Water Schemas

2.1 WATER MANAGEMENT ALGORITHM: METHODOLOGY

2.1.1. Potable Water Demand and Graywater Production

The first step in the water management algorithm calculates the neighborhood scale potable water demand and resulting light and heavy graywater outflow arising from all indoor water uses, except toilets. Typically, light graywater is defined as drain flows coming from showers, bathroom faucets, and clothes washers, while heavy graywater results from kitchen sinks and dishwashers.(Cohen, 2009) Flow rates are determined by multiplying previously calculated demographic data for the neighborhood by averaged per person use rates, which in turn is multiplied by averaged appliance/faucet flow rates. Each factor is parametrically controllable. As stated above, the algorithms calculation of graywater outflows does not presume its use as such, but nevertheless provides a critical data point towards understanding the relative costs and benefits of all potential system configurations.

Parallel to this step, potential rainwater capture is calculated from monthly averages or daily totals (if available), and multiplied by the total area of selected impervious surfaces and a loss coefficient simulating evaporation and other losses.(Preul, 1994)

2.1.2. Water Treatment and Recycled Water Production

Once rainwater, light graywater, and heavy graywater outflows are calculated, the next step allows users to simulate where each type of outflow is sent, whether to a neighborhood (or city) scale graywater treatment facility, or to the municipal wastewater treatment plant. This will be a Boolean parameter designating the presence or absence of a graywater recycling plant. The algorithm calculates graywater and blackwater recycling volumes at the neighborhood scale because graywater treatment, historically done at the household scale, is more efficient, better regulated, and less costly at larger scales (Memon et al., 2005), and because differences in supply and demand can be potentially balanced internally within the neighborhood system boundary without needing costly city scale storage and treatment, and finally.

2.1.3. Recycled Water Use and Make-up Demand from Desalination

The next step simulates the return of treated graywater and blackwater from their respective facilities as useable, recycled water flows. Each flow type remains separated in the algorithm so it can be applied to the most appropriate uses and deployed according to use hierarchies depending on the relative quality of the recycled water flows. For example, recycled blackwater may still contain a high enough level of biological contaminants that is should be used for edible plants only as a last resort, or not at all. Boolean logics and if/else statements allow for the modelling of complex scenarios and decision making for which recycled flow is used for which use type and when. The four major categories of recycled water use the algorithm models for are toilet flushing, outdoor cleaning (including car-washing), both edible and non-edible vegetation, and turf grasses. Other uses, such as district cooling and industrial processes, could easily be appended to the algorithm later as needed.

Water demand for landscaping is determined by multiplying the number of instances of trees and shrubs, and total area of turf grasses modelled by the designer in Rhinoceros, by each species regional yearly watering schedules. These schedules are typically available from local municipalities or universities. Future work on the algorithm could add a more precise calculation of watering needs of each species based on hourly or daily environmental factors including rainfall, humidity, radiation, wind, and ambient temperature. Water flows for vegetation and other outdoor uses is assumed to be fully lost through evaporation or permeation into the ground. Water used for toilet flushing (regardless of source) is designated as blackwater and fed into the stream of municipal waste water for treatment and recycling. It is worth noting that toilet water can become a nearly infinite loop of use, treatment, and recycling, minus losses to evaporation and leakage.

2.1.4. - Unmatched Demand and Supply Balancing

The last step in the algorithm calculates any over or under supply of recycled water. In the former case, an economic multiplier can be applied to estimate the net benefit of this scenario. In the latter case, user inputs determine how much of the needed make-up supply is from other sources of recycled water (industry for example), and how much is from the desalinated potable water supply. The latter also helps designers and public agencies diagnose factors leading to increased water demand, and develop strategies for reducing it.

2.2 WATER MANAGEMENT: APPLICATION

The final output parameters from the water use algorithm include per day and per capita flow rates of all water types (desalinated, graywater, blackwater, recycled water) through the neighborhood, the amount of available graywater and blackwater, the percentage of those streams that is recycled and percentage reused, the amount of water permeated into the ground, and finally, the costs associated with each flow type. The parametric nature of the algorithm allows the user to adjust and test the relative effects of different values for each input parameter. These parameters quantify human behaviors, shifts in technological efficiencies, and larger scale system configurations. It allows designers, therefore, to use the water module to explore and understand the trade-offs each scheme produces between environmental, economic, and social costs. Finally, the tool normalizes these costs on a per capita and per area basis which in turn allows comparison between the designed neighborhood typology within the Rhinoceros program, and preexisting local, regional, and global neighborhood typologies. As such, the tool provides governments, academics, developers, and designers alike with critical metrics to examine which configurations, technologies, and behavioral modifications are most effective in providing an efficient, resilient, and sustainable supply of water to local populations.

3. Conclusion

This paper outlines an algorithm for simulating and analyzing water metabolism for an inputted neighborhood design in the Rhinoceros and Grasshopper software environments. When situated within the larger sustainability toolkit, planners and designers will be able to dynamically model, simulate, and compare multiple environmental, economic, and social factors. Because the other environmental modules will share many of the same input parameters, such as vegetation and built form, the completed toolkit will allow for complex feedback loops and interdependencies not only within the water use module itself, but also among all the modules. This will provide designers a robust understanding of the tradeoffs between various design input parameters including built and natural form, transportation infrastructure and networks, demographics patterns, system configurations, and technologies.

Even though this toolkit is being designed specifically for Emirati neighborhoods in Abu Dhabi, it is anticipated that the toolkit will have broader applicability due to the inherent parametric nature of the existing modules, as well as the expandability of the toolkit through the addition of regionally or city specific modules as needed.

The potential impact of the water module is significant given the current lack of existing tools which allow for the fast inputting of multiple design scenarios and attending data at the schematic phase, the disaggregated assessment of all potential water flow types and their environmental and economic costs, and the interdependency of water flows to other, equally critical factors of environmental and social sustainability.

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