The Washington Water RESOURCE

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Message from the Director

This quarter's Newsletter covers two topics whose broad differences help illustrate the range of "urban water resources management." They also demonstrate the variety of support that we have been able to marshal for pursuing research topics of regional and national concern.The first article, addressing the physical condition of streams in response to nearby and watershed-scale urbanization, continues a focus of study that has been advanced here for nearly a decade by a variety of investigators under several distinct research projects. This particular project is the result of collaborative research supported by the National Science Foundation, through both a fellowship to the author (Maeve McBride) and a separate grant that is supporting a broader investigation of urban development patterns and their ecological effects, which involves faculty and students from the colleges of Architecture and Urban Planning, Forestry, and Engineering.

The second article investigates the status of reclaimed water for human and other uses, based on a literature review of recent research and application. Unlike the first article, this investigation was supported entirely by Center funds in response to an articulated need by the Center's advisory board. The work was conducted under the guidance and review of Dr. David Stensel here in the Civil and Environmental Engineering Department, with the close cooperation of agency staff in King County's Department of Natural Resources.

In addition to this work, we coordinated the fourth annual stream temperature survey on August 1st. Data compilation is still in progress, but it looks as though we caught a middling-warm day (about the norm for this summer!) with an extensive, high-quality data set. Look for a posting of all four years of data on the web site within a month.

❖ Derek Booth

Spatial effects of urbanization on physical conditions in Puget Sound Lowland streams

By Maeve McBride, Graduate Research Assistant, Center for Urban Water Resources Management

INTRODUCTION

Urban development, coupled with human population growth, threatens local and global ecosystems and biodiversity. The urbanization of the Puget Sound region has dramatically altered the natural stream-flow regime and the physical and geomorphic conditions within stream systems. As a result of development, once-forested land has been replaced with buildings, roads, and lawns. These impervious surfaces, as well as the extensive associated changes to the soil profile and the native vegetation com-

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munity, have changed conditions and processes in lowland streams that in turn result in impaired stream health.

Urban development will undoubtedly continue in this region and elsewhere; managers and policymakers may only be able to influence the location and distribution of that development. We must find less detrimental ways of developing our landscapes and more effective stream rehabilitation efforts so that we can preserve functioning and healthy stream systems in an ever-more populated area. There is a need for studies that identify those patterns of urbanization that exert the least harm on stream systems.

This study has three main objectives. The first objective is to assess the physical and geomorphic features within and among watersheds spanning a range of urbanization. The second objective is to determine more comprehensive and sophisticated methods to measure urbanization than the standard measure of percent total impervious area in the watershed. Work on this objective of the study proceeded with the collaboration of an interdisciplinary research group at the University of Washington including Marina Alberti (Urban Planning), Derek Booth (Civil & Environmental Engineering), Kristina Hill (Landscape Architecture), and Daniele Spirandelli (Landscape Architