Ecohydrology in semiarid urban ecosystems: Modeling the relationship between connected impervious area and ecosystem productivity

Catherine Shields1,2 and Christina Tague1

1Bren School of Environmental Science and Management, University of California, Santa Barbara, California, USA, 2Now at Pacific Gas and Electric Company, San Francisco, California, USA

Abstract

In water-stressed, semiarid urban environments, connections between impervious surfaces and drainage networks may strongly impact the water use and ecosystem productivity of neighboring vegetated areas. We use an ecohydrologic model, the Regional Hydro-Ecological Simulation System (RHESSys), to quantify the sensitivity of vegetation water use and net primary productivity (NPP) to fine-scale impervious surface connectivity. We develop a set of very fine-scale (2 m²) scenarios that vary both the percentage of impervious surface and fraction of this impervious surface with direct hydrologic connections to urban drainage systems for a small hillslope. When driven by Mediterranean climate forcing, model estimates suggest that total vegetation water use declines with increasing impervious area. However, when impervious area is hydrologically disconnected from the urban drainage network, declines in water and carbon fluxes with decreased vegetated area can be partially, or in some cases even completely, offset by increased transpiration and NPP in the remaining vegetation. Relative increases in water use and NPP of remaining vegetation are much greater for deeply rooted shrubs and trees and negligible for shallow rooted grasses. We extrapolate our findings to the catchment scale by developing a first-order approximation of fine-scale impervious connection impacts on aggregate watershed water and carbon flux estimates. Our approach offers a computationally and data-efficient method for estimating the impact of impervious area connectivity on these ecohydrologic fluxes. For our only partially urbanized Santa Barbara watershed, estimates of water use and NPP that account for fine-scale impervious connection differed by more than 10% from those that did not.

1. Introduction

A key aspect of urban spatial heterogeneity is the degree of connection between impervious surfaces and the stream network. There is a long history of studying the impact of urbanization on watershed hydrology, specifically the effects of increases in impervious surface and basin connectivity on streamflow and water quality [e.g., Leopold, 1968; Arnold and Gibbons, 1996; Walsh et al., 2005; Wollheim et al., 2005]. The total amount of impervious area in a catchment is often used to explain the increases in peak flows and runoff associated with urbanization. However, a growing body of literature [Alley and Veenhuis, 1983; Boyd et al., 1993; Booth and Jackson, 1997; Lee and Heaney, 2003; Walsh and Kunapo, 2009] suggests that the driver of these changes in runoff is specifically the amount of impervious surface with a direct hydrologic connection to the urban drainage network, termed effective impervious area (EIA). Impervious surfaces that lack this direct connection may do little to increase runoff. The impacts of increases in EIA on terrestrial vegetation, however, are less well studied. For example, if increases in EIA result in increases in seasonal or annual streamflow, there should be a corresponding decrease in soil water storage and the availability of water to vegetation. In contrast, an increase in impervious area not directly connected to the urban drainage network might result in an increased delivery of water to the remaining vegetated areas, as water will flow from impervious surface to vegetation rather than bypassing vegetation and draining directly to the stream. In a semiarid Mediterranean climate, this increase in water delivery could prompt an increase in transpiration and productivity, as these systems are generally water-limited. Since some species of urban vegetation in semiarid and arid climates have been shown to transpire large amounts of water received via irrigation [Pataki et al., 2011], rerouting water from impervious areas could potentially allow vegetation to maintain high...
transpiration rates while reducing the need for irrigation inputs, an attractive prospect in municipalities facing increasing stress on water supplies. However, it is also possible that the influence of EIA and hydrologically disconnected impervious area (HDIA) on water delivery will be limited by the temporal disconnect between periods of peak precipitation (typically the fall and winter months) and periods of peak potential for plant growth (typically the spring and early summer) that characterize semiarid Mediterranean climates.

In this paper, we will present a modeling approach that can be used to evaluate the impact of EIA relative to total impervious area on both water fluxes and net primary productivity (NPP). We perform a two-step analysis to first evaluate the impact of EIA on vegetation water use and productivity at the local scale, and secondly to assess the potential implications of an EIA-productivity relationship for catchment-scale fluxes. We use a study site near Santa Barbara, California (described in more detail below). We use a representative hillslope to model transpiration and photosynthesis estimates from a series of impervious surface scenarios. In these scenarios, we explicitly differentiate between EIA, HDIA, and vegetated areas. The model output analyzed with the goal of answering three questions. First, does the amount of total impervious area (TIA) classed as EIA or HDIA have a discernible influence on transpiration or NPP? Second, is this influence limited to a short period immediately following storm events or is it sustained over a longer period of time? Finally, does this influence vary with vegetation type and factors such as rooting depth? We are especially interested in testing the hypothesis that impervious area can be distributed in a way that increases the total transpiration and NPP of the hillslope (Figures 1 and 2). We hypothesize that replacing a low to moderate portion of vegetated area with

Figure 1. Conceptual representation of hypothesized EIA impact on vegetation. In the undeveloped scenario (0% TIA) (top), precipitation inputs are routed evenly across a fully vegetated hillside. In an example scenario with approximately 20% TIA and 100% EIA (middle) some precipitation that falls on impervious surfaces is routed directly to the stream, completely bypassing vegetation. In an example scenario with approximately 20% TIA and 0% EIA (bottom), precipitation that falls on impervious is routed from impervious surface to the soil of a downslope neighboring patch, potentially increasing transpiration and NPP in the remaining vegetated areas.
HDIA may increase water delivery to the remaining vegetated areas sufficiently to increase NPP beyond what would be expected from an area with no impervious surface. In contrast, we expect a decline in hillslope NPP when vegetation is replaced by EIA (Figure 2) and water is not routed to vegetated areas.

The second part of our analysis addresses the problem of representing EIA at the catchment scale in hydrologic models. The fine-scale heterogeneity of urban catchments presents a major challenge to modelers. While very fine (<5 m²) scale spatial data are increasingly available, modeling at such fine scales is computationally intensive and the modeler’s ability to translate fine-scale processes into a cumulative catchment-scale effect can be limited. In the case of impervious area, modelers will typically account for impervious surface by assuming an overall level of coverage at a relatively coarse spatial scale and adjusting runoff coefficients accordingly [e.g., Thorndahl and Schaarup-Jensen, 2007]. However, explicit modeling of fine-scale impervious surface connections has generally been limited to relatively small drainage areas [Aronica and Cannorozzo, 2000; Amaguchi et al., 2012; Rodriguez et al., 2008]. Recently, Dewals et al. [2012] have investigated the impact of differentiating between drained (effective) and undrained surfaces when modeling storm events over a larger catchment and found that accounting for the faster routing of water from drained surfaces improved model predictions of peak quick flow. The sensitivity of model output to fine-scale impervious surface characteristics over a longer (seasonal or multiyear) time...
scale has not yet been studied in detail. For modelers interested in ecohydrologic processes such as vegetation water use and NPP, the effect of accounting for EIA over a longer period of time is of particular interest.

