3.5 INTERDISCIPLINARY STUDY OF COUPLED WATER-BIOPHYSICAL-CLIMATE SYSTEMS IN A SEMI-ARID URBAN ENVIRONMENT

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1. INTRODUCTION

This paper describes on-going interdisciplinary urban hydrology research at the University of Utah. A team consisting of researchers from water resources engineering, hydrologic sciences, biology, mechanical engineering, and architecture and urban planning has formed as a subset of a much larger group with mutual interests in planning, analysis, and design of sustainable urban systems. The diverse team has instrumented a residential neighborhood in the Salt Lake City metropolitan region with a micrometeorological observation tower, a rain gage, soil moisture sensors, and flow meters for observing water, wastewater, and stormwater flows – providing observation of the complete urban water cycle. Data from this observation network is coupled with a high fidelity database of physical (built environment), biophysical (tree/vegetation), and socioeconomic information. Additional sensors and observation networks continue to be installed across the Salt Lake Valley to complement the residential neighborhood site providing a transect of rural to urban sites covering a range of land uses. In this paper an overview of current results will be presented and on-going research enhancements including infrastructure installations and new collaborations will be described.

2. BACKGROUND

Urban hydrology is evolving from the traditional civil engineering field focused on flood forecasting and stormwater control to encompass a much broader interdisciplinary focus (McCray and Boving 2007). The evolution is being driven by the emergence of the need for ecological protection and the realization that the human dimension must be taken into consideration to effectively plan, design, manage, and operate urban hydrologic systems. Furthermore, the realm of urban hydrology has expanded from rainfall-runoff to include water supply and wastewater collection as the separation of these systems is blurred by conservation efforts (e.g., recycling and reuse) and modified in alternative development styles focused on reducing impact on the water cycle. Today's urban hydrologist in many cases will need to be equipped with knowledge of hydrology, infrastructure systems, environmental engineering, ecology, geochemistry, biology, public policy, law, social and behavioral sciences, organizational psychology, and more to address the complex problems of water in cities. For example, in the western United States (U.S.) urban hydrologists may need to address the following type of interdisciplinary research questions:

- How will widespread landscape modifications (e.g., xeriscaping) synergistically impact water use, surface runoff, and climate?
- How does one make and communicate the need for conservation to reduce water use?
- How will planting trees (i.e., the commonplace million tree campaign) impact stormwater runoff quantity and quality, water use, human comfort, and energy use?
- How does climate variability influence tree transpiration and how does that feedback to water demand and microclimate?

These research questions can be further compounded by urban growth, societal change, and climate variability. The challenge to address these critical questions expands beyond the core knowledge of the classically-trained urban hydrologist (i.e., civil engineer) and stresses the need for interdisciplinary research teams producing new urban designs and training the next generation of urban water specialists. This paper describes the initial efforts of researchers at the University of Utah to develop research infrastructure and collaborative ties to address complex urban hydrology questions from an interdisciplinary perspective. The interdisciplinary research team emerged from the UTES (Urban Trace Gas Emissions) project (slvairshed.utah.edu/index.html) funded through the NSF Biocomplexity program. UTES focused on urban trace gases. Part of the UTES team refined their research focus to the water cycle and new collaborators were integrated into the team. The modified vision required new hydrologic observation instruments to be installed in concert with existing infrastructure originally observing trace gases. In addition, a new broader vision for research collaborations was developed.

3. RESEARCH INFRASTRUCTURE

A residential neighborhood in the Salt Lake City metropolitan area was chosen to serve as the initial

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place-based experiment station for this interdisciplinary urban hydrology collaboration. The first catchment we instrumented with this effort is located approximately 12 km south of downtown Salt Lake City, in the suburb of Murray (Fig. 1). Murray has more than 34,000 residents in predominantly residential land use, with small areas of commercial and industrial land uses, a large health care complex, open space, and a major interstate highway. Murray's age (established in 1849, but with continued urbanization of open spaces), net population density (~3500 persons/urbanized sq. km), population growth (~10% from 1990 to 2000), and land use distribution (predominantly single family residential) are very similar to the characteristics of Salt Lake City and similar to other urbanized areas in the mountain west. The Murray neighborhood was chosen because it has mature landscaping facilitating our study of urban land-atmosphere-subsurface interaction with human and biophysical factors.

