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From Rain Tanks to Catchments: Use of Low-Impact Development To Address Hydrologic Symptoms of the Urban Stream Syndrome

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Supporting Information

ABSTRACT: Catchment urbanization perturbs the water and sediment budgets of streams, degrades stream health and function, and causes a constellation of flow, water quality, and ecological symptoms collectively known as the urban stream syndrome. Low-impact development (LID) technologies address the hydrologic symptoms of the urban stream syndrome by mimicking natural flow paths and restoring a natural water balance. Over annual time scales, the volumes of stormwater that should be infiltrated and harvested can be estimated from a catchment-scale water-balance given local climate conditions and preurban land cover. For all but the wettest regions of the world, a much larger volume of stormwater runoff should be harvested than infiltrated to maintain stream hydrology in a preurban state. Efforts to prevent or reverse hydrologic symptoms associated with the urban stream syndrome will therefore require: (1) selecting the right mix of LID technologies that provide regionally tailored ratios of stormwater harvesting and infiltration; (2) integrating these LID technologies into next-generation drainage systems; (3) maximizing potential cobenefits including water supply augmentation, flood protection, improved water quality, and urban amenities; and (4) long-term hydrologic monitoring to evaluate the efficacy of LID interventions.

1. INTRODUCTION

Catchment urbanization is associated with a reduction in stream health, a condition known as the urban stream syndrome.[1−3] Marked symptoms of the urban stream syndrome include altered streamflow, morphology, water quality, and ecosystem structure

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Figure 1. Symptoms, causes, and cures of hydrologic perturbations associated with the urban stream syndrome. (A) Symptoms include: (1) altered streamflow (base flow, peak flow, annual runoff volume, flow variability); (2) altered stream morphology (stream width, depth, complexity, and disconnection from the riparian zone, hyporheic zone, and flood plain); (3) impaired water and sediment quality (trash, nutrients, dissolved oxygen, toxicants, suspended solids, temperature); and (4) shifts in biological composition (loss of native species, reduction in sensitive species, increase in tolerant species, increase in invasive species) and loss of ecosystem services (organic matter retention and processing, nutrient removal, primary production, and respiration). (B) Causes include: (1) replacing grassland and/or forests with impervious surfaces such as roads, parking lots, roofs, and sidewalks; (2) building stormwater drainage and flood control infrastructure to convey rapidly stormwater runoff to streams (formal drainage systems); (3) reducing stream complexity by burying, straightening, and concrete-lining streams; and (4) altering overall water and sediment budgets through water importation, the construction of debris dams, and surface water impoundments. (C) Examples of LID technologies that can potentially address the hydrological challenges associated with the urban stream syndrome include unlined technologies that infiltrate stormwater runoff (e.g., unlined biofilters and permeable pavement) and technologies that harvest and export stormwater runoff from the catchment (e.g., green roofs and rainwater tanks used for irrigation or indoor toilet flushing). Top row includes images of urban creeks and drains in Orange County, California (from left to right: San Diego Creek, Costa Mesa Channel, Fullerton Creek, and a drain in the City of Irvine). Middle row includes two streetscapes and a buried stream in Orange County California, and Parker Dam at the start of the Colorado Aqueduct on the California−Nevada border. Bottom row includes an unlined biofilter in Melbourne (Australia); permeable pavement in Westminster, California; green roof on a public building in Houston, Texas; and a rainwater tank in Melbourne (Australia).

and function (Figure 1A). Although underlying causes of the urban stream syndrome will vary among catchments, its hydrologic symptoms are generally associated with replacing grassland and/or forests with impervious surfaces such as roads, parking lots, roofs, and sidewalks; building drainage and flood control infrastructure to convey rapidly stormwater runoff to streams (so-called formal drainage systems); and altering catchment water budgets (e.g., through water imports and exports) (Figure 1B).[1,4−8]

Increasing catchment imperviousness generally reduces infiltration and evapotranspiration of rainfall, whereas formal drainages increase the hydraulic connectivity between catchments and streams.[9−12] These two modifications have opposing effects on streamflow during wet and dry weather. During wet weather, the volume of stormwater delivered to a stream increases, the lag time between rainfall and storm flow gets shorter, and peak flow rate increases.[13−15] During dry weather, streamflow decreases due to reduced infiltration over interannual time scales,[16,17] although there are exceptions to this rule. Water importation can increase dry weather streamflow by increasing:[6] perennial discharge of wastewater effluent and nuisance runoff; and/or groundwater seepage into streams from leaks in subterranean drinking water supply and sewage collection pipelines. Management of surface water impoundments (e.g.,

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dams and reservoirs) can also increase dry weather streamflow.[18] All of these catchment modifications, in addition to altering stream hydrology, degrade streamwater quality by raising stream temperature, changing the balance of nutrients, carbon, and oxygen in a stream, and facilitating the mobilization and transport of fine sediments, chemical pollutants, and human pathogens and their indicators.[1−3,19−25] Changes in water quality and hydrology (both symptoms of catchment urbanization) affect stream morphology, stability, ecology, and chemistry.[23−30]

Catchment urbanization is commonly quantified using two metrics: total imperviousness and effective imperviousness.[1−3,24,25] Total imperviousness is the fraction of catchment area covered with constructed impervious surfaces such as asphalt and roofs. Effective imperviousness represents the impervious fraction of the catchment area with hydraulic connection to a stream through a formal drainage system. Compared to total imperviousness, effective imperviousness is a better predictor of streamwater quality, ecological health, and channel form.[31−33] Total imperviousness does not take into account whether flow from an impervious surface is conveyed directly to a stream, or instead drains to adjacent pervious areas where opportunities for filtration, infiltration, and flow attenuation are provided. The ecological condition of streams typically exhibits a wedge-shaped dependence on total imperviousness: streams in catchments with low total imperviousness exhibit a range of ecological conditions (from degraded to healthy) that narrows with increasing total imperviousness due to reduction in the maximum attainable stream health.[1−3] Effective imperviousness exhibits a less variable negative correlation with stream ecological condition, water quality, and channel form.[12]

The negative correlation between effective imperviousness and stream health raises the question: can hydrologic symptoms of the urban stream syndrome be prevented and/or reversed through urban forms that keep effective imperviousness low? Effective imperviousness can be kept low as an urban community develops (or reduced through retrofits of an already developed catchment) using technologies that intercept runoff from impervious surfaces at a variety of scales.[34,35] The intercepted runoff can be infiltrated to support groundwater (e.g., with unlined biofilters and permeable pavement), exported to the atmosphere by evapotranspiration (e.g., using green roofs, rain gardens, vegetated swales, wetlands, and urban forests), redirected from storm sewer systems to pervious surfaces (e.g., with downspout disconnection), and/or exported through the sanitary sewer system to downstream receiving waters (e.g., using rainwater tanks for toilet flushing) (Figure 1C, see also Table S1 in the Supporting Information). These environmentally sensitive stormwater management systems go by a variety of names, including green infrastructure and low-impact development (LID) technologies in the U.S., Water Sensitive Urban Design in Australia and Canada, and Sustainable Urban Drainage Systems in England.[36] In this review, we adopt the term LID technologies.