We use our hillslope-level model output to calculate a first-order approximation of the potential impact of accounting for fine-scale impervious surface characteristics at the catchment scale on modeled NPP and transpiration. To do this, we compare our spatially explicit model estimates to estimates based on a "lumped" scenario where no distinction is made between EIA and HDIA. The goal of this extrapolation is to estimate the impact of accounting for EIA versus TIA at a catchment scale, without conducting computationally intensive model runs over a large area at very fine (<5 m²) spatial resolution.

2. Data and Methods

2.1. Study Site

The Mission Creek catchment (Figure 3) is a coastal, semiarid, and moderately urbanized catchment located in Santa Barbara, CA. The local climate is Mediterranean, characterized by long, dry summers and cool, wet winters. Annual precipitation averages 470 mm yr⁻¹ at sea level over the 1971–2000 period (National Climate Data Center, Climatography of the United States No. 20 1971–2000, Coop ID: 047902, available at http://cdo.ncdc.noaa.gov/climatenormals/clim20/ca/047902.pdf, 2004) and increases with elevation, averaging 888 mm yr⁻¹ for the same time period at a 2200 m elevation rain gauge located near the catchment (Santa Barbara County Flood Control District, Official monthly and yearly rainfall record, available at http://www.countyofsb.org/pwd/water/downloads/hydro/212mdd.pdf, 2011). The majority of precipitation is delivered during winter storms. While the headwaters of the catchment are largely steep terrain unsuitable for major development, the base of the catchment (approximately 50% of total area) is a mix of urban and suburban development. In the developed portion of the catchment, impervious surface coverage averages 21% of total area. In the most developed parts of the catchment, impervious surface can account for as much as 81% of total area. For our hillslope scale analysis, we selected a small (0.9 ha) test-case hillslope located within the Mission Creek catchment (Figure 3). The hillslope is currently not developed, but has relatively gentle slopes (ranging from 2° to 6°), making it a potential site for future development. Hillslope elevation ranges from 189 to 195 m.

Meteorological inputs were obtained from two locations near the study hillslope. Daily temperature data were obtained from a National Climate Data Center monitoring station near the base of the Mission Creek catchment (3 m elevation). Hourly precipitation data from a midelevation (700 m) gauge operated by the Santa Barbara County Flood Control District were used to generate precipitation inputs, followed by adjustment to account for orographic scaling effects. All model runs were made at a daily time step over a 16 year series of climate data, from water year 1993– to 2009. This time period covers a range of both wet and dry years, allowing us to explore system responses to different urbanization scenarios over a spectrum of climate conditions representative of this region. The extent and connectivity of impervious area (EIA and TIA) in each scenario was held constant over the 16 year study period.

2.2. RHESSys Model

All simulations were run using the Regional Hydro-Ecological Simulation System (RHESSys; version 5.14) [Tague and Band, 2004]. RHESSys is a spatially distributed model of coupled hydro-biogeochemical cycling and has been successfully used to model daily runoff and evapotranspiration (ET) in the Mission Creek catchment [Shields and Tague, 2012] and in watersheds with similar climate and topography to Mission Creek [Tague and Band, 2004; Tague et al., 2009; Tague and Pohl, 2008]. RHESSys is a spatially explicit model, routing both subsurface and overland flow. Both vertical and lateral water fluxes are considered. Vertical infiltration is based on the Green and Ampt model [Green and Ampt, 1911] and includes a vertical infiltration capacity parameter that can be adjusted to reflect surface impermeability. Infiltrated water recharges a rooting zone and an unsaturated layer; any excess drainage is routed to shallow subsurface or deeper groundwater layers as a function of hydrologic parameters. Routing of subsurface saturated flow is based on topography and soil characteristics following the distributed hydrology soil vegetation model (DHSVM) [Wigmosta et al., 1994]. Excess surface water is routed into downslope patches, where there is the potential for reinfiltration. Both surface and subsurface routing in RHESSys allow for multiple flow paths; flux out from a given patch is partitioned into multiple downslope neighbors. Road networks in RHESSys are assumed to be directly connected to the stream unless otherwise specified; water that is routed into a road is therefore
immediately routed to the stream network, bypassing all downslope patches and functioning as EIA in modeling scenarios (described below). Model calibration is required to define parameters that control flow rates through soils and permeable bedrock layers. For this analysis, we calibrated for two shallow subsurface soil parameters: saturated hydraulic conductivity ($k$) and decay of $k$ with depth ($m$); and three parameters used to define bypass flow to deeper groundwater stores and groundwater drainage rates: $gw1_{shallow}$ (fraction of precipitation automatically routed to groundwater storage from areas where slope $< 20^\circ$), $gw1_{steep}$ (fraction of precipitation automatically routed to groundwater where slope $> 20^\circ$), and $gw2$, which controls the drainage rate of deep groundwater to the stream. A Monte Carlo style split-sample calibration and evaluation process was used to determine the parameter values that yield the most accurate estimates of daily and annual streamflow. A detailed description of the model calibration process can be found in Shields and Tague [2012].

RHESSys includes a moderately complex model of vegetation carbon and nitrogen cycling and water-stress response. Transpiration is modeled using the Penman-Monteith [Monteith, 1965] approach, where stomatal conductance is computed using the Jarvis model [Jarvis, 1976] that varies conductance with rooting zone water availability and atmospheric conditions, including radiation, temperature, vapor pressure deficit, and CO$_2$ concentration. Canopy radiation attenuation follows Beer's law and the model accounts for differences between sunlit and shaded leaves and diffuse and direct radiation. The canopy radiation, transpiration, and conductance submodels include parameters to define species-specific physiological characteristics that account for differences in water use due to rooting depth, canopy structure, and stomatal closure behaviors [see Tague and Band, 2004 for details]. Evaporation of canopy and litter interception as well as any surface ponded water is also based on the Penman approach [Monteith, 1965]. RHESSys models gross photosynthesis using the Farquhar model [Farquhar et al., 1980] and uses stomatal conductance to link carbon sequestration to moisture availability. Net primary productivity is calculated as the difference between gross photosynthesis and respiration. Respiration varies with plant component biomass and temperature following Ryan [1991]. Net primary productivity is then allocated to plant growth by allocating fixed proportions of NPP among roots, stems, and leaves. Allocations proportions were set following White et al. [1997]. Additional detail on submodels used to estimate respiration, carbon allocation, turnover and other carbon-cycling processes are provided in Tague and Band [2004].

### 2.3. Impervious Surface Scenarios

We considered a total of 36 different scenarios, encompassing a range of TIA and EIA fraction combinations for the test-case hillslope (Figure 1). This scenario set includes an end-member case of 0% impervious surface cover, referred to as the "undeveloped" scenario. In each scenario, the hillslope is divided into 2 m$^2$ patches. For any patch, a direct impervious connection to a drainage point at the base of the hillslope results in an area being classed as EIA. In RHESSys, classifying a patch as EIA means any surface water that flows into that patch or any precipitation falling on that patch will be immediately routed from the patch to a downslope drainage point, completely bypassing any downslope patches. Drainage points are either a stream or road network. In this study, all roads are considered to act as drainage points, as we assume that water flowing onto a road is typically routed directly into a storm drain in an urban setting.

Our scenarios include a total of seven possible levels of TIA coverage (5, 10, 15, 25, 35, 50, and 65%). We chose not to test scenarios with TIA $> 65\%$ as we wanted to consider a full range of EIA fractions for each level of TIA coverage, and developing realistic scenarios with a low EIA fraction when TIA $> 65\%$ was not feasible. Within each level of TIA coverage, we created scenarios where the EIA fraction constituted 5, 25, 50, 75, and 100% of TIA (e.g., in a scenario with 10% TIA and a 50% EIA fraction, EIA would represent 5% of total hillslope area, see Table 1 for the total hillslope area associated with EIA in each scenario).

### Table 1. Percentage of Total Hillslope Area Associated With Effective Impervious Area (EIA) for Each of the 35 Impervious Surface Scenarios Considered

<table>
<thead>
<tr>
<th>TIA</th>
<th>5%</th>
<th>10%</th>
<th>15%</th>
<th>25%</th>
<th>35%</th>
<th>50%</th>
<th>65%</th>
</tr>
</thead>
<tbody>
<tr>
<td>5% EIA fraction</td>
<td>0.25</td>
<td>0.5</td>
<td>0.75</td>
<td>1.25</td>
<td>1.75</td>
<td>2.5</td>
<td>3.25</td>
</tr>
<tr>
<td>25% EIA fraction</td>
<td>1.25</td>
<td>2.5</td>
<td>3.75</td>
<td>6.25</td>
<td>6.75</td>
<td>12.5</td>
<td>16.25</td>
</tr>
<tr>
<td>50% EIA fraction</td>
<td>2.5</td>
<td>5</td>
<td>7.5</td>
<td>12.5</td>
<td>17.5</td>
<td>25</td>
<td>32.5</td>
</tr>
<tr>
<td>75% EIA fraction</td>
<td>3.75</td>
<td>7.5</td>
<td>11.25</td>
<td>18.75</td>
<td>26.25</td>
<td>37.5</td>
<td>48.75</td>
</tr>
<tr>
<td>100% EIA fraction</td>
<td>5</td>
<td>10</td>
<td>15</td>
<td>25</td>
<td>35</td>
<td>50</td>
<td>65</td>
</tr>
</tbody>
</table>
maintained a similar spatial distribution of impervious area across the hillslope (e.g., between upslope and downslope areas) for all scenarios. For each scenario, we use the model to estimate annual transpiration and NPP for each year of our 16 year climate record. For each combination of TIA and EIA fractions, we repeat our model-based analysis for three different vegetation types. We model grass and coast live oak as representatives of some common urban vegetation covers in the Santa Barbara area. We also model a chaparral/shrub vegetation cover. Although chaparral species are not as common in urban landscaping, they are representative of the native and drought-resistant vegetation types that are increasingly encouraged as xeriscape landscaping choices. Land surface parameters for these vegetation types are assigned according to literature estimates [see Tague et al., 2009; Tague and Pohl, 2008; White et al., 1997 for details].

While regular irrigation is not typical for coast live oak or chaparral plants, it is quite common for lawn grasses to be watered on a regular basis. No water inputs beyond precipitation were applied in the coast live oak and chaparral scenarios, but additional irrigation water inputs were applied to the grass scenarios. Using total water use data supplied by the City of Santa Barbara, we estimated monthly outdoor water use (OWU) values over the WY 1993–2009 study period using the methodology described in Shields and Tague [2012]. These total monthly values were then applied evenly throughout the month as irrigation inputs to the irrigated grass scenarios.

In our analysis of the impact of EIA on transpiration and NPP, we consider transpiration and NPP averaged over the entire hillslope (T and NPP) and over the vegetated areas only (T_veg and NPP_veg). Estimates of total hillslope-averaged T and NPP provide information on the net effect of TIA and EIA fractions on total water and carbon fluxes from a given land unit, in this work the example hillslope. Per vegetated area estimates (shown through T_veg and NPP_veg) provide insight into the impact of EIA and TIA on the productivity of the remaining vegetation and allow us to evaluate under what conditions the additional water inputs from impervious areas are likely to reduce seasonal water stress of adjacent vegetation. If reduction in water stress is substantial, results may have implications for landscape management and the need for irrigation inputs.

We also consider the persistence of the impact of additional water inputs from HDIA on adjacent vegetation through the dry season (May–September). For each developed scenario, we calculate the fraction of dry season days with T_veg or NPP_veg at least 1% greater than T_veg or NPP_veg for the undeveloped scenario. The >1% cutoff was imposed to minimize interference from small rounding errors or other minor discrepancies. By comparing these fractions across developed scenarios, we can determine the degree to which increases in either T_veg or NPP_veg can be sustained over an extended period. This issue of persistence is especially important in cases where reducing summer irrigation levels is a goal: if increases in T_veg and NPP_veg occur only in a short period of time after storm events, they have little meaningful impact on the need for dry-season irrigation or as a means to reduce summer water stress vulnerability in nonirrigated vegetation.