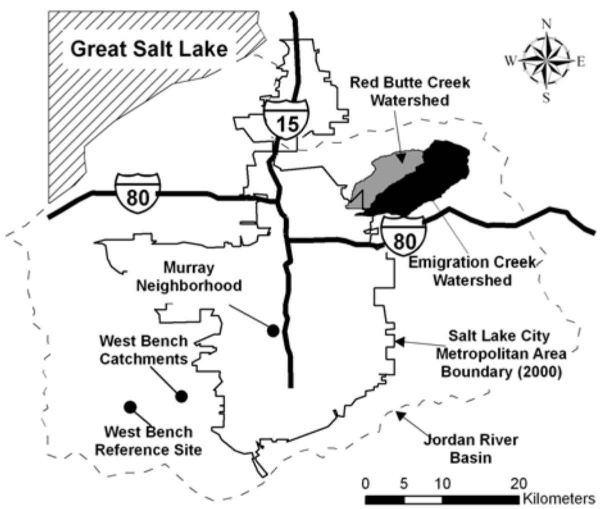

Fig. 1. Vicinity map of urban hydrology related experiment locations in the Salt Lake City metropolitan area.

The neighborhood was instrumented with a micrometeorological tower midway through 2005 as part of the UTES NSF Biocomplexity project. At the tower site, fluxes of H_2O, CO_2, momentum, sensible heat, net radiation, and ground heat, as well as pressure, wind speed/direction, temperature, humidity, and soil moisture have been observed regularly. In the past year we have installed a tipping bucket rain gauge at the tower site and area-velocity flow meters at stormwater outfalls discharging from two drainage subcatchments (0.1 and 0.3 km^2) in the neighborhood. The two drainage subcatchments cover the majority of the tower source area footprint as defined by mean meteorological conditions. To complete the observation of inflows and outflows from the subcatchments we are in the process of installing water use meters at a selected number of houses to complement the bulk water input to the neighborhood currently observed by Murray City. The household water meters will be used to observe the indoor/outdoor water use so we can separate the two. The metering technology will include a meter, transmitter/receiver, and relay installed at a residence. To enhance the water metering data collection effort we have scheduled focused case studies to measure water consumption by specific activities (e.g., automatic sprinkling). The water use for the activity can be quantified and then the activity can be tracked using an alternative (i.e., less costly) monitoring approach. In this way we can have continuous metering at some locations by direct observation of consumption and quasi-continuous metering by observation of activity. To complete our observational coverage of outflows we will work with Murray officials to monitor sewage flows from the neighborhood. We have received a strong commitment from the Murray City mayor and administrators to aid our interdisciplinary urban hydrology research effort. Their commitment will provide not only their cooperation on all aspects of research (access to data and facilities and support in working with community groups and citizens), but also access to wireless water and sewer flow meters in the city.

Our most recent addition to the Murray neighborhood observation resources installed over the summer months of 2007 is two soil moisture sensors with HOBO microstation data logger systems. One is installed at a non-irrigated location and another at an irrigated residence. Our current and planned resources account for inflows, outflows, internal fluxes, and storage of water in the catchment. In sum, the existing, planned, and proposed observation resources installed in the Murray neighborhood will enable quantification of inflows, outflows, and changes in storage comprising the primary components of the urban water budget and will facilitate quantification of human-biophysical interactions with the hydrologic cycle.

In addition to the observation infrastructure in the Murray catchment, a tremendous effort has been undertaken to collect detailed data describing the physical characteristics of the catchment. The data collection has included remote sensing data acquisition (e.g., IKONOS, ASTER, LANDSAT), tree species and size surveys, infrastructure location surveys, and irrigated/non-irrigated determination. The neighborhood has been walked numerous times identifying key water-related features. All the data has been compiled into a geographic information system (GIS) database.

