Modeling Soil Moisture and Plant Stress under Irrigated Conditions in Semiarid Urban Areas

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I. Abstract

Climatological and hydrological models typically ignore anthropogenic irrigation, despite its notable effects on water, energy and biomass conditions. This omission is noteworthy in semiarid cities, such as Phoenix, Arizona, where native and exotic vegetation in urban landscapes are well watered, inducing changes in their phenology and productivity. To our knowledge, the impact of irrigation on urban ecohydrology has yet to be addressed in a quantitative fashion, partially due to a general lack of appropriate soil moisture data from irrigated areas. Thus a rare and valuable opportunity for new avenues of research in urban ecohydrology is presented by the extensive soil moisture data from the North Desert Village neighborhood, funded by CAP-LTER: soil moisture observations have been collected at the site for several years under multiple landscape treatments. This study adapts a point-scale model of the soil water balance and plant stress, utilizing nearby daily records of potential evapotranspiration and rainfall as well as metered irrigation data as model forcing, calibrated using the available soil moisture data. The calibrated model will then be used as a basis to study the sensitivity of soil moisture and plant stress on such factors as soil classification, vegetative cover, meteorological forcing, and irrigation amounts and schedules that are representative of the conditions found in the broader Phoenix metropolitan area. Our results are intended to inform water and landscape managers in making decisions regarding the relationship between water use rates and plant response for different landscape treatments, based on a quantitative model.

II. Study Site: North Desert Village

Located at the ASU Polytechnic campus in Mesa, and adjacent to the Phoenix-Mesa Gateway Airport, North Desert Village (NDV) includes four residential neighborhoods, each with a different landscape and irrigation treatment typical of the Phoenix metropolitan area:

- Mesic (shown in green in Figure 1): turf grass lawns and shade trees with sprinkler irrigation
- Xeric (orange): gravel base with native and exotic plants and individual drip irrigation
- Oasis (purple): mix of turf grass with sprinkler irrigation, and individual drip-irrigated plants in gravel base
- Native (yellow): Sonoran Desert plants in gravel base, no irrigation

Fig. 1 North Desert Village neighborhoods

Fig. 2 Xeric site

Fig. 3 Native site

Though the current extent of this study focuses primarily on the native and xeric sites, each of the four sites contains two soil moisture sensors at a depth of 30cm, recording volumetric water content hourly. The xeric site has one sensor installed adjacent to a palo verde and within range of the drip irrigator watering that tree, and a second sensor at a distance (~20ft) from any of the plants and irrigation outlets. The native site, which includes no irrigation, has one sensor adjacent to a saguaro cactus, and the other at a distance from any vegetation.