Acquiring and maintaining public support for LID technologies requires demonstrating that they are effective at minimizing flood risk and the negative impacts of urbanization on human and ecosystem health.[1,37,38] In this review, we explore: (1) the variety of modeling approaches available for supporting LID selection and evaluation; (2) technologies available for stormwater infiltration and harvesting; and (3) implementation challenges including maintenance, climate change, path dependence, and site-specific constraints. A number of review articles have been written on LID technologies and their use for mitigating hydrologic, water quality, and ecological symptoms of the urban stream syndrome.[39−46] However, these tend not to consider simultaneously the international scope of the problem, its potential solutions, and policy and technological barriers to practical implementation. Our review adopts a multidisciplinary (hydrology, engineering, social science, and ecology), multiscale (from individual LID types to whole catchments), and binational (U.S. and Australia) perspective. The binational perspective is warranted because severe and persistent droughts in Southeast Australia and Southwest U.S. have set the stage for creative multibenefit solutions to urban water management in both countries.[34,47−49] Australia, in particular, is spearheading a number of innovative government−industry−university collaborations dedicated to the testing and adoption of LID technologies.[34,47,48]

2. CATCHMENT-SCALE URBAN WATER BALANCE

Case for Volume over Peak Flow Rate. In many countries, stormwater regulations place limits on the peak flow rate or high flow duration allowed to enter a stream from individual properties.[25] To comply with these regulations, property owners typically install stormwater detention ponds that capture and slowly release runoff from large storms.[50] There are a number of well-documented problems with this approach, including:[25,51−53] (1) the simultaneous release of stormwater from many properties within the catchment can cause downstream peak flows to exceed predevelopment conditions and erode downstream channels, even if the peak flows from individual properties remain within regulatory limits; (2) reduced infiltration associated with impervious surfaces cuts off the primary means by which water is normally supplied to a stream (through subsurface flow paths and resupply of shallow groundwater), and detention ponds do not typically address the problem; and (3) the superposition of poststorm flows from multiple detention basins in a catchment distorts downstream dry weather flow regimes. Although a number of stream "sustainability" metrics have been proposed,[54,55] controlling (and ideally eliminating) the volume of stormwater runoff flowing to a stream through formal drainage systems is a prerequisite for maintaining and restoring the preurban flow regime (for reasons that will be detailed in the following sections).[17,51−53]

Impact of Urbanization on Catchment-Scale Water Budgets. Drawing on analogies with environmental flow management, Walsh et al.[17] proposed a catchment-scale water balance (or "bucket") model to estimate the volume of water that should be infiltrated and harvested to maintain stream hydrology as close as possible to its preurban state. Eq 1 represents an annual water balance for a typical natural catchment assuming: the volume of water associated with soil moisture and shallow groundwater does not change appreciably over annual and longer time scales; and all water that infiltrates into the catchment eventually flows to the stream through subsurface routes (i.e., the infiltrated water is not lost from the catchment by deep seepage).[56,57]

$$\mathrm{MAR} = \mathrm{ET} + S \tag{1}$$

Variables appearing in this equation include the mean annual rainfall depth in the catchment (MAR, volume of rainfall per catchment area per year), evapotranspiration depth (ET, volume of water returned to the atmosphere per catchment area per year), and annual streamflow depth (S, volume of water flowing in a stream per catchment area per year). The units of "depth per year" can be interpreted as the depth of water that would be obtained if the annual water volume associated with each term in eq 1 was evenly distributed over the catchment area.

Over annual time scales, subsurface flow constitutes the majority of streamflow in most natural catchments, including during storm events.[58−61] In this context, subsurface flow (sometimes referred to as "old water") is defined as rainfall that infiltrates and flows to a stream through shallow groundwater or the vadose zone as interflow and throughflow. By contrast, the contribution of overland flow (technically, Horton Overland Flow) to annual streamflow is generally small in natural catchments.[58−61] Neglecting overland flow, the annual water balance for a natural catchment can be approximated by eq 2 where S_{sub}^{pu} represents the contribution of subsurface flow to preurban streamflow (note the superscript "pu" refers to "preurban").

$$MAR = ET^{pu} + S_{sub}^{pu} \quad (2)$$

Urbanization perturbs this water balance in a number of ways by (1) redistributing MAR between ET and S, generally decreasing ET (except in regions where significant water importation occurs, see below) and increasing S; and (2) altering how water is delivered to the stream, from subsurface flow paths in the preurban state ($S = S_{sub}^{pu}$) to a mixture of subsurface flow (S_{sub}^{u}) and overland flow from effective imperviousness (S_{EI}) in the urban state: $S = S_{sub}^{u} + S_{EI}$ (note the superscript "u" refers to "urban"). Thus, eq 3 represents an annual water balance for an urbanized catchment (Figure 2A).

$$MAR = ET^{u} + S_{sub}^{u} + S_{EI} \quad (3)$$

Values for S_{sub}^{u} and S_{EI} can be calculated from the mean annual rainfall (MAR), the fraction of the total catchment area that is covered with effective imperviousness (f_{EI}), and the stream coefficients for undeveloped (C_S) and effective impervious (C_{EI}) areas:

$$S_{sub}^{u} = MAR \times C_S \times (1 - f_{EI}) \quad (4a)$$

$$S_{EI} = MAR \times C_{EI} \times f_{EI} \quad (4b)$$

To illustrate the effect of urbanization on catchment water balance, evapotranspiration, subsurface flow, and overland flow are plotted against effective imperviousness in Figure 2B. To generate this plot, we adopted stream coefficient and impervious runoff coefficient values of $C_S = 0.3$ and $C_{EI} = 0.8$, respectively; a region-specific procedure for calculating these coefficients is described later. As illustrated in the figure, the Walsh bucket model predicts that urbanization is associated with a decline in evapotranspiration (because forests and/or grassland is replaced with impervious surface, denoted as the gray region in Figure 2B), a decline in subsurface flow to streams (because resupply of the shallow groundwater by infiltration is reduced with increasing imperviousness, blue region), and an increase in the volume of overland flow entering the stream on an annual basis from effective imperviousness (red region).

Maintaining Preurban Hydrology through Infiltration and Harvesting. Two categories of LID technologies can be deployed to support preurban streamflow as a catchment develops. The first type, infiltration-based LID technologies, transfer stormwater runoff to the subsurface where it can recharge groundwater supplies and provide base flow for local streams. The second type, harvest-based LID technologies, capture the remaining runoff (i.e., the stormwater not infiltrated) and use it for any purpose that keeps it out of the stream (e.g., irrigation of ornamental plants and toilet flushing).[62] In theory, preurban streamflow can be maintained if the right number and mix of these two LID types are deployed; namely, enough infiltration- and harvest-based LID technologies to exactly compensate for the infiltration and evapotranspiration lost by replacing forests and grassland with impervious surfaces.

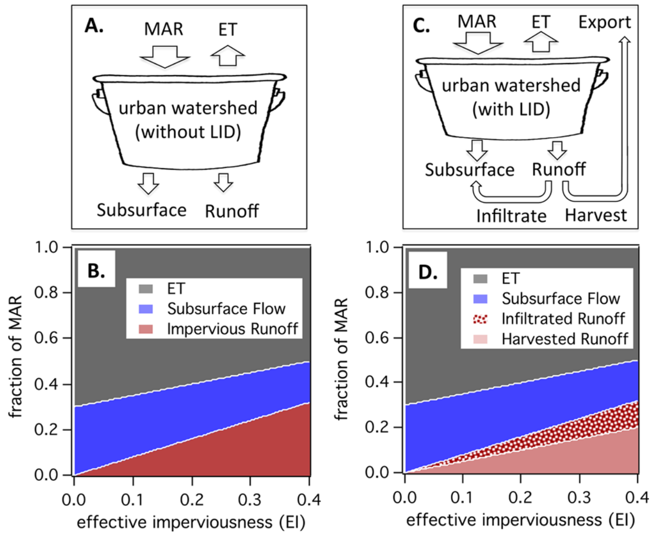

Figure 2. Catchment-scale water balance (or "bucket model") for calculating the volume of stormwater runoff that should be infiltrated and harvested. (A) Simplified form of the steady-state annual water budget for a catchment in which LID technologies are not implemented. Mean annual rainfall (MAR) is partitioned between evapotranspiration (ET), streamflow associated with subsurface infiltration (S_{sub}^{pu}), and streamflow associated with storm water runoff from connected imperviousness (S_{EI}). (B) Influence that urbanization (represented by effective imperviousness, f_{EI}) has on the distribution of MAR between ET, subsurface flow S_{sub}^{u}, and impervious runoff S_{EI}. These curves were generated using rearranged versions of eqs 3, 4a, and 4b. (C) LID technologies can mitigate the effects of effective imperviousness on catchment water balance by capturing impervious runoff for infiltration (LID_I, to support subsurface flow to the stream) and harvesting and exporting impervious runoff from the catchment (LID_H, to compensate for the decline in evapotranspiration frequently associated with urbanization). (D) By infiltrating and harvesting stormwater runoff in the right proportions (determined by eqs 6a and 6b), it is theoretically possible to maintain annual streamflow at preurban levels as effective imperviousness rises. Note that, technically speaking, if all runoff from effective imperviousness is harvested or infiltrated, then by definition effective imperviousness is zero. Thus, the horizontal axis in panel D should be regarded as the effective imperviousness that would have resulted if LID technologies had not been implemented. Curves in this panel were generated using rearranged versions of eqs 5, 6a, and 6b. In all cases, the following stream and impervious runoff coefficients were assumed: $C_S = 0.3$, $C_{EI} = 0.8$.