The Murray site was the first catchment to be instrumented and characterized as part of this interdisciplinary hydrologic research effort. Beyond the Murray site we are seeking to establish a series of place-based hydrologic experiment stations across the Salt Lake Valley to facilitate the study of a broader set of research questions. Fig. 1 shows a set of observation locations traversing the Salt Lake Valley from a national research water (Red Butte Creek watershed) to the northeast to a rapidly urbanizing area to the southwest. The Red Butte Creek watershed is instrumented with a wireless data collection system consisting of five weather stations and four flow monitoring stations. Sap flux experiments are routinely conducted to measure tree transpiration. In addition, the watershed has been surveyed extensively to characterize tree location, species, and size. The West Bench area is unique because it is historically open space owned by a large mineral extraction company that is now being converted into urban areas. The unique feature is the focus of the development on sustainability (http://www.daybreakutah.com/) with cluster development being the common urban configuration. The techniques being implemented at Daybreak to address water conservation, energy conservation, water quality, social interaction, and other sustainability concerns are potential models for future developments in the Salt Lake Valley and the mountain west U.S. Thus, study of the effectiveness of the development is a necessity for the future success of the Daybreak development and other developments that follow its model. We are currently in the process of installing observation infrastructure at a catchment in the Daybreak development that will be similar to the instrumentation in the Murray catchment.

4. PRELIMINARY OBSERVATIONS

There are numerous discipline-specific and interdisciplinary research activities related to urban water currently underway or planned for the Salt Lake Valley. This paper will provide an overview of four in particular. The key interdisciplinary elements and future interdisciplinary extensions will be highlighted.

4.1 *Seasonal Variation of Hydrologic Processes*

The mountainous western U.S. region experiences the four seasons with hot, dry summers and cold winters with significant snowfall. Long-term simulation of hydrologic processes is a challenge because creating parameter databases with seasonal variation is difficult. Part of our work has involved characterizing hydrologic variables and processes in the Salt Lake Metropolitan area continuously to quantify variability across seasons. One hydrologic process we have studied this past summer is infiltration. Infiltration measurements were made at regular intervals (every two weeks) for a four-month period starting at spring melt (March) using double-ring infiltrometers. The field measurements were taken at five locations in the Murray catchment and the parameters of the Horton infiltration model were determined to translate the field results to hydrologic models of the catchment. Accompanying the surface infiltration measurements were measures of soil compaction, moisture, and temperature. The preliminary results from this study have indicated almost no variability of infiltration across the spring to summer seasons (Fig. 2). The data suggest, counter-intuitively, that nearly constant or increasing soil moisture produced increases in infiltration rates.

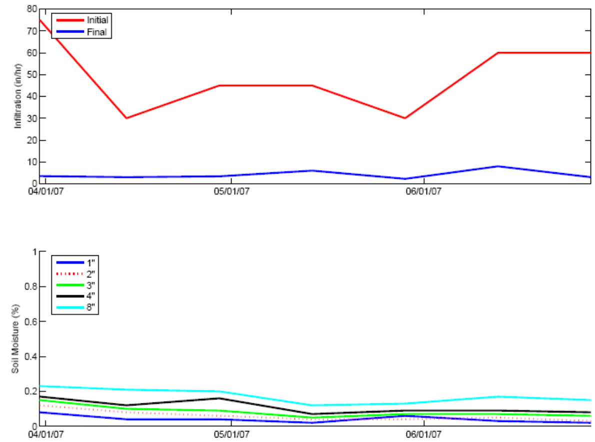

Fig. 2. Infiltration rate and soil moisture observations from one site in the Murray catchment. The other four sites exhibited similar patterns.