III. Soil Moisture Balance Model

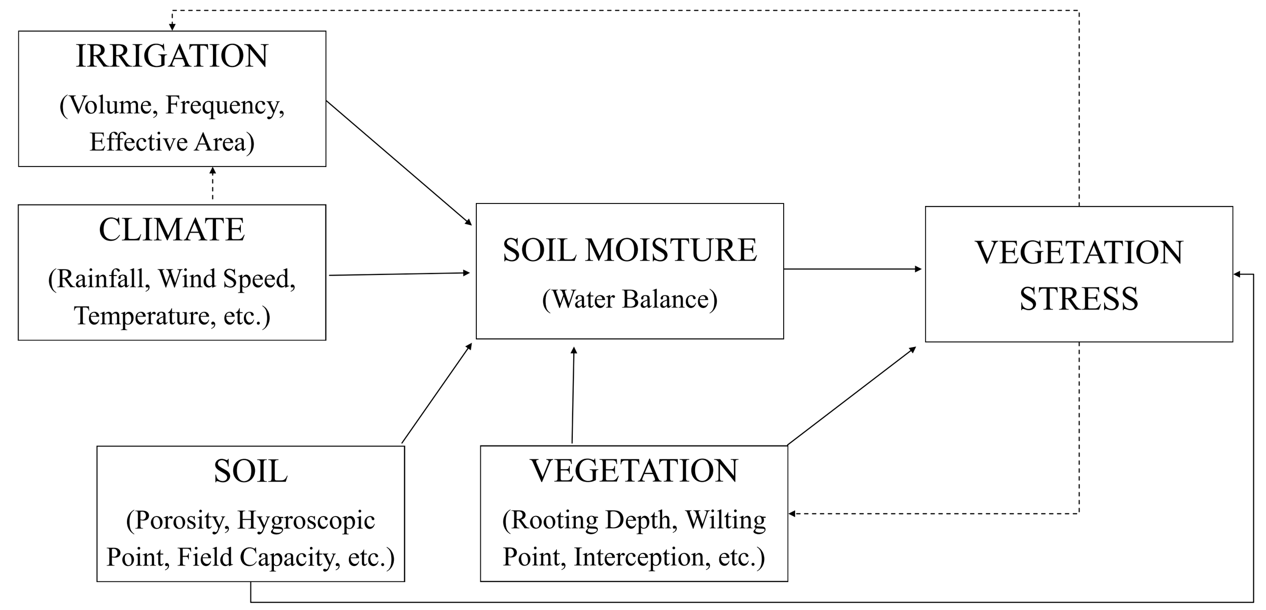


Fig. 4 Conceptual schematic of modeled system used for this analysis. Solid lines show modeled interactions; dotted lines represent secondary interactions not directly considered (adapted from Rodriguez-Iturbe, et al., 2001).

The analytical model used to simulate soil moisture at a point scale is adapted from Laio et al. (2001) to include model forcing through historical precipitation and evapotranspiration data, as well as water input through irrigation. Daily values for potential evapotranspiration were obtained from the Arizona Meteorological Network (AZMET) site at Queen Creek. Daily precipitation totals were collected from the nearby Phoenix-Mesa Gateway Airport through the National Climatic Data Center (NCDC), and from AZMET stations in Queen Creek and Mesa. Furthermore, the Soil Survey Geographic (SSURGO) Database was used to determine a soil classification of loamy sand for the entire NDV area. Figure 5 shows the soil moisture time series for a site without irrigation, resulting from these model forcings, and from appropriate soil and vegetative parameters as published by Laio et al. and summarized in Table 1.

Porosity	n	0.42 [-]
Hygroscopic Point	s_h	0.08 [-]
Wilting Point	s_w	0.11 [-]
Stress Threshold	s^*	0.31 [-]
Field Capacity	s_{fc}	0.52 [-]
Pore Disconnectiveness Index	b	4.38 [-]
Saturated Hydraulic Conductivity	K_s	1000 mm/d
Interception	Δ	0 mm/d
Evaporation at Wilting Point	E_w	0.1 mm/d
Rooting Depth	Z_r	600 mm

Table 1 Published parameter values used for soil moisture series in Figure 5. Rooting depth set at twice the sensor depth, thereby assuming that sensor reads depth-averaged value for full rooting depth. Interception set at zero for native and xeric sites (see Figures 2 and 3).

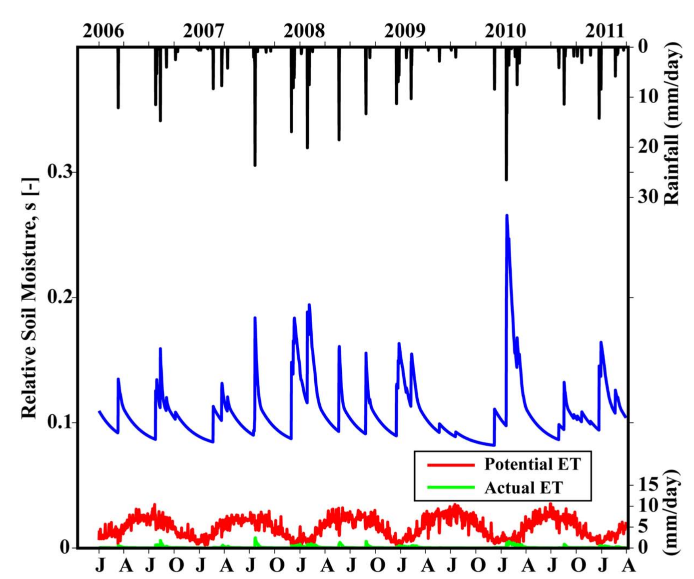


Fig. 5 Soil moisture time series with model forcing

IV. Model Calibration

The simulated soil moisture series was then calibrated to the data from the sensor at the xeric site at a distance from the drip irrigation system. Nine of the ten parameters in Table 1 (interception was still assumed to be zero) were adjusted within reasonable ranges, first manually to achieve a visual fit to the data, then using an automated calibration routine. The shuffled complex evolution method developed at the University of Arizona (SCE-UA, Duan, et al., 1992) was used to minimize the root mean square error (RMSE) between the data and the modeled soil moisture time series. A 2-year calibration period was used, from 1/1/2008 to 12/31/2009. The results of the calibration are shown in Figures 6 and 7, and in Table 2.