Applying these concepts to the catchment water balance described above, we arrive at eq 5, where LID_I and LID_H denote the annual stormwater runoff depths that should be infiltrated and harvested, respectively (Figure 2C):

$$MAR = (ET^{u} + LID_H) + (S_{sub}^{u} + LID_I) \quad (5)$$

The first term in parentheses equals the preurban evapotranspiration (ET^{pu}), whereas the second term in parentheses equals the preurban subsurface flow to the stream (S_{sub}^{pu}). The volumes of runoff that should be infiltrated and harvested depend on the fraction of the catchment area covered with effective imperviousness f_{EI}:

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$$\mathrm{LID_I} = \mathrm{MAR} \times C_S \times f_{EI} \tag{6a}$$

$$\mathrm{LID_H} = \mathrm{MAR} \times (C_{EI} - C_S) \times f_{EI}, \quad C_{EI} > C_S \tag{6b}$$

Returning to the example presented above, subsurface flow to the stream is maintained at preurban levels (30% of mean annual rainfall), provided that a portion of stormwater runoff is captured and infiltrated as dictated by eq 6a; i.e., the sum of the blue and brown stippled regions equals 30% across the entire range of f_{EI} in Figure 2D. The portion of stormwater runoff not infiltrated, eq 6b, should be harvested and kept out of the stream (light burgundy color, Figure 2D). In this hypothetical example, the hydrology of the local stream is unchanged as the catchment urbanizes because: (1) subsurface flow to the stream is maintained at predevelopment levels, and (2) no stormwater runoff flows overland to the stream via effective imperviousness.

Tailoring Infiltration and Harvesting to Specific Regions. An interesting and previously overlooked consequence of the Walsh bucket model is that, for a given set of values for C_S and C_{EI}, the relative proportion of runoff volume that should be infiltrated and harvested is constant; i.e., their ratio does not depend on the fraction of the catchment area covered by effective imperviousness:

$$\frac{\mathrm{LID_I}}{\mathrm{LID_H}} = \frac{1}{(C_{EI}/C_S - 1)}, \quad C_{EI} > C_S \tag{7}$$

In the hypothetical example presented above, we arbitrarily selected values for C_S and C_{EI}. Region-specific stream coefficients and impervious runoff coefficients can be estimated from previously published correlations. For example, the impervious runoff coefficient can be estimated from an empirical correlation proposed by Walsh and collaborators[17] based on runoff data collected in and around Melbourne (Australia):

$$C_{EI} = 0.230 + 0.206\log_{10}(\mathrm{MAR}) \tag{8}$$

Because this correlation is for impervious surfaces (as opposed to natural landscapes), it will likely apply to cities other than Melbourne (although this is an obvious target for future research). The stream coefficient C_S can be estimated from a correlation developed by Zhang and co-workers[56,57] based on streamflow measurements from 250 catchments worldwide. Zhang's correlation depends on the fraction f_F of the preurban catchment area covered with forest, together with evapotranspiration depths for forests ($\mathrm{ET_F}$) and herbaceous plants and soil moisture ($\mathrm{ET_H}$):

$$C_S = 1 - \mathrm{ET}/\mathrm{MAR} \tag{9a}$$

$$\mathrm{ET} = f_F \mathrm{ET_F} + (1 - f_F)\mathrm{ET_H} \tag{9b}$$

$$\mathrm{ET_F} = \frac{1 + 2(1410/\mathrm{MAR})}{1 + 2(1410/\mathrm{MAR}) + \mathrm{MAR}/1410} \tag{9c}$$

$$\mathrm{ET_H} = \frac{1 + 0.5(1100/\mathrm{MAR})}{1 + 0.5(1100/\mathrm{MAR}) + \mathrm{MAR}/1100} \tag{9d}$$

After substituting these correlations into eq 7, we find the ratio $\mathrm{LID_I}/\mathrm{LID_H}$ required to maintain preurban streamflow depends on only two variables: the mean annual rainfall MAR and the fraction of the preurban catchment area covered with forest f_F (Figure 3). The thick black curve in the figure denotes combinations of MAR and f_F for which equal volumes of stormwater runoff should be infiltrated and harvested; i.e., $\log_{10}(\mathrm{LID_I}/\mathrm{LID_H}) = 0$. For most of the climate and preurban

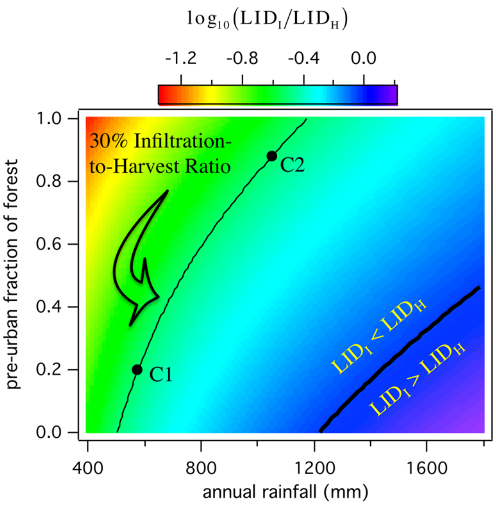

Figure 3. Relative volumes of runoff that should be infiltrated and harvested ($\mathrm{LID_I}/\mathrm{LID_H}$) to maintain a preurban flow regime in catchment streams, plotted as a function of mean annual rainfall (MAR) and the fraction of the preurban catchment covered with forest (f_F). Color denotes logarithmically transformed values of the ratio $\mathrm{LID_I}/\mathrm{LID_H}$ calculated by combining eqs 7, 8, and 9a−9d. Most of the plot area is located to the left of the thick black curve (which corresponds to combinations of MAR and f_F where the infiltration and harvest volumes are equal, $\log_{10}(\mathrm{LID_I}/\mathrm{LID_H}) = 0$), implying that more stormwater should be harvested than infiltrated across most climates and preurban forest covers. The thin black curve corresponds to all values of MAR and f_F where the required infiltration volume is 30% of the required harvest volume. The dots on the curve (labeled C1 and C2) represent two cities with very different climates and preurban land covers but the same required infiltration-to-harvest ratio (see main text).

states encapsulated in the figure, considerably more stormwater should be harvested than infiltrated (i.e., most of the plot is occupied by regions to the left of the thick black curve). This result calls for an emphasis on LID technologies that harvest stormwater over a wide range of climates.

Another interesting implication of eq 7 is that cities with very different climates and geographical locations can have similar infiltration-to-harvest ratios, as illustrated in Figure 3 for two hypothetical cities with an infiltration-to-harvest ratio of 30%. The first city (point labeled C1) is located in a relatively dry climate (MAR = 575 mm year^{-1}) and was mostly unforested prior to urbanization ($f_F = 0.3$). The second city (point labeled C2) is in a wetter climate (MAR = 1050 mm year^{-1}) and was mostly forested prior to urbanization ($f_F = 0.9$). Pasadena (California) and Baltimore (Maryland) are two U.S. cities that meet the criteria for C1 and C2, respectively.

In practice, some fraction of water volume infiltrated by LID will be exported from the catchment, for example, to the atmosphere by evapotranspiration and/or to deep aquifers by seepage. Thus, the ratio $\mathrm{LID_I}/\mathrm{LID_H}$ needed to restore catchment water balance may be larger than predicted by eq 7, because some portion of infiltrated stormwater is automatically exported from the catchment before it reaches the stream (LID technologies are discussed in Section 3).