2.4. Extrapolation to the Catchment Level
The small area of the test hillslope (0.9 ha) allows us to utilize relatively small (2 m²) patches and explicitly represented connections between EIA and hillslope drainage points and HDIA and downslope patches. To scale results from our test hillslope up to a larger watershed, we develop a first-order approximation of the
We note that the lumped approach is the current approach used in RHESSys and other hydrologic models where the basic modeling unit (patch) is of relatively coarse scale and contains both vegetation and impervious areas, but the within-patch spatial arrangement of these areas is not resolved. In this case, a lumped hydrologic modeling approach would estimate fluxes for a patch based on its classification as suburban or urban, while the spatially distributed version resolves fine-scale features within the patch. In the current version of RHESSys, infiltration of net precipitation (after interception by canopy and litter) for each patch is represented as a fraction of total area. The spatially explicit approach is the same as described above where the hillslope is divided into 2 m² patches. In this case the flow between specific patches allows us to explicitly resolve the impact of EIA and HDIA for a given TIA.

To develop our adjustment of T and NPP estimates for lumped patches, we ran one lumped scenario for each classed as completely impervious (no vegetation cover, vertical infiltration of zero) and 65% of patches classed as completely vegetated or completely impervious and water is routed to downslope neighbors. For example, in the lumped scenario, a patch with 35% impervious surface cover would be assigned a vegetation cover fraction of 65%, and vertical infiltration capacity would be reduced by 35% to represent the effect of impervious surface cover. In the spatially explicit scenario, this same situation would be represented as 35% of patches classified as completely impervious (no vegetation cover, vertical infiltration of zero) and 65% of patches classified as completely vegetated (100% vegetation cover, no reductions in the vertical infiltration rate).

To develop our adjustment of T and NPP estimates for lumped patches, we ran one lumped scenario for each of the TIA cover fractions tested in the hillslope-scale analysis using the explicit patches (as described above; 5, 10, 15, 25, 35, 50, and 65% TIA). Annual T and NPP output from each of the 36 spatially explicit scenarios was then regressed against the corresponding lumped scenario output and found to have a strong linear relationship in all cases. We then calculate the slope (m) of each of these regression relationships. Finally, we develop simple regression models for calculating m and i as a function of TIA and EIA. Several possible regression forms were considered (see equations (1a)–(1h), below). For each scenario, we chose the equation that gave the best fit (highest r²) with the least number of terms (i.e., if an additional term did not provide a significant improvement in fit (e.g., significant increase in r²), it was not used)

\[ m(TIA, EIA) = a + b \times TIA + d, \]

\[ i(TIA, EIA) = a + b \times TIA + d, \]

\[ m(TIA, EIA) = a + b \times TIA + d, \]

\[ i(TIA, EIA) = a + b \times TIA + d, \]

\[ m(TIA, EIA) = a + EIA + b \times TIA + d, \]

\[ i(TIA, EIA) = a + EIA + b \times TIA + d, \]

\[ m(TIA, EIA) = a + EIA + c \times TIA^2 + d, \]

\[ i(TIA, EIA) = a + EIA + c \times TIA^2 + d. \]

Note that coefficients a-d differ for m and i, and for NPP and T. These estimates of slope (m) and intercept (i) are used to adjust lumped estimates of T and NPP, given a particular TIA and EIA:

\[ T_{EIA} = m_{TIA} \times T_{(lumped, TIA)} + i_{(lumped, TIA)} \times TIA, \]

\[ NPP_{EIA} = m_{NPP} \times NPP_{(lumped, TIA)} + i_{NPP} \times TIA. \]

These relationships were calculated separately for each vegetation type (one each for chaparral, live oak, and grass) and for both NPP and T.
We then modeled the entire Mission Creek catchment for the 16 year period (WY 1993–WY 2009). The full catchment is divided into approximately 2000 patches, which are derived from a digital elevation model (DEM) with 120 m × 120 m resolution created by coarsening a National Elevation Data Set 10 m × 10 m DEM (United States Geological Survey, National Elevation Data Set, http://gis-data.usgs.net/ned/, 2007). To create the patch map, spatially adjacent cells with the same elevation values within the DEM were grouped; patch area therefore varies with the elevation gradient. We used model estimates of T and NPP calculated in each patch as our T_{lumped} and NPP_{lumped} values when applying equations (2a) and (2b) above to each patch in the catchment.

We used a fine-scale map of impervious surface cover in the Mission Creek catchment, developed by Beighley et al. [2009], to calculate the TIA and EIA fractions for each 2 m² patch in the catchment. To distinguish between effective and noneffective impervious surface, we created an EIA seed map (Figure 4), where the centerlines of roads and the stream network were classed as the initial EIA seeds while all other impervious surfaces in the fine-scale map were classed as noneffective. We assumed that the storm sewer network will closely parallel the road network; thus, our decision to use roads as EIA seeds. We then analyzed the eight pixels neighboring each EIA seed: if a neighbor pixel was found to be noneffective impervious, it was reclassed as EIA. We repeated this process until all EIA pixels were found to have either nonimpervious (vegetated) surface or EIA as neighbors (Figure 4). We note that this methodology will likely result in a small undercounting of EIA since we do not explicitly account for the presence of storm sewers that are not directly associated with the road network. After completing our classification of EIA, we calculated the TIA and the EIA fraction for each patch in the catchment. Using these estimates in conjunction with the T_{lumped} and NPP_{lumped} values described above, we were then able to use equations (2a) and (2b) to apply a first-order adjustment to model estimates of patch-level T and NPP to account for EIA/TIA effects. These results were then aggregated to create a catchment-level estimate of the impact of incorporating information about EIA fractions into the RHESSys model.

3. Results

3.1. Annual Transpiration

In our hillslope-scale analysis, a negative TIA-transpiration relationship was found for all vegetation types and all levels of EIA fraction (Figure 5). The decline in transpiration (per unit hillslope area) with increasing TIA reflects the effect of removing vegetation from the hillslope. For any given level of TIA coverage,
hillslope T was consistently highest for the lowest EIA fraction scenarios, while higher EIA fractions were associated with lower rates of hillslope T. The difference between T across different levels of EIA coverage also increased as TIA increased, meaning that the impact of EIA is greater and more pronounced at higher levels of TIA. For example, when TIA was only 5%, the difference between 5% and 100% EIA fractions for grass, live oak, and chaparral was only 7, 9, and 9 mm yr\(^{-1}\), respectively, a decrease of approximately 5% in each case. In contrast, when TIA is 65%, the difference between 5% and 100% EIA fractions is 24, 61, and 53 mm yr\(^{-1}\) for grass, live oak, and chaparral, respectively; or a decrease in hillslope T of 24%, 47%, and 56%. The larger differences in T across EIA at high levels of TIA are indicative of the larger range in absolute area classed as EIA and the impact of additional water inputs from HDIA on T in the remaining vegetated area.