4.2 *Water Use*

Historical daily and monthly water use data reveal the patterns of indoor and outdoor water use in the Salt Lake Valley at both the service district and neighborhood scales. These patterns of use, in turn, are reflected in the sewer flows, stormwater drain, and landscape evapotranspiration rates, which together comprise key elements of the urban water budget. Daily flows of water into the entire Salt Lake City Department of Public Utilities (SLCDPU) delivery system (92,344 residential and commercial connections serving 328,190 people) are available for the calendar years 2000, 2002-2005 (Fig. 3) and follow a seasonal pattern with low water use in winter and high use in summer. Indoor use in the SLCDPU system is relatively stable during the period 2000 to 2005 at about 17,000 million gallons per year.

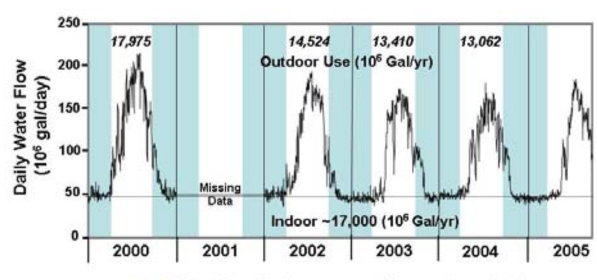

Fig. 3. Daily water inflow to Salt Lake City Department of Public Utilities delivery system for the period 2000 through 2005. Data courtesy of Salt Lake City Department of Public Utilities.

In 2003, the system-wide volume of water delivered by the SLCDPU (data obtained from S. Duer, SLCDPU) for apparent outdoor use (15.9 billion gallons) during the irrigation season approximately equals the volume of precipitation (15.3 billion gallons) falling within the water service district (130 mi^2) over the same time period. Thus, human activity delivers as much water to the urban environment as the natural system during the irrigation season. Fig. 3 shows the significant increase in daily water use that occurs during the irrigation season as the number of daily cooling degree days increases and the frequency of precipitation events declines. Data used to create Fig. 3 indicates that outdoor water use comprises about 50% of the total annual water delivered to customers in the SLCDPU.

Outdoor use (estimated by subtracting the average wintertime use) in the SLCDPU system declined from 17,975 million gallons per year in 2000 to 13,062 million gallons per year in 2004. The decline in outdoor water use corresponds to the timing of a multi-year drought and is attributed to success in changing water use behavior through water conservation programs that included delaying the start of the irrigation season and reduced daily water use (Fig. 3). Linkages between water use and climate are shown in Fig. 4. As the number of daily cooling degree days decline in autumn, people reduce outdoor water use. Staff of the SLCDPU suspect that further reductions in autumn water use can be effected by focusing education efforts on convincing people that their landscaping will not be harmed by reducing autumn irrigation rates sooner than in past years. The combination of precipitation events and cooler temperatures in June 2003 (Fig. 4) produced a temporary, major decline in water use that likely reflects, in part, how some automatic irrigation systems restrict water flow immediately after rain events.

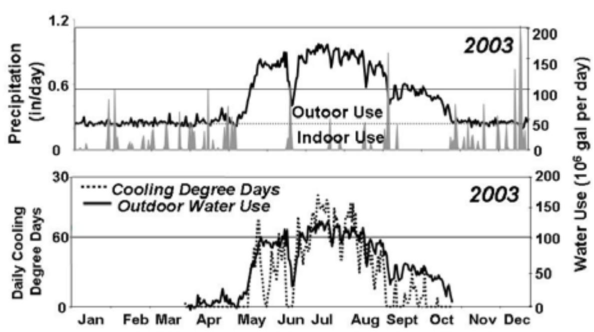

Fig. 4. Daily water use data for the 2003 calendar year combined with the corresponding daily precipitation rate and cooling degree days. Water use data were provided by the Salt Lake City Department of Public Utilities. Precipitation data were obtained from the National Climate Data Center.