Strengths and Limitations of the Walsh Bucket Model. The strength of the catchment-scale water balance model presented above is its simplicity and the fact that it can be readily applied to various regions around the world; however, the model entails a number of assumptions that may not be satisfied in practice.

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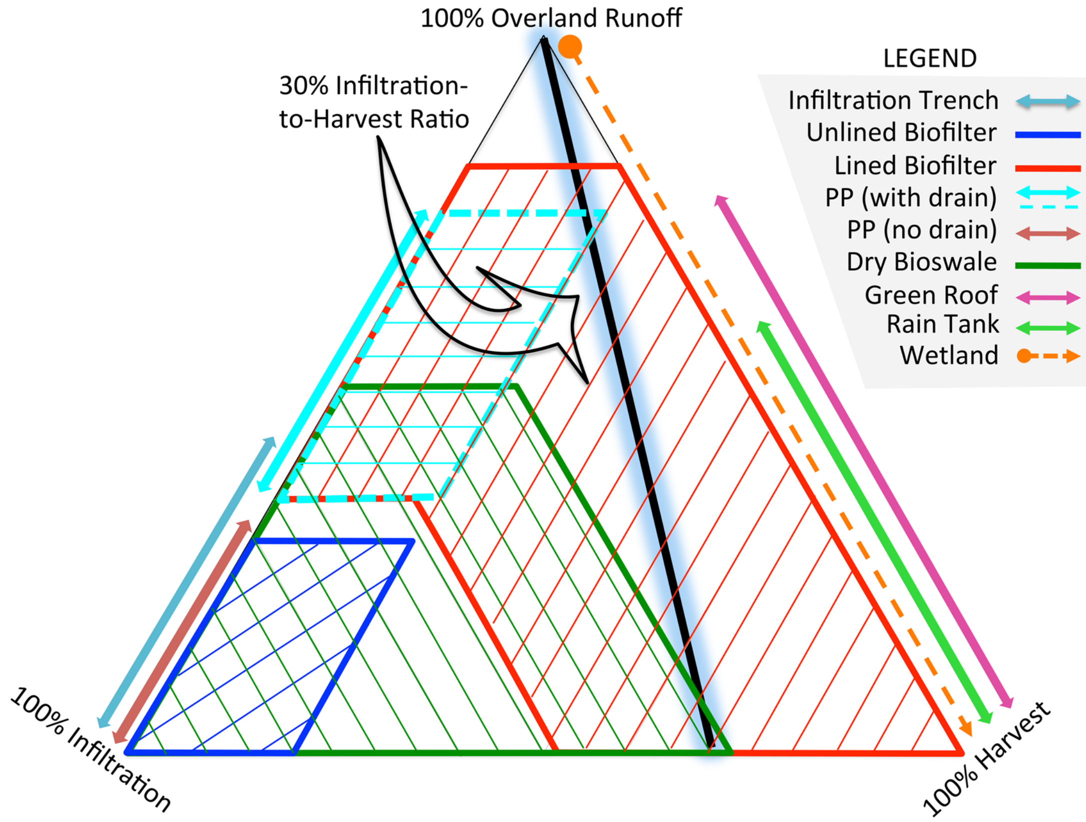

Figure 4. Ternary representation of field and laboratory data on the performance of popular LID technologies relative to percentage of runoff volume infiltrated (lower left vertex), harvested (lower right vertex), and allowed to flow to the stream through connected imperviousness (top vertex). The abbreviation PP refers to permeable pavement. The designation "with drain" refers to systems in which treated effluent can be routed to storage facilities for nonpotable uses, such as garden irrigation and toilet flushing. The designation "without drain" refers to systems in which treated effluent leaches directly into the subsurface. Arrows along the side of the ternary diagram denote systems that are used primarily for infiltration (left leg of the triangle) or for harvesting (right leg of the triangle). Polygons indicate hybrid systems that can be "tuned" to provide specific infiltration-to-harvest ratios. Solid colored lines reflect observed performance, whereas colored dashed lines denote theoretical performance (i.e., the performance is possible but not documented). The thick black line with a blue halo marks the location of hybrid systems that achieve a 30% infiltration-to-harvest ratio (corresponding to the black curve in Figure 3, see text). Data used to generate this figure are discussed in the main text.

First, the catchment water balance eq 1 may not apply in all cases. For example, the importation of water to Los Angeles has caused dry weather flow in the region's urban impacted rivers to increase 250% or more over the past 50 years; summer flow in the iconic Los Angeles River has increased approximately 500% over that period of time.[6] In other regions, the withdrawal of water from urban streams, together with sewer infiltration and inflow (I&I), can significantly alter a catchment's water balance. The Ipswich River in Massachusetts has gone dry for extended periods due to municipal water withdrawal.[63] In metropolitan catchments surrounding Baltimore, Maryland, I&I can exceed annual streamflow.[64]

Second, in some urban catchments, subsurface water (i.e., "old water") is still a dominant source of storm flow in urban impacted rivers.[58] Although the underlying mechanism for this observation is not well understood, a possible implication is that urbanization may induce excess storm flow in urban rivers via two mechanisms: (1) by increasing effective imperviousness (as assumed in the Walsh bucket model); and (2) by altering the rate at which old water is delivered to a stream during storms (e.g., by accelerating the transfer of rainfall to the subsurface through leaky storm and/or sanitary sewer systems). In urban areas where the second process applies, reducing effective imperviousness alone may not control the volume of water delivered to a stream during storms.

Third, the Walsh bucket model does not take into account regional physiography and geology that can influence both patterns of urbanization as well as intrastorm stream responses (e.g., the effects of urbanization on stream flashiness tends to be buffered in catchments with permeable soils, level slopes, and high lake density).[18]

In principle, the first limitation can be addressed by adding terms to the catchment water balance eq 1 that account for regional variations in the import and export of water over annual time scales. Addressing the second and third limitations, on the other hand, may require more sophisticated (spatially and temporally explicit) models that capture the influence of surface and subsurface storage and local hydrogeology on intrastorm, as well as interstorm, streamflow variability (see modeling tools in Section 4). Next we turn our attention to commonly adopted LID technologies, and discuss their utility in light of the catchment water balance model described above.

3. LID TECHNOLOGIES FOR MAINTAINING OR RESTORING PREURBAN HYDROLOGY

The Walsh bucket model presented above suggests that LID technologies have the potential to remedy hydrologic symptoms associated with the urban stream syndrome. Translating theory to practice will require a diverse set of LID technologies tailored to (1) capture all stormwater runoff before it enters the stream;