The differences in hillslope-scale T across different EIA fractions for a given TIA reflect differences in per-vegetated-area transpiration in the remaining vegetated areas (T\(_{\text{veg}}\)) (Figure 6). For scenarios with a low EIA fraction, T\(_{\text{veg}}\) generally increases with TIA as a result of additional water from hydrologically isolated impervious areas being routed to vegetation and effectively forming an additional precipitation input. The increase is slightly nonlinear such that the relative gains in T\(_{\text{veg}}\) are greater at higher TIA, particularly for chaparral and live-oak vegetation. As the EIA fraction increases, more of the runoff from impervious surfaces are routed directly out of the hillslope and water inputs to vegetated areas therefore remain more constant across the range of TIA coverage modeled. As a result, T\(_{\text{veg}}\) shows less sensitivity to TIA as the EIA fraction increases; for the 100% EIA fraction scenarios, there is little or no change in T\(_{\text{veg}}\) as TIA increases from 5% to 65%. The differences in sensitivity of T\(_{\text{veg}}\) to TIA result in a widening gap between low and high EIA fraction scenarios as TIA increases. At 5% TIA, the differences in T\(_{\text{veg}}\) between the 5 and 100% EIA fraction scenarios are \(<10\) mm yr\(^{-1}\) for all three vegetation types. When TIA increases to 65%, the differences in modeled T\(_{\text{veg}}\) between 5% and 100% EIA fraction have increased by an order of magnitude or more.

While the general effect of lower EIA fraction and higher TIA resulting in an increased T\(_{\text{veg}}\) is consistent across vegetation types, the extent of the impact varies substantially among vegetation types. The effect of EIA fraction on modeled T in the grass scenarios is considerably less than for either the chaparral or live oak scenarios, with a low EIA fraction showing a negligible mitigating effect. These differences are largely attributable to differences in the ability of the different vegetation types to access stored water (as represented by their rooting depths) and the potential for each vegetation type to use available water. In the case of shallowly rooted grass, additional water inputs from HDIA can only be utilized while they remain in a

Figure 6. Mean annual T\(_{\text{veg}}\) as a function of TIA for (a) grass, (b) live oak, and (c) chaparral. As TIA increases, T\(_{\text{veg}}\) shows large increases in scenarios with low EIA fractions due to the transfer of water from impervious to vegetated areas.
relatively shallow portion of the soil profile. In contrast, the more deeply rooted chaparral and live oak can access a larger portion of the soil profile; thus, they will be able to take better advantage of additional runoff input from HDIA. Our results are consistent with studies from natural semiarid ecosystems that show greater transpiration losses from deeply rooted species, particularly during summer droughts [e.g., Baldocchi et al., 2004]. The larger biomass and leaf area associated with live oak and chaparral mean that they are more photosynthetically active and will transpire more water than grass when additional water is available. We also considered the possibility that in the case of grass, irrigation might be moderating the differences between low and high EIA scenarios by providing additional water and thus reducing the importance of additional water from impervious surfaces. However, when we ran the grass scenarios with no irrigation inputs (results not shown), the modest differences between low and high EIA fraction scenarios remained unchanged despite the decline in overall rates of vegetation water use.

3.2. Annual NPP
In our hillslope-scale simulations, modeled NPP shows a somewhat different sensitivity to EIA and TIA relative to T (Figure 7). As TIA coverage increases, hillslope NPP shows a generally increasing trend. As with T, low EIA fractions generally increase NPP and differences between low and high EIA fraction scenarios become more pronounced as TIA increases; scenarios with high EIA fractions show modest increases in NPP, while scenarios with low EIA fractions show generally greater increases. The general increase in hillslope NPP with increasing TIA is at first glance somewhat counterintuitive since we might expect that removing vegetation should decrease NPP per hillslope area. However, hillslope NPP in the baseline (no impervious area) is negative. This negative NPP results from a disproportionate number of years with below average annual precipitation in the simulation period. Mature vegetation in these years is thus a slight carbon source with respiration rates exceeding photosynthesis. When vegetation with a negative mean NPP over the simulation period is replaced by impervious area with an NPP of zero, the result is slightly less negative rates of hillslope NPP and a trend of NPP increasing with TIA. Differences between low and high EIA fraction scenarios are largely attributable to changes in the behavior of the remaining vegetation, as NPP\textsubscript{veg} for the low EIA fraction scenarios show large increases with TIA, while NPP\textsubscript{veg} for high EIA scenarios remains relatively constant across TIA (Figure 8).

As with T, there were differences in the sensitivity of different vegetation types to variations in the EIA fraction. Once again, grass was relatively insensitive, with comparatively modest differences between NPP\textsubscript{veg}...
for low and high EIA fraction scenarios, even at high levels of TIA coverage. This low level of sensitivity reflects the shallow rooting depth, smaller leaf area, and generally lower amount of biomass associated with grass. These physiological characteristics mean grass is both less suited to accessing additional stored soil water and less able to utilize additional water when it is available. Both the live oak and chaparral scenarios are considerably more sensitive to the EIA fraction. At high levels of TIA (50 and 65%), NPP$_{\text{veg}}$ for 5% EIA fraction scenarios is three or more times greater than NPP$_{\text{veg}}$ in scenarios with a 75 or 100% EIA fraction. There is a unique drop in annual NPP$_{\text{veg}}$ for chaparral as TIA increases from 50% to 65% for the 5% EIA scenario. Despite having the greatest increases in additional moisture, t NPP$_{\text{veg}}$ is actually lower than several drier scenarios (e.g., the 50% TIA/5% EIA case or the 65% TIA/25% EIA scenarios). This transition in behavior occurs due to rapid growth of chaparral biomass with the additional moisture. As the biomass increases so do respiration costs, eventually additional gains in gross primary production are less than gains in respiration. Most of the scenarios considered are strongly water limited and the additional water is not sufficient to lead to a rate of biomass accumulation that reaches this point; however, it appears that the crossover point may have been reached in this instance.

The relationship between NPP and EIA is slightly nonlinear and changes with increasing TIA. We note that in the case of the live oak and chaparral scenarios, increases in NPP with TIA become less pronounced as TIA increases. In the case of chaparral, the increasing trend appears to cease when TIA exceeds 50%, and NPP rates for 65% TIA coverage are either the same or lower than NPP rates for 50% TIA coverage and the same EIA fraction. These results indicate that there is a point at which water availability is no longer the primary limiting factor on hillslope productivity and that another variable (such as the total hillslope area allotted to vegetation) becomes dominant. Past this point, the decreases in hillslope NPP that might result from decreased vegetated area cannot be as effectively offset by increasing NPP$_{\text{veg}}$ in the remaining vegetated area.