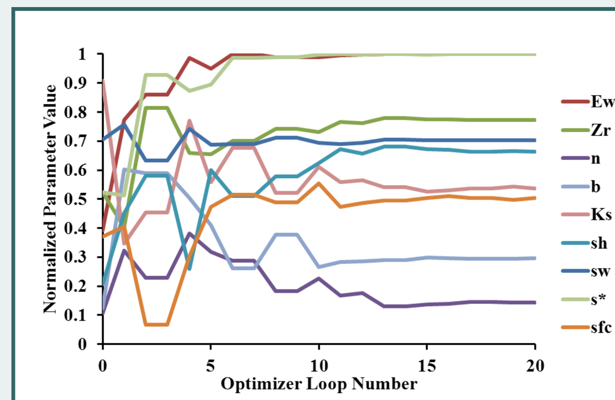


Fig. 8 Progression of optimized parameter values

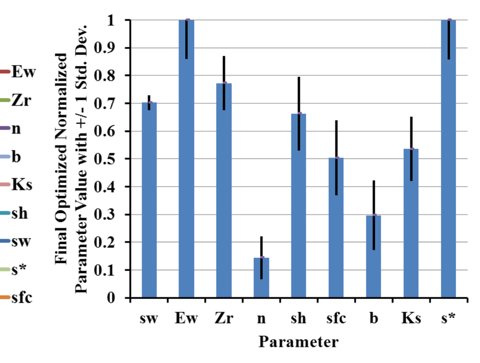


Fig. 9 Optimized values with standard deviations among all model runs

Parameter	Lower Bound	Upper Bound	Final Value
n [-]	0.25	0.60	0.30
s_h [-]	0.00	0.15	0.10
s_w [-]	0.15	0.30	0.26
s* [-]	0.30	0.45	0.45
s_{fc} [-]	0.45	0.75	0.60
b [-]	1	10	3.67
K_s (mm/d)	1	10000	5358
E_w (mm/d)	0.01	0.20	0.20
Z_r (mm)	50	800	630

Table 2 Parameter ranges

V. Simulated Soil Moisture Scenarios

Parameter	Published Value	Manual Calibration	Automated Calibration
n [-]	0.25	0.60	0.30
s_h [-]	0.00	0.15	0.10
s_w [-]	0.15	0.30	0.26
s* [-]	0.30	0.45	0.45
s_{fc} [-]	0.45	0.75	0.60
b [-]	1	10	3.67
K_s (mm/d)	1	10000	5358
E_w (mm/d)	0.01	0.2	0.20
Z_r (mm)	50	800	630
RMSE	0.1175	0.0598	0.0385

Table 3 Parameter values used in Figures 10 and 11.

In determining the parameter set for a minimum RMSE, the calibration program created approximately 800 sets of the nine parameters. The daily soil moisture was determined for each parameter set, with +/- 1 standard deviation on the mean daily soil moisture displayed in Figures 10 and 11.

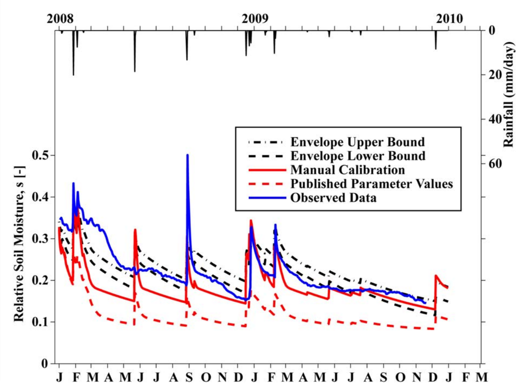


Fig. 10 Xeric site (calibration)