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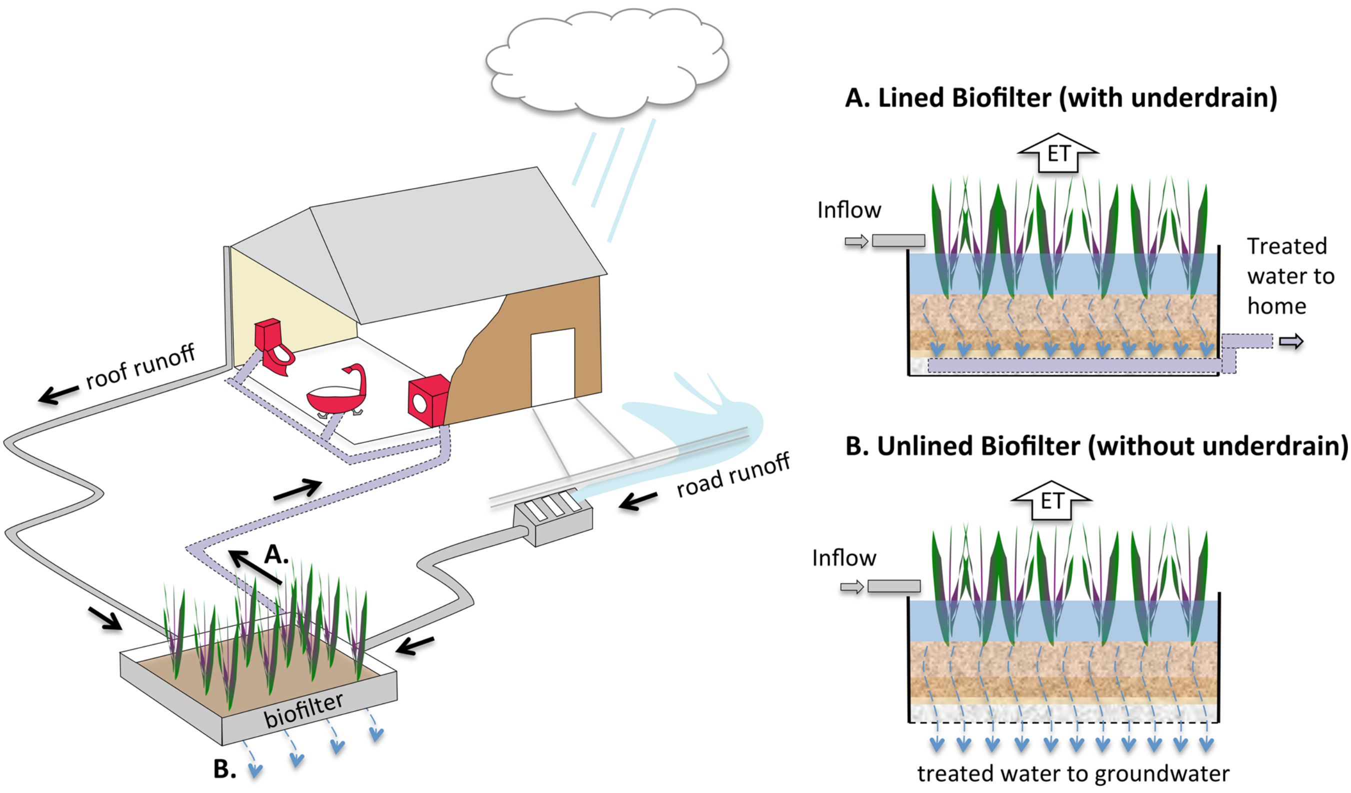

Figure 5. Biofilters are a hybrid LID technologies that can be tuned to achieve different levels of stormwater harvest and infiltration. In the example illustrated here a biofilter is configured to receive both roof and road runoff. In a harvest configuration, treated water from the biofilter can provide nonpotable water to the home for toilet flushing, laundry, and hot water supply (lined biofilter with underdrain, A). In an infiltration configuration, the biofilter supports groundwater recharge and stream baseflow (unlined biofilter without underdrain, B). In both configurations, a portion of the water processed by the biofilter is lost to the atmosphere through evapotranspiration (ET), another form of harvesting. Colored layers in the biofilters (upper and lower right panels) delineate ponding zone (blue), filter media (brown), transition layer (light brown), and gravel layer (gray). Adapted from Figure 2 of Grant et al.[48] and Grant et al.[62]

and (2) infiltrate and/or harvest the captured runoff in the proper proportions. In practice, many different factors go into the selection of LID technologies (e.g., flood protection, operation and maintenance costs, site-specific constraints, and human and ecosystem cobenefits).[65,66] Here we take the position that the first-order concern in LID technology selection should be maintaining (or restoring) preurban flow regimes, with secondary consideration given to other constraints and benefits. Accordingly, in this section we classify several popular LID technologies relative to the three end points that underpin the Walsh bucket model presented in Section 2: the percent of runoff volume harvested, infiltrated, or left as overland flow (represented by vertices of the ternary diagram in Figure 4; see also Table S1). Given our focus on restoring a preurban flow balance, we opted not to discuss technologies that work only by storage and attenuation, despite their utility for mitigating peak storm flows[50,67] (see beginning of Section 2).

Infiltration Technologies. Examples of infiltrative systems include infiltration trenches[68,69] and permeable pavement[70,71] (represented in Figure 4 by a teal arrow, cyan arrow, cyan dashed box, and brown arrow). Infiltration trenches and permeable pavement without under-drains (i.e., drains that collect some fraction of the outflow from a system) infiltrate the highest percentage of runoff (60−100% runoff removed).[72] Permeable pavement with under-drains infiltrate less runoff because a fraction of outflow is piped to the storm sewer system (25−66% runoff removed,[72] cyan arrow, Figure 4). Rerouting this piped fraction to a storage facility can transform permeable pavement with under-drains from infiltration to hybrid systems (i.e., technologies that both infiltrate and harvest, dashed cyan box, Figure 4), assuming that the captured water is used for irrigation (evapotranspiration) or in-house activities (e.g., toilet flushing) that transfer the water to the sanitary sewer system.[35,73] Although treated stormwater is rarely used for domestic purposes in the U.S., such systems are actively being trialed in Southeast Australia (see Section 4).[47]

Harvesting Technologies. Examples of harvest-based LID include green roofs,[74−76] rainwater tanks,[77,78] and wetlands[79,80] (shown as a pink arrow, green arrow, and orange dashed arrow, respectively, Figure 4). A broad range of harvest efficiencies have been noted for green roofs (23−100% runoff removed).[72,81] Green roofs export runoff mostly in the form of evapotranspiration, with the soil/media matrix dominating export in the winter (low harvest: ∼34% runoff removed) and the "green" component contributing to export in the summer (high harvest: ∼67% runoff removed).[74] Rainwater tanks harvest between 35 and 90% of runoff on average[72] depending on the ratio of tank size to roof area, storm frequency and duration, the number of acceptable rainwater uses (e.g., toilet flushing, clothes washing, hot water supply, or garden irrigation), and building occupancy. Human use of rainwater is expected to be higher in multistory residential and office buildings than in commercial/industrial buildings, given the greater number of inhabitants per unit area of imperviousness.[82] Although wetlands typically export relatively small volumes of runoff in the form of evapotranspiration (0−3% runoff removed[5,72]), outflow can be tapped for human use,

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substantially increasing the overall percentage of runoff harvested. Upward of 50–100% harvest has been reported for wetland systems in South Australia and New South Wales, resulting in potable water savings of $120,000 to $663,120 per year (in 2006 AUD).[83]

Hybrid Technologies. LID technologies that both harvest and infiltrate stormwater runoff, or "hybrid technologies", appear as polygons in Figure 4. Examples of hybrid technologies include unlined biofilters (no under-drain, blue polygon), partially or completely lined biofilters (with under-drain, red polygon),[84,85] and dry bioswales (unlined with an under-drain, green polygon).[86,87] The term "dry bioswales" refers to swales that are intended to dry out between storms. Two configurations for a household biofilter (lined with an underdrain versus unlined with no underdrain) are illustrated in Figure 5.

To date, few studies have quantified the percent runoff harvested through evapotranspiration for hybrid systems. Values as low as 2–3% runoff removal have been reported for unlined biofilters; however, these percentages may be low because a substantial portion of infiltrated runoff passes into upper soil layers where additional (unquantified) evapotranspiration may occur.[5,88] Higher evapotranspiration values (>19% runoff removed) have been reported in lined biofilters.[88] Thus, a tentative range for percent runoff harvested via evapotranspiration across biofilters (lined and unlined) is 2–19%. Unlined biofilters are primarily infiltration systems, with evapotranspiration constituting their primary contribution to harvest (total runoff removed ranging from 73 to 99%; evapotranspiration, 2–19%; and infiltration, 71–97%).[67,82,83] In contrast, lined biofilters are often used to treat stormwater prior to discharge to a storm sewer system; the treated effluent can also be captured and stored for subsequent human use, increasing harvest potential (total runoff removed ranging from 20 to 100%; evapotranspiration, 2–19%; human use, 0–80%; and infiltration, 1–63%).[72,88,89] Dry bioswales are effective for harvesting and infiltrating runoff, with near 100% runoff removal achieved over a broad combination of infiltration and harvesting percentages (total runoff removed ranging from 46 to 100%; evapotranspiration, 2–19%; human use, 0–54%; and infiltration, 27–96%).[72,88,89] The effectiveness of dry bioswales for harvesting runoff can be attributed to their relatively large surface area to catchment area ratio, compared to other hybrid systems.[72]