### 3.3. Dry Season Transpiration and Productivity: Persistence of the EIA Effect

Our analysis of the persistence of increased transpiration and NPP through the dry season (May–September) revealed that all scenarios showed at least some days with T$_{\text{veg}}$ and NPP$_{\text{veg}}$ at least 1% greater than for an undeveloped scenario with the same vegetation type (Figures 9 and 10). As with overall rates of T and NPP, there was a divergence between the shallowly rooted grass scenarios and the more deeply rooted live oak and chaparral

![Figure 8. Mean annual NPP$_{\text{veg}}$ as a function of TIA for (a) grass, (b) live oak, and (c) chaparral. As TIA increases, the live oak scenarios show large increases in NPP$_{\text{veg}}$ for low EIA fraction scenarios. Increases are more modest with increasing EIA fraction. As with T, grass scenarios show less sensitivity to EIA fraction, most likely as a result of their much shallower rooting depth.](image)
scenarios. These differences were evident in several ways: the typical fraction of days exceeding a >1% threshold, the variation in days exceeding a >1% threshold between scenarios, and the change in dry season $T_{veg}$ and $NPP_{veg}$ relative to changes in rainy season $T_{veg}$ and $NPP_{veg}$.

For the live oak and chaparral scenarios, both daily $T_{veg}$ and daily $NPP_{veg}$ met a >1% threshold for >90% of the growing season for a large number of scenarios (Figures 9 and 10). An EIA fraction effect was still visible; scenarios with low EIA fractions achieved a high percentage of days exceeding the >1% threshold at relatively low levels of TIA coverage. As the EIA fraction increased, a higher level of TIA coverage was required for a large fraction of days to exceed the >1% threshold. For scenarios with a 100% EIA fraction, the fraction of days exceeding the >1% threshold was consistently low relative to other scenarios. These trends suggest that increasing runoff inputs from surrounding impervious areas to vegetated areas does result in an increase in long-term water storage and a corresponding increase in $T_{veg}$ and $NPP_{veg}$ beyond the end of the winter rainy season.

In contrast to the live oak and chaparral scenarios, grass scenarios generally had a lower fraction of days meeting the exceedance threshold. Only two scenarios (65% TIA coverage with 5% and 25% EIA fraction) had >90% of dry season days meeting the >1% threshold $T_{veg}$, and no scenarios at all meeting this mark for $NPP_{veg}$. These results are consistent with our earlier findings that grass scenarios show less sensitivity to the EIA fraction, and support our hypothesis that this lesser sensitivity is in part due to the shallow rooting depth of grass. The deeper roots of chaparral and live oak can access the deeper water stores that continue to be available later in the dry season, while the shallowly rooted grass can access a much smaller amount of stored water.

While our persistence analysis does suggest that impervious surface can impact $T_{veg}$ and $NPP_{veg}$ long after the end of the rainy season, it is important to remember that the persistence fractions only represent the number of days meeting a minimum productivity or water use threshold and are not indicative of the magnitude of increase beyond an undeveloped scenario. The fraction of days meeting the exceedance threshold tells only part of the story. An analysis of the mean monthly change in $T_{veg}$ and $NPP_{veg}$ (Figures 11 and 12) completes the picture. These barplots show the mean changes in both the dry (gray) and rainy (black) seasons. First, the overall trend apparent throughout our analysis that a low EIA fraction is associated with the greatest positive changes in $T_{veg}$ and $NPP_{veg}$ is seen again, with progressively smaller changes as the EIA fraction approaches 100%. Second, while the change in $T_{veg}$ and $NPP_{veg}$ is consistently greater in the wet season than in the dry season, we still observed a substantial increase in dry season rates of both $T_{veg}$ and $NPP_{veg}$, particularly in the chaparral and live oak scenarios. This result indicates that increases in water delivery will not only provide an immediate increase in productivity, but also boost...
soil water storage sufficiently to allow for a prolonged and sizable increase in productivity after the end of the winter rainy season.

3.4. Comparisons With Lumped Approach and Extrapolation to the Catchment Scale

We found strong and statistically significant ($p < 0.01$) linear correlations between lumped and spatially explicit model estimates of hillslope scale $T$ and $NPP$ for each of the TIA and EIA fractions considered (see e.g., Figure 13), with $r^2$ values frequently exceeding 0.99. For all scenarios, both $m_T$ and $m_{NPP}$ were consistently $<1$ and decreased as TIA increased. These results indicate that the spatially explicit scenarios show a narrower range of $T$ and $NPP$ across the study period. The difference between lumped and spatially explicit scenarios also varied considerably between dry years (associated with low rates of $T$ and $NPP$) and wet years (associated with higher rates of $T$ and $NPP$). In years with low precipitation, the difference between lumped and spatially explicit $T$ was relatively small, and spatially explicit $T$ sometimes slightly exceeded lumped $T$. As $T$ increased, the difference between approaches also increased (e.g., Figure 13a), and wet-year lumped rates of $T$ occasionally approached twice the rates observed in spatially explicit scenarios with 50 or 65% TIA coverage. In the case of $NPP$, lumped $NPP$ typically exceeded spatially explicit $NPP$ in wet years, when $NPP$ is positive and vegetation is accumulating biomass. Correspondingly, during dry years, when $NPP$ is negative and vegetation is acting as a carbon source, the lumped scenarios display more negative $NPP$ (i.e., greater loss of carbon/biomass) than the spatially explicit scenarios.