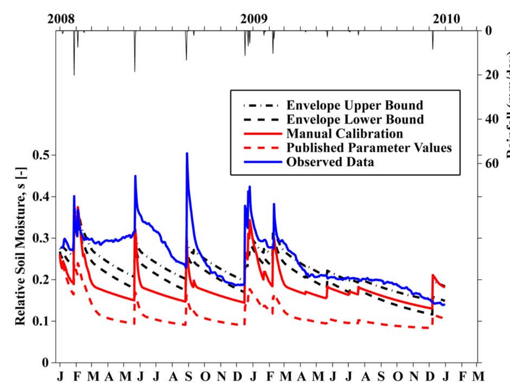
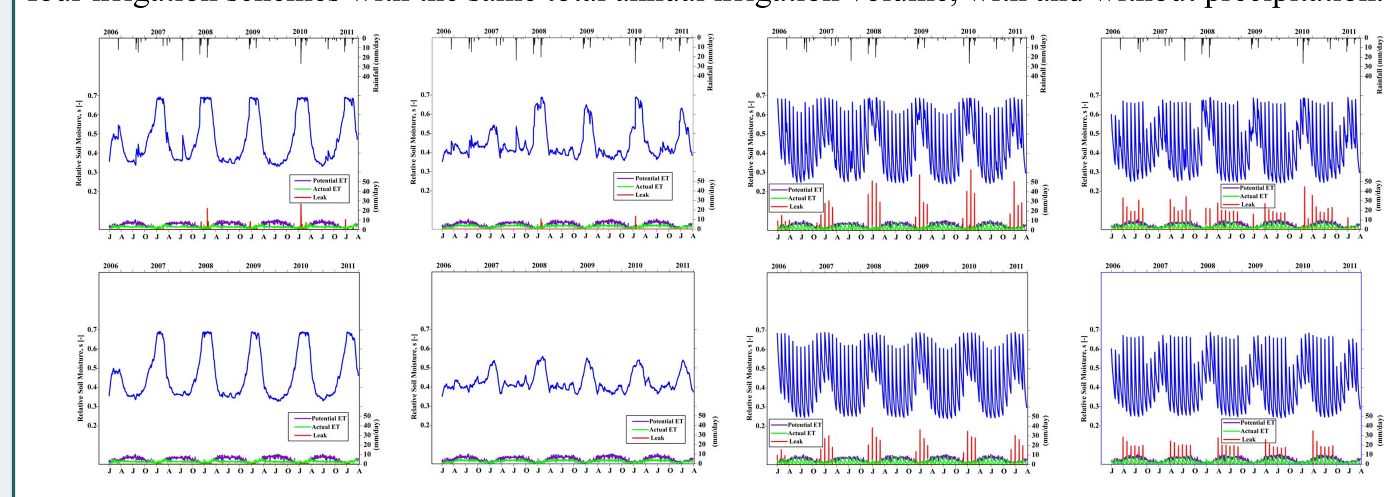


Fig. 11 Native site (validation)

Using the calibrated parameters, soil moisture resulting from irrigation can be plotted. Figure 12 shows four irrigation schemes with the same total annual irrigation volume, with and without precipitation.



(a) Scheme 1: constant daily (b) Scheme 2: seasonal daily (c) Scheme 3: constant monthly (d) Scheme 4: seasonal monthly

Fig. 12 Soil moisture time series with four irrigation schemes, shown with and without precipitation forcing

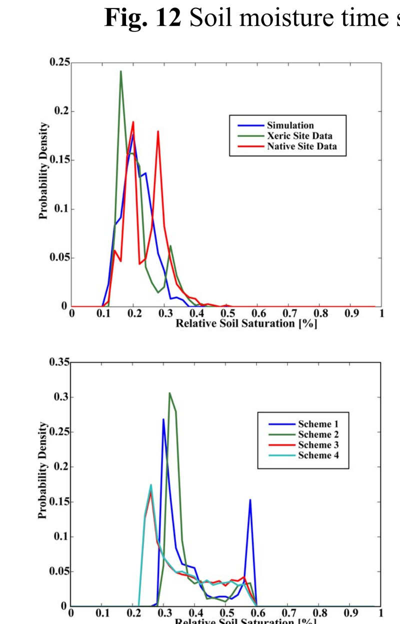


Fig. 13 Probability density functions of soil moisture for two unirrigated data sets and unirrigated simulation (above), and for four irrigation schemes described in Figure 12 (below)