Matching LID Technologies to Storm Water Management Goals. According to Figure 3, the volume of stormwater that should be harvested far exceeds the volume that should be infiltrated for most climates and preurban forest cover. Thus, in many locales, the emphasis should be on harvest-based LID technologies. This may prove challenging in practice, because distributed harvest systems that capture stormwater runoff at its source (e.g., rainwater tanks and green roofs) only treat one form of impervious area (rooftops) leaving runoff from other, potentially much more extensive imperviousness (e.g., roads parking lots and residential driveways) untreated.[35] Although regional (or end-of-catchment) LID such as wetlands can be employed to harvest the remainder, this approach is at the expense of water quality in reaches upstream of regional facilities.[5] Alternatively, runoff from roads and driveways can be captured and harvested using distributed hybrid systems (e.g., lined biofilters, dry bioswales, and permeable pavement with underdrains) configured to provide nonpotable water for human use (configuration "A" in Figure 5).

At the parcel scale, LID technologies (or combinations of LID technologies) can be selected to match catchment-scale goals for the volume of runoff to be infiltrated and harvested. For the two hypothetical cities described in Section 2 (see points C1 and C2, Figure 3), the required infiltration-to-harvest ratio is 30%, which translates to a straight line in Figure 4 (see thick black line with blue halo). In practice, this infiltration-to-harvest ratio can be achieved by selecting hybrid technologies that cross or enclose the line (e.g., lined biofilters "tuned" to achieve the 30% target) and/or by a combination of infiltration and harvest technologies designed to operate toward the harvesting end of the spectrum (e.g., treatment trains consisting of large rain tanks that overflow to unlined biofilters).[5]

4. OPTIMIZING LID SELECTION AT THE CATCHMENT SCALE

Modeling Tools. A number of modeling tools are available for optimizing the selection and siting of LID technologies so as to minimize flood risk, maximize human and ecosystem cobenefits, and stay within capital, maintenance, and operation costs.[90−92] These optimization schemes have several elements in common, including: (1) a spatially explicit (e.g., GIS-based) platform that includes information on the informal and formal drainage for a site and candidate locations for LID technologies; (2) a rainfall-runoff model that routes stormwater through the catchment; (3) an objective function that quantifies hydrologic performance (e.g., relative to stormwater harvest and infiltration targets, see Section 2) and costs of candidate LID configurations; and (4) an algorithm that identifies optimal solutions (e.g., by minimizing one or more objective functions)[51,54,93−95] or finds the greatest unit improvement in stormwater control per unit incremental cost.[96−98] Examples include software packages developed by university researchers,[93,99,100] the Model for Urban Storm water Improvement Conceptualization (MUSIC),[101] and the U.S. Environmental Protection Agency's System for Urban Storm water Treatment and Integration (SUSTAIN).[96]

Rainfall/runoff models can also be used to explore how a particular stormwater management strategy might impact receiving water quality. An example is the U.S. Environmental Protection Agency's study of the Illinois River (a multijurisdictional tributary of the Arkansas River in the states of Arkansas and Oklahoma) in which a catchment model based on Hydrologic Simulation Program Fortran (HSPF) was calibrated for nutrients and the output linked to a hydrodynamic and water quality model for Lake Tenkiller.[102] EPA used the resulting HSPF model to identify a set of stormwater management scenarios that met total maximum daily load targets for the lake.

Recent advances in uncertainty quantification can be exploited to improve the utility of stormwater modeling tools. An example is the DREAM and AMALGAM statistical toolboxes[102−106] that quantify model parameter and predictive uncertainty using Markov chain Monte Carlo simulation. DREAM has been widely used for model-data synthesis, hypothesis testing, and analysis of model malfunctioning in various time series applications. AMALGAM uses a multiple objective approach to produce a suite of equally acceptable (Pareto optimal) solutions from which stakeholders can select the option best suited to their collective needs.[107] Importantly, both statistical packages take into account all forms of uncertainty, from model formulation error to data noise and bias, and thus reveal both what is known and what is not known about a system. Such information can assist managers and stakeholders by clarifying how much confidence can be placed in model predictions, and by identifying areas where targeted investment (e.g., in data collection or model development) would significantly improve model predictions.

Two unknowns that contribute to model uncertainty include: (1) long-term maintenance of LID technologies (will their hydraulic performance degrade over time?) and (2) changing climate (how will LID form and function change under future climate scenarios?). With the exception of rain tanks and wetlands, all of the LID technologies summarized in Figure 4 include a step in which the captured stormwater is filtered through a granular media. As a consequence these systems are vulnerable to clogging (reduction in permeability over time) due to a variety of influent and filter-specific physical, chemical, and biological processes.[109,110] Because clogging reduces the volume of stormwater that can be harvested or infiltrated (and potentially effects pollutant removal[111]), sustained hydraulic performance requires routine inspection, cleaning, and replacement of the filter media. In a recent comparison of biofilters in Melbourne (Victoria) and Los Angeles (California), Ambrose and Winfrey[112] noted that larger systems tend to be maintained by the government agency responsible for their construction. On the other hand, the responsibility for maintaining smaller distributed systems is often transferred to land owners with uncertain results. If hydraulic performance of these systems degrades over time, model simulations premised on as-built permeability will overestimate stormwater volumes that can be harvested and infiltrated postconstruction, and potentially pose a flood risk. Confounding this maintenance issue is the fact that stormwater management systems, in general, are sized based on the idea that historical climate is a good predictor of future climate[25]—an assumption that is violated under climate change.[113] Climate change also has implications for the "green" component of many LID systems.[112,114] In the end, both challenges (uncertain maintenance and uncertain climate) are probably best addressed by using uncertainty quantification where possible (e.g., with DREAM and AMALGAM, see above), factoring in redundancy, and designing smart (perhaps modular) LID systems that can readily adapt to a changing world.[113,115]

Practical Constraints. One of the primary outcomes of the catchment water balance described in Section 2 is that, for most areas of the world, restoring catchment water balance will require a focus on harvest-based LID technologies. A win-win example is using harvested rainwater and road runoff for in-home activities (e.g., for toilet flushing, laundry, and hot water supply, configuration A, Figure 5), thereby protecting streams and reducing potable water consumption.[62] However, in the U.S. a number of institutional barriers presently limit the indoor use of nonpotable water. These include:[116−118] (1) low uniform water prices that create an environment where consumers and developers have little incentive to invest in schemes to reduce potable water consumption, although this is changing in the southwestern U.S.; (2) plumbing codes that do not explicitly address rainwater use or inadvertently prohibit it by requiring that downspouts be connected to the storm sewer collection system; (3) a patchwork of local, state, and federal regulations with various and conflicting treatment standards; (4) prohibitions against indoor use of nonpotable water in some locales that prevent local water utilities from sponsoring such schemes; (5) different interpretations of who owns stormwater runoff, with some states (e.g., Colorado) prohibiting residential capture and reuse of stormwater on the premise that all rainfall has been already allocated to downstream users; and (6) resistance from drinking water providers over concerns that wide-scale adoption of rainwater and stormwater harvesting may endanger public health, or lead to revenue loss.