The result that spatially explicit scenarios yield lower rates of $T$ and a narrower range of $NPP$ values reflects the assumptions made by the hydrologic model in the lumped case when impervious surface must be parameterized as a fraction of total modeling unit area. We note that different assumptions would lead to different relationships between spatially explicit and lumped $T$ and $NPP$; thus, results are specific to RHESSys treatment of fractional impervious area. In RHESSys and for this semiarid region with flashy storm events, representing percent impervious surface cover as a percentage decrease in soil infiltration capacity actually allows for greater overall infiltration than the spatially explicit (and arguably more accurate) representation of impervious surface, even when the EIA fraction is low. In the spatially explicit scenarios, if there is any EIA at all (as was the case with all scenarios), some fraction of precipitation in each storm event will always be routed immediately out of the hillslope, regardless of the intensity of rainfall, antecedent soil moisture levels, or infiltration capacity of the soils. In contrast, with a lumped scenario, infiltration capacity is reduced

Figure 10. Mean percentage of dry season (May–September) days with $NPP_{veg}$ at least 1% greater than $NPP$ of undeveloped scenarios as a function of TIA for (a) grass, (b) live oak, and (c) chaparral. As with $T$, low EIA fractions are generally associated with a high percentage of days meeting this exceedence threshold.
proportionally; thus, it is possible that all precipitation inputs from an individual storm event would infiltrate into the soil if antecedent moisture levels and precipitation intensity were both sufficiently low. For the lumped scenarios then, there is consistently a larger amount of precipitation with the potential to infiltrate. We also note that the spatially explicit representation of hydrologically disconnected impervious surface creates a less uniform areal distribution of effective water inputs by swiftly concentrating precipitation into vegetated portions of the hillslope. Therefore, while there is no reduction in the infiltration capacity of vegetated soils, there is an increase in the intensity of water inputs (as precipitation plus overland flow from adjacent impervious surfaces), which may ultimately increase quick flow. In wet years especially, with more water entering the drainage area, relatively small differences in the fraction of water routed to subsurface versus overland flow can translate to large differences in the amount of water stored in the soil for use by vegetation. In summary, using the default approach of RHESSys (and other models) of lumped scenarios will tend to underestimate runoff losses relative to spatially explicit scenarios particularly for high EIA and TIA. An alternative approach for the lumped scenario would be to route all water falling on the percent of the hillslope that was classed as impervious directly to the stream. This approach would lead to an overestimation of runoff losses, particularly for low EIA and high TIA. Here we analyze the implications of ignoring EIA versus HDIA given the RHESSys approach to treating fractional impervious coverage but note that a similar analysis could be done using this alternative assumption.

Based on our lumped versus spatially explicit T and NPP estimates, we fit the slope \( \frac{m}{m} \) and intercept \( \frac{i}{i} \) values as a function of TIA and EIA fraction (Table 2), using the most appropriate (linear or quadratic incorporation of TIA) form of equation (1). All of the values shown in Table 2 are statistically significant \( p < 0.01 \).

We then use these relationships to refine our T and NPP estimates from the lumped model. Using the lumped model (for each patch) we estimate patch annual T and NPP for each of the approximately 2000 patches in the 31 km² Mission Creek catchment. The regression models derived from the hillslope-level analysis (Table 2) were applied to mean annual T and NPP output for each patch. This adjusted output was

Figure 11. Mean monthly change in dry and rainy season daily \( T_{\text{veg}} \) relative to baseline undeveloped scenario for (a) grass, (b) live oak, and (c) chaparral. Each set of seven bars represents the seven TIA scenarios (5, 10, 15, 25, 35, 50, and 65%) with each EIA fraction. Note that increases in \( T_{\text{veg}} \) for the live oak and chaparral scenarios remain relatively high during the dry season, while for grass increases occur overwhelmingly during the rainy season. This divergence suggests that the live oak and chaparral are better able to take advantage of increased soil water storage as temperatures and PAR increase following the end of the rainy season.
then aggregated to arrive at adjusted annual rates of T and NPP for the entire catchment. Overall, changes in annual T were quite modest and showed little interannual variability, with decreases of 5.3–7.5% (Figure 14a). When NPP was initially negative (dry years), the adjusted NPP increased by up to 19% when the EIA adjustment was used. When NPP was initially positive (wet years), the adjusted NPP decreased by as much as 16% (Figure 14b).

Watershed-scale NPP estimates when adjusted for EIA versus HDIA were within 20% of original estimates but often greater than 10%. The magnitude of these changes is largely attributable to the nature of the study catchment and time period considered. The overall level of impervious surface coverage, prevailing vegetation types in urban areas, and climate conditions during the study period were all contributing factors. While portions of the Mission Creek catchment are heavily developed, the upper half of the catchment is almost completely undeveloped. Within developed areas, only a relatively small area is developed to the level of having TIA > 50%. While the maximum patch TIA is 81%, mean patch TIA across the entire catchment is 12% and, within patches with some impervious surface area the mean patch TIA is 21%. Given that our regression models indicated greater differences between the lumped and spatially explicit approaches with increasing TIA, we might expect a greater divergence between approaches in a more heavily developed catchment. Furthermore, the dominant vegetation in the urbanized portion of the Mission Creek catchment is grass, occupying approximately 70% of developed patches in the catchment. Of our three vegetation types, grass showed the least sensitivity to the approach taken to account for impervious surface characteristics. If vegetation in urbanized patches was more heavily represented by more sensitive vegetation types (such as the chaparral and live oak considered here), greater divergence would also be expected. Prevailing climate patterns within our study period also played a role, as there were a number of years with below average precipitation. Had we instead selected a study period with a greater incidence of wet years, or with more extreme wet and dry years, we would expect to see a different range of change in T and NPP.

4. Discussion

Our analysis shows that the effect of increased impervious surface on ecohydrologic processes, specifically transpiration and NPP, is a function of not only total area but also the connection between

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**Figure 12.** Mean monthly change in dry and rainy season NPP_{veg} for (a) grass, (b) live oak, and (c) chaparral. Each set of seven bars represents the seven TIA scenarios (5, 10, 15, 25, 35, 50, and 65%) with each EIA fraction. As with T_{veg}, substantial increases in NPP_{veg} for the live oak and chaparral scenarios are seen in both the wet and dry seasons, while for grass increases occur largely during the rainy season.
impervious surface and the drainage network. Our ecohydrologic results parallel empirical and modeling studies that link stream hydrograph responses to urbanization—to both the total impervious area and fraction of connected impervious area [Alley and Veenhuis, 1983; Walsh and Kunapo, 2009; Dewals et al., 2012]. Here we demonstrate that by reducing the EIA fraction and explicitly accounting for disconnections between impervious surface and the stream, the reductions in total hillslope scale T and NPP associated with increased impervious area and vegetation loss are substantially less. In our example, shifting between high (75–100%) and low (0–25%) EIA fractions for TIAs above 35% actually results in a shift in vegetation acting as a carbon source to the atmosphere (NPP < 0) to a carbon sink (NPP > 0) over the simulation period. The effects of reducing EIA fraction are seen even at relatively high (50–65%) levels of TIA, although our analysis also indicated that at these higher levels of TIA the net effects of adding hydrologically disconnected impervious surface on total hillslope T or NPP were reaching a point of diminishing returns. The diminishing increases, particularly evident in rates of NPP_{avg} are especially important to note since they indicate an upper limit on the “optimal” range of TIA for which lowering EIA fraction will produce the greatest returns. We also find that the impacts of TIA and EIA fraction are not limited to the immediate time periods following storm events, but extend into the dry season, an especially significant result given the study site’s Mediterranean climate characterized by dry summer months. Our results also indicate that the impact of the EIA fraction depends on the vegetation type being modeled. Larger, more deeply rooted chaparral and live oak are substantially more sensitive to the EIA fraction than the smaller, more shallowly rooted grass.