Fig. 5 shows that an approximately linear correlation is found between daily water use and cooling degree days SLCDPU. Similar, but less detailed, results are obtained using monthly, customer billing data for the ~93,000 SLCDPU customers and ~800 Murray neighborhood customers (Fig. 5). These correlations appear to provide a sound foundation for estimating neighborhood-scale and delivery-system-scale water usage for alternative future climate scenarios; when adjusted for future changes in per capita water usage. The details of the linkages between human behavior and water use, however, are poorly resolved with monthly billing data. As a consequence, we are working with the Murray City water department to develop a pilot study that will monitor water use on a daily-to-hourly, basis at several homes in the target neighborhood.

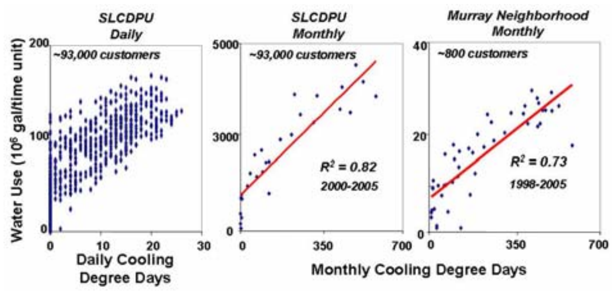

Fig. 5. Water use data were provided by Salt Lake City Department of Public Utilities and Murray City Public Utilities. Cooling degree data were obtained from the National Climate Data Center.

4.3 *Evapotranspiration*

One of the observations at the micrometeorological tower at the Murray catchment is the latent heat flux. Our interest is in studying the variability of the evapotranspiration (ET) fluxes in response to landscape and behavior changes, altered water use and climate, and in comparison to alternative neighborhoods and land uses. One comparison we have made is the magnitude of latent heat flux in the Murray catchment (a mature suburban neighborhood) and non-urbanized land cover in the Salt Lake Valley (Fig. 6). Despite the fact that these sites are subject to similar large scale external forcing, the latent flux at the residential site is much greater than at the non-urban site, particularly in the late growing season when natural vegetation at the non-urban site is largely dormant. The sensible heat fluxes are quite similar at both sites but slightly larger at the non-urban site, resulting in much smaller Bowen Ratios at the residential site. Differences in net radiation appear to be driven primarily by the surface albedo (the non-urban site has a higher albedo). This accounts for the increased energy available for the large latent heat flux at the mature vegetated site.

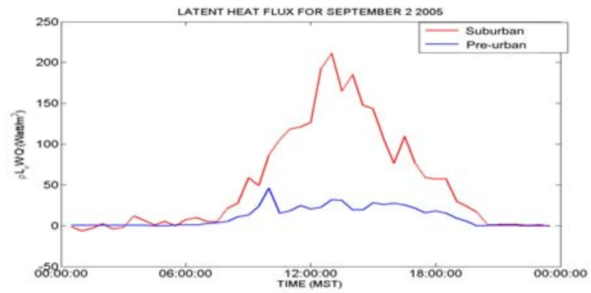

Fig. 6. Comaprison of latent heat flux in Murray catchment with non-urban site in the Salt Lake Valley.

4.4 *Irrigation Effects on Flows in Stormwater Drains*

We installed continuous flow meters in a storm drain in the Murray catchment in May of 2006. Our objective was to capture the rainfall generated runoff from the catchment and eventually to quantify pollutant fluxes when coupled with water quality sampling. During the summer months we made an interesting observation when reviewing the data. During periods with no rainfall we noted regular variation in flow rates in the underground pipe draining the neighborhood (Fig. 7). Knowledge of automated irrigation patterns in the Salt Lake Valley and surveys of irrigation practices in the early morning suggests significant flows from lawn irrigation are discharging from the catchment in the stormwater drains. Based on the August record shown in Fig. 7 the volume of runoff from irrigation inputs (imported water) is much greater than the volume of runoff from a rainfall event (the one large spike towards the end of August was a small rainfall event). This observation is consistent with observations in other semi-arid urban environments where nuisance flows exceed rainfall-runoff in dry seasons (McPherson et al. 2004, 2005; Stein and Ackerman 2007). The unexpected part was the observation of this at the small scale (a relatively small catchment compared to larger urban watersheds).