Although public health concerns are often cited as a barrier to the adoption of harvested rainwater and stormwater for nonpotable uses in the U.S., the scientific evidence (and practical experience) generally do not support that contention. Public health concerns stem from the fact that both sources of water can harbor microorganisms that cause human disease.[119,120] Human infection depends on multiple factors—including pathogen type and load, the mode of exposure, and susceptibility—that are best assessed through epidemiological studies and/or a Quantitative Microbial Risk Assessment (QMRA) framework that includes hazard identification, exposure assessment, dose−response assessment, and risk characterization.[121,122]

An epidemiological study of children in rural South Australia found that drinking roof harvested rainwater posed no more risk of gastroenteritis than drinking water from a reticulated supply.[123] However, concerns have been raised about the study's sensitivity (ability to detect an effect against background rates of infection) given that only 1016 people participated.[119] QMRA studies, which have been advocated as a more sensitive alternative to epidemiological investigations,[119] indicate that minimally treated stormwater and rainwater may be acceptable for certain in-home uses, such as toilet flushing.[119,122] Rainwater also appears acceptable for garden irrigation and showering.[119,121] However, the suitability of stormwater runoff (e.g., from parking lots or roads) for these purposes is less well understood.[122] Across the board, proper design and maintenance of collection systems as well as appropriate disinfection measures such as UV disinfection and chlorination are necessary to achieve public health targets for in-home use.[119] Currently, more than 2 million Australians use roof-harvested rainwater for potable or nonpotable supply.[119] The State of Victoria now requires new homes to have a rainwater tank for garden watering and in-home uses such as toilet flushing (although solar hot water heating can be installed as an alternative, suggesting that this instrument has a broad focus on "sustainability", rather than a specific focus on water management).[47] Australia's ongoing experiment with rainwater tanks (and more recently biofilters) should provide a wealth of data and experience with which health officials around the world can objectively evaluate the risks and benefits for in-home use.

Site-specific constraints may also impede infiltration schemes. For example, the City of Irvine (California, U.S.) discourages stormwater infiltration at certain locations due to low soil permeability, locally perched shallow groundwater, and concern that groundwater contaminants (such as selenium) may be mobilized into local streams or the deep aquifer used for potable supply.[124] This concern is shared by the Orange County Water District (which manages the local groundwater basin that supplies drinking water to more than 2 million residents) and the Orange County Healthcare Agency (which manages public health for the county), and is enshrined in County regulatory statutes.[125] Thus, for this particular region of Southern California, infiltration may be feasible in only a few locations and under fairly strict control; for example, at large centralized facilities strategically placed to facilitate runoff treatment and recharge to deep groundwater aquifers.[126]

5. EVALUATING LID EFFICACY

Once LID technologies have been selected and implemented, ongoing monitoring programs are needed to ensure goals are being met. A number of recent reviews summarize field data and

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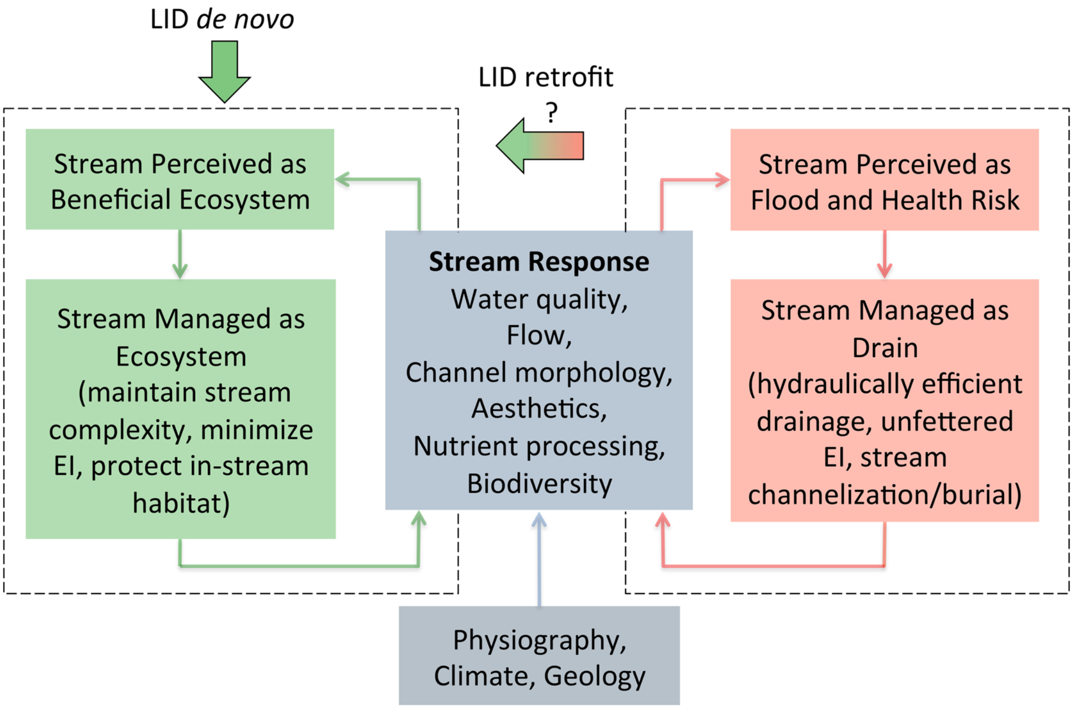

Figure 6. Social−ecological feedback loops can lead to "cognitive lock-in" in which streams are maintained in either a degraded state (because they are perceived primarily as storm drains, right loop) or healthy state (because they are perceived as ecologically valuable assets, left loop). The left loop may be more likely to occur if LID technologies are incorporated into an urban space as a city develops ("LID de novo"). Retrofitting an already developed area with LID technologies may or may not trigger a transition from the right loop to the left loop ("LID retrofit") (see main text). Adapted from Figure 3 in Walsh et al.[1] and Figure 3 in Grimm et al.[176] The abbreviaton "EI" refers to effective imperviousness.

modeling approaches for evaluating the effects of land-use and land-cover change (in general) and LID interventions (in particular) on catchment-scale hydrologic budgets and streamflow.[81,127−134] Generally, the available techniques can be classified into three types: (1) modeling approaches; (2) time-series analyses; and (3) paired catchments. Modeling approaches simulate the influence of land-cover change on the rainfall-runoff relationship, potentially revealing a causal link between the former and latter while controlling for climate variability. This approach is particularly useful when the goal is to evaluate "what if" scenarios (e.g., evaluating how the storm hydrograph might change in response to various LID interventions, see discussion of modeling tools in Section 4),[135,136] and in cases where long-term rainfall-runoff records are not available. Alternatively, when the goal is a post de facto evaluation of an LID intervention, time series analysis can be conducted on rainfall and hydrograph data, provided quality data are available both before and after the intervention. A variety of time series tools are available including graphical methods,[137−139] autoregressive models,[140,141] linear and curvilinear regression models,[142−144] multiple linear regression models,[145−147] trend identification tools,[148−152] and change point analysis.[153] Interpretation of time series data can be complicated by climate variability over the time of observation.[140,154−157]

The gold standard for assessing the hydrologic impact of land-use change is paired (or triplicated) catchment studies, in which the catchment of interest is paired with a control catchment (and a reference catchment, in the case of a triplicate design) of similar climate and physiography.[158,159] There is a long history of using paired catchment studies to assess the impact of vegetation change on catchment hydrology,[56,57,160] but the technique has been applied only recently to assess the impacts of LID interventions on stream health. Such studies collectively demonstrate that adopting LID technologies for stormwater management (over conventional centralized retention and detention basins) markedly improves the hydraulic performance of streams, as measured by higher baseflow, lower peak discharge and runoff volumes during moderate storms, increased lag times, and retention of smaller more frequent precipitation events.[67,161−164] These field results are generally supported by modeling studies, although centralized stormwater control measures may perform better than distributed LID systems for controlling peak discharge from large storms,[165,166] a problem that could presumably be overcome by proper LID technology placement and design. Not surprisingly, none of the urban stormwater management approaches perform as well as unurbanized (reference) catchments.[67] Thus, it can be argued that the best approach for protecting stream health is to place strict limits on urban development within a catchment. Short of this goal, however, distributed LID technologies should be used for managing stormwater runoff.[25,67]

The next frontier is paired catchment studies that evaluate how LID interventions simultaneously influence the hydrologic, water quality, and ecological response of streams. One example is Little Stringybark Creek in Melbourne (Australia). In collaboration with a local water utility, researchers developed a financial incentive scheme to encourage homeowners to install rainwater tanks and unlined biofilters, and worked with the local municipality to install larger neighborhood-scale infiltration and harvesting systems.[167−170] To determine if these retrofits are impacting flow, water quality, and ecology in Little Stringybark Creek, researchers are employing a "before/after control reference impact" (BACRI) study, consisting of the study catchment (where LID technologies are implemented), two urban control catchments (with similar levels of effective imperviousness, but where LID technologies are not imple-