While our study focused on the amount of TIA, EIA fraction, and vegetation type as the primary variables of interest, other factors that we were unable to consider within the scope of this study may also merit consideration. Soil depth and porosity ultimately determine the capacity for soils to store water, and we expect that the importance of the EIA fraction would show some dependence on soil type. We also did not consider the impact of placing impervious surface in specific locations within the hillslope (i.e., upslope

![Figure 13. Example of relationship between lumped and spatially explicit approaches for annual (a) T and (b) NPP, with the best fit line (solid) and y=x line (dashed) for comparison. The graphs show results for chaparral modeled with 35% TIA, modeled with a lumped approach (x axis) and an EIA fraction of 50% (y axis). As T and NPP increase, the lumped approach tends to yield higher rates of water use and productivity.](image)

![Table 2. Equation Forms, Coefficients, and Intercepts for Calculating mT, mNPP, iT, and iNPP.](table)

<table>
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<tr>
<th>Vegetation Type</th>
<th>Function Form</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>r²</th>
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<td>mT</td>
<td>aEIA + bTIA + d</td>
<td>-9.58 x 10⁻⁴</td>
<td>-7.02 x 10⁻³</td>
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<td>1</td>
<td>0.92</td>
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<td>Live oak</td>
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<td>-6.43 x 10⁻³</td>
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<td>0.95</td>
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<td>aEIA + bTIA + d</td>
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<td>-9.84 x 10⁻³</td>
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<td>1.03</td>
<td>0.99</td>
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<td>mNPP</td>
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<td>N/A</td>
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<td>N/A</td>
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<td>N/A</td>
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<td>0.32</td>
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versus riparian areas) and instead attempted to maintain a relatively uniform spatial distribution of impervious surface. However, we expect that the placement of impervious surface within a hillslope likely does influence its impact on ecohydrologic processes. For example, if a hydrologically disconnected patch is placed near the bottom of a drainage network, the shorter distance between the patch and the stream network will likely result in less water being stored and used by vegetation than if a hydrologically disconnected patch is placed near the top of the drainage network.

When comparing lumped and spatially explicit approaches to modeling $T$ and $NPP$, we observed the potential for large divergences between the two approaches, in particular for higher levels of TIA coverage and during especially wet years. The significant differences in estimates of ecohydrologic fluxes as a function of the EIA fraction confirm the importance of accounting for impervious surface connection characteristics within larger-scale models. In the case of our particular study period and catchment, the estimated differences between approaches could be substantial at an annual time scale, indicating that a more accurate accounting for impervious surface characteristics is needed when modeling urban catchments. That we found years with substantial divergence between estimates that did and did not account for EIA fractions even in a catchment such as Mission Creek where the degree of urbanization is relatively modest suggests that such accounting has the potential to significantly change transpiration and $NPP$ estimates for more heavily developed semiarid catchments. Similarly, in a catchment with higher or more evenly distributed precipitation, deeper soils, or a greater prevalence of more deeply rooted vegetation, we would expect greater divergence.

Our hillslope scale results emphasize the need to account for EIA/TIA fractions within larger-scale eco-hydrologic models. In theory, fine-scale models that include meter scale routing between impervious surfaces such as roof, driveways, streets, and interspersed vegetated patches can capture these effects. However, data and computation requirements for such models when applied at a watershed scale often preclude this. As a computationally efficient alternative, we presented a first-order adjustment of the impact of accounting for EIA fraction that relies on calibration of an initial hillslope. We note that calibration of parameters to correct for EIA differences would need to be repeated for watersheds with substantially different climate, vegetation, or soil.

Our results have implications for urban design and water resource management. Historically, the impetus for studying and reducing EIA has been to reduce flood risk or to reduce the negative impacts on stream ecosystem health that can result from impervious surfaces and the associated flashier hydrographs [e.g., Alley and Veenhuis, 1983; Booth and Jackson, 1997; Alberti et al., 2007]. Our results suggest a potential additional ecosystem service benefit of reducing EIA fraction, specifically the increased water availability for adjacent vegetation areas. Estimates for our semiarid modeling study argue that the increased vegetation productivity with relatively small shifts in EIA fraction can be significant, particularly in the case of more deeply rooted vegetation (chaparral and live oak). This finding has implications for both managed and native landscapes in or closely adjacent to urban areas. In the case of managed landscapes, there is an increasing interest in and promotion of using drought tolerant plants for landscaping in water stressed urban and suburban areas (e.g., Hendricks, Xeriscaping gains favor among lawn experts, http://www.mysanantonio.com/real_estate/article/Xeriscaping-gains-favor-among-lawn-experts-3778956.php, 2012; San Francisco Department of Public Works, San Francisco Sidewalk Landscaping: Recommended Drought Tolerant Plant List, http://www.sfdpw.org/Modules/ShowDocument.aspx?documentid=856, 2013; Central Basin Municipal Water District, Creating your drought tolerant garden, http://www.centralbasin.org/drought-tolerant-garden.html, 2013); these plants would be better able to take advantage of the additional water inputs offered by disconnected impervious surfaces. Combining the use of drought tolerant plants with a decrease in EIA could therefore result in substantial decreases in irrigation, while encouraging greater productivity of
the urban vegetation. In the case of adjacent native vegetation, our results also raise the question of whether altering the connectivity of the urban landscape creates the potential for imbalance or encouragement of nonnative species. If precipitation delivery to a patch of native vegetation can be increased enough to significantly alter productivity, this effect should be accounted for, especially in the case of fringe urban areas where there is considerable overlap with the undeveloped landscape. Given these potential benefits our model-based study argues for further research into how the combination of strategically selected urban vegetation and the design of impervious surface hydrologic connection can be used to improve urban ecosystem function while at the same time reducing irrigation demand and protecting adjacent native vegetation patches.

Acknowledgments
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References


Jarvis, P. (1976), The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field, Philos. Trans. R. Soc. London B, 273(927), 593–610.


Rodriguez, F., H. Andrieu, and F. Morena (2008), A distributed hydrological model for urbanized areas—Model development and application to case studies, J. Hydrol., 357, 268–287.