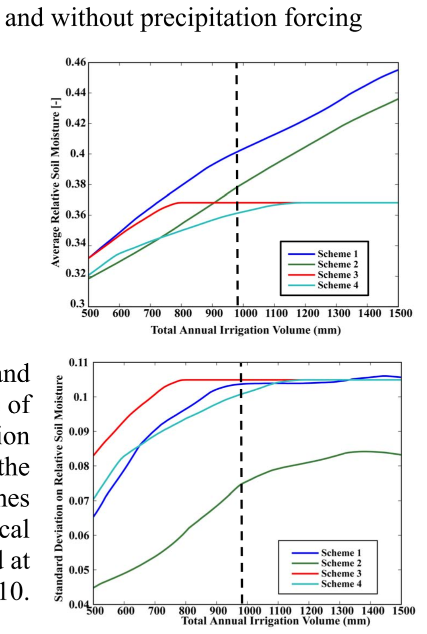


Fig. 14 Average (above) and standard deviation (below) of daily soil moisture as a function of yearly irrigation input for the four irrigation schemes described in Figure 12. Vertical line represents volume used at xeric site in 2010.

VI. Impacts of Irrigation

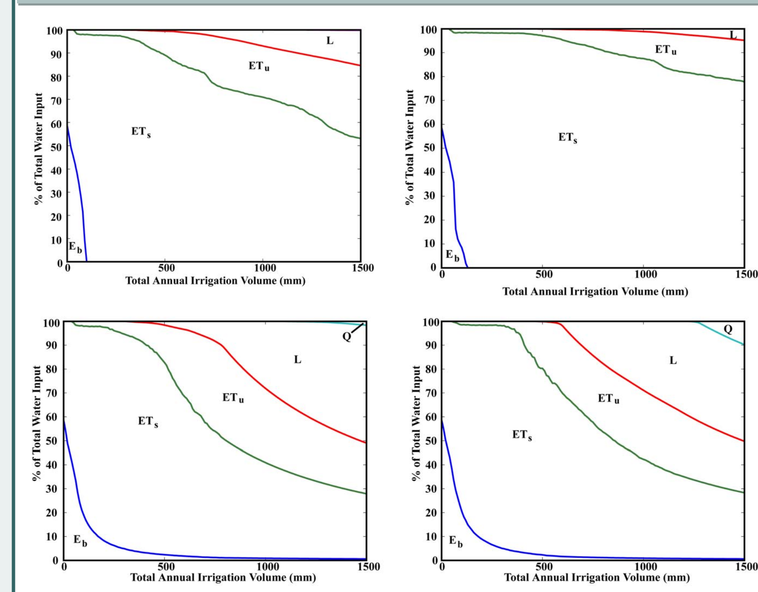


Fig. 15 Partitioning of water input for four irrigation schemes

The figure at left shows the fate of water input (combined irrigation and precipitation) as a function of total annual irrigation volume (held constant across all four irrigation schemes), partitioned between runoff (Q), leak (L), unstressed ET (ET_u), stressed ET (ET_s), and evaporation below the wilting point (E_b). The figure shows the partition for (clockwise from top-left) constant daily irrigation, constant monthly (flood-style) irrigation, seasonal monthly irrigation, and seasonal daily irrigation. (Under seasonal irrigation, applied quantities were twice as high in summer months as in the winter.)

VII. Conclusions and Future Work

Despite the substantial role on plant productivity that irrigation plays in semiarid developed areas, there is still a great need for a quantitative understanding of the urban water budget (Pataki, et al., 2011). This study calibrates a point-scale soil water balance model to available soil moisture data, using historical meteorological records as model forcing. The calibrated model is then adapted to include irrigation, in order to examine the partitioning of water input under varying irrigation amounts and schedules.

- Soil moisture under daily irrigation exhibited a much higher dependence on potential ET than on water input (combined precipitation and irrigation), even with seasonal irrigation patterns.
- Under moderate irrigation, the vast majority of soil moisture is lost through ET.
- Daily irrigation, as compared to monthly, showed less leakage and time below the wilting point, despite higher stressed ET. This could have the benefit of maintaining plant health while limiting productivity.

Future work for this study includes:

- Continued refinement of model calibration, including calibrating vegetative and irrigation parameters based on metered water use records at the irrigated sites (mesic, oasis, xeric).
- An examination of plant water stress as a function of the soil moisture time series.
- An analysis of soil moisture and plant water stress as functions of soil, vegetative, and meteorological parameters, as well as irrigation input, that can aid in sustainable water and landscape management.
- Transfer of knowledge gained to a more robust, integrated, fully-distributed model of urban ecohydrology.

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Acknowledgements

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