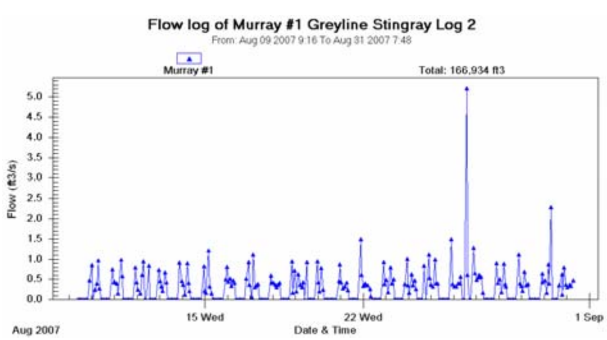

Fig. 7. Flow rates during the month of August 2007 in an underground storm drain in the Murray catchment.

5. SUMMARY

Researchers at the University of Utah have initiated a long-term interdisciplinary research direction with the central theme of urban water. Our initial steps have been to create collaborative relationships, develop integrating research questions, and to instrument place-based experiment stations in a semi-arid urban environment. Our near future efforts will involve expanding the observation network to include additional sites and more instruments. Ultimately we intend to monitor the complete water cycle at several urban and non-urban locations in the Salt Lake Valley. Currently, we have one mature residential neighborhood instrumented. The preliminary data from the instruments in the established neighborhood were reported in this paper. Many more observations could be reported, e.g., sap flux measurements of tree transpiration, soil moisture variability, outdoor water use analyses, indoor water use surveys but the integration of these results to study research questions related to the complete urban water budget and integration with non-science disciplines is our long-term goal. Here is a brief list of several of these integrated activities currently in progress:

- Estimating recharge based on residual of the observed water budget
- Feasibility analysis of rainwater harvesting for meeting water demands in mature and newer alternative development styles
- Over-watering effects on soil moisture and the impacts on ET and CO_2 fluxes
- Modeling development style and water use pattern influence on ET

Beyond infrastructure and observations a key aspect of current expansion of research is the integration of additional disciplines. Researchers from humanities, social sciences, law, and business are being engaged to participate in broader interdisciplinary urban water research. The key objective with the new collaborations is to improve the transfer of technology to researchers through improved communication and improve the transfer of scientific information to the public and decision makers.

In addition to research collaboration we are involved in developing interdisciplinary water education collaborations. Compiling and creating interdisciplinary courses is part of a strategic effort at the University of Utah and water-related courses will most certainly play a part.

Students are also involved in the interdisciplinary urban water research thrust at the University of Utah. One recent activity is the formation of a student water resources and environmental research group composed of a variety of disciplines. The student group is comprised of two student chapters of professional organizations – American Water Resources Association (AWRA) and Water Environment Federation (WEF). Their goal will be to foster interdisciplinary collaboration among graduate and undergraduate students with the central theme of water.

The combined effort described in this paper is moving interdisciplinary urban water research and education forward at the University of Utah.

7. REFERENCES

McCray, J.E. and Boving, T.B. (2007). "Introduction: Urban watershed hydrology." *Journal of the American Water Resources Association*, 43(4), 839-840.

McPherson, T.N., Burian, S.J., Stenstrom, M.K., Turin, H.J., Brown, M.J., and Suffet, I.H. (2005), "Comparison of dry and wet weather flow nutrient loads from a Los Angeles watershed." *Journal of the American Water Resources Association*, 41(4), 959-969.

McPherson, T.N., Burian, S.J., Stenstrom, M.K., Turin, H.J., Brown, M.J., and Suffet, I.H. (2005). "Trace metal pollutant loads in urban runoff from a southern California watershed." *Journal of Environmental Engineering*, 131(7), 1073-1080.

Stein, E.D. and Ackerman D. (2007). "Dry weather water quality loadings in arid, urban watersheds of the Los Angeles basin, California, USA." *Journal of the American Water Resources Association*, 43(2), 398-413.