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mented), and two nonurbanized reference catchments representing natural conditions.[167] Although such experiments are ambitious and challenging,[169] they are a rigorous field test for how well LID technologies insulate streams from catchment urbanization. The project has already generated important lessons in relation to community engagement,[37,170] institutional aspects,[171] and the performance of LID technologies in flood reduction.[172] There are some early signs that the retrofit may be improving water quality in the creek.[173]

Regardless of which approach is adopted (modeling, time series, or paired catchment), appropriate statistical methods should be used to link LID intervention to changes in stream performance, after taking into account instrument accuracy and precision.[174] A critical consideration is the predicted change of the response variable (e.g., baseflow or peak discharge) relative to extraneous sources of variation and noise. For example, if modeling studies suggest that baseflow will increase by 1 to 2 L s^{-1}, then flow measurements must have precision less than half this value.[175]

6. CONTEXT- AND PATH-DEPENDENCE OF THE URBAN STREAM SYNDROME

In this final section, we describe social, environmental, and ecological factors that may make the urban stream syndrome context and path dependent. By this we mean that the hydrologic, water quality, and ecological state of a stream depends not only on the extent of LID intervention (as measured, for example, by the volume of stormwater harvested and infiltrated) but also on the environmental context and historical path by which the catchment arrived at its current state.

Cognitive Lock-in. Cognitive lock-in is one form of path-dependence that can arise from positive feedback between the societal perception, management, and the physical and biological condition of a stream; it tends to vary within communities depending on their state(s) of economic development.[1,176,177] The term "cognitive lock-in" originates from the field of social psychology, where it has been applied to understanding consumer habits and choices with respect to a product or service.[178,179] The idea is that repeated consumption or use of a product results in a (cognitive) switching cost that increases the probability that a consumer will continue to choose that product or service over alternatives. As applied here, cognitive lock-in can affect stream health in postive or negative ways (Figure 6). If a community perceives their stream is a threat (e.g., due to the damage it might cause by flooding), local managers may be pressured to enact policies that degrade a stream's aesthetic and ecological value (e.g., through installation of formal drainage with high effective imperviousness, and stream burial), unintentionally reinforcing negative perceptions of the stream as a drain (red loop in the figure). Conversely, if a stream is perceived as a valuable asset, local managers may respond by enacting policies that protect the stream from urbanization, reinforcing positive perceptions of the stream as an asset through increased property value and the provision of green space and other ecosystem services (green loop). Examples of cognitive lock-in abound in stormwater management,[1,51] and its manifestations are evident in urban centers as diverse as Los Angeles, Paris, Moscow, and Melbourne.[51,180−182] A common pattern is that, as cities industrialize, prevailing public values call for harnessing and restraint of urban rivers for flood control and property development (favoring the red loop), while postindustrial development leads to demand for restoration of recreational, aesthetic, cultural heritage, and ecological values (favoring the green loop).

Urbanization Thresholds. Path dependence can also play a role in observed urbanization thresholds. Urbanization thresholds are defined as a critical level of urban intensity (e.g., as measured by effective imperviousness, road density, or the metropolitan area national urban intensity index, MA-NUII[183]) at which symptoms of the urban stream syndrome begin to manifest if the catchment is urbanizing, or disappear if an already urbanized catchment is being retrofitted with LID technologies. Most evidence for the existence of urbanization thresholds comes from comparing metrics of stream health (hydrology, water quality, and/or ecology) across two or more nearby catchments with different levels of imperviousness (i.e., paired catchment studies, see Section 5). For example, Walsh et al.[17] found that stream health (as measured by hydrologic indicators, water quality, and biodiversity) was good in two catchments with low effective imperviousness (<1%), but poor in two nearby catchments with elevated effective imperviousness (5 and 22%). Effective imperviousness thresholds of up to 10% have been associated with significant degradation in one or more stream metrics.[25] As noted by Hopkins et al.,[18] this particular threshold may reflect the tendency of urban communities to transition from mostly informal (unsewered) drainages below 10% to mostly formal (sewered) drainages above 10% imperviousness (although their measure of imperviousness is a satellite product that may not equate to effective imperviousness). Collectively, such studies suggest that preventing the urban stream syndrome requires keeping effective imperviousness well below 10% and perhaps below 1%, although there is considerable study-to−study variability depending on climate, physiography, geology, land-use, and stream history.[184−188]

In some streams urbanization thresholds may not be observed.[25] As part of the U.S. Geological Survey's National Water Quality Assessment (NAWQA) Program, Cuffney et al.[189] evaluated the impact of urbanization on in-stream invertebrate assemblages (a measure of stream ecosystem structure and function) across urban-to-rural gradients in nine metropolitan areas of the U.S. They found that invertebrate assemblages were strongly related to urban intensity (MA-NUII), but only when the urban development occurred within forests or grassland. A much weaker (or nonexistent) correlation was observed in areas where agriculture or grazing predominated, presumably because those streams were already degraded. Importantly, in forests and grassland there was no urbanization threshold below which ecosystem assemblages were resistant to urbanization. Even small impervious fractions were associated with "significant assemblage degradation and were not protective."[189]

That imperviousness thresholds are not always present is not surprising, given that effective imperviousness is only one of many stressors that can negatively impact urban stream health. For example, salinization has an enormous ecological toll on streams worldwide.[190] Although road runoff clearly contributes to the problem (particularly in northern climates where salt is used for deicing roads[191,192]), there are other sources of salt that would not be eliminated by reducing effective imperviousness alone (e.g., irrigation return flows). Other examples of urban stream stressors include loss of riparian habitat and tree canopy, impoundments that alter flow regimes and elevate temperatures, point source discharges of nutrients, heavy metals, and contaminants of emerging concern, to name a few.[1−3] Thus, reducing effective imperviousness may be a necessary, but not

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sufficient, condition for curing the urban stream syndrome in some catchments.

For all of the reasons stated above, it is difficult to predict the imperviousness threshold (if one exists) at which stream conditions will markedly improve as an urbanized catchment undergoes an LID retrofit. Shuster and Rhea[164] reported a small but significant improvement in the hydrological condition of a small suburban creek (Shepherd Creek, Cincinnati, Ohio) after installing 165 rain barrels and 81 unlined biofilters in the 1.8 km^2 catchment (reducing effective imperviousness by approximately 1%, mostly from roofs). However, a follow-up study of the same field site reported little change in water quality and ecology of the stream compared to a control stream in the nearby catchment.[187] The authors suggest a number of possible explanations for the lack of a water quality and ecological response, most notably that, despite the relatively large investment in LID retrofits, effective imperviousness in the catchment was not reduced to levels where improvements in stream health would be expected (after retrofits, the effective imperviousness in the Shepherd Creek catchment was still above 10%). The authors concluded that, "additional research is needed to define the minimum effect threshold and restoration trajectory for retrofitting catchments to improve the health of stream ecosystems".[187] Ongoing retrofits in the Little Stringy Bark Creek project (see Section 5), which will reduce effective imperviousness below 1%, may eventually shed light on this important issue.

Although it is fair to say that LID technologies are not a cure for all symptoms of the urban stream syndrome in all catchments, they do address critical hydrologic and geomorphic symptoms of the disease while providing myriad cobenefits and subsidiary ecosystem services, including water quality improvement, flood protection, green space, recreation and aesthetic value, wildlife habitat and corridors, carbon sequestration, pollination services, urban heat island cooling, and a much needed supply of nonpotable ("fit-for-purpose") water in drought prone areas such as Southeast Australia and Southwest U.S.[1,47,62,76,193−195]

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.5b01635.

Table of LID technologies and supplemental references (PDF).

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Notes

The authors declare no competing financial interest.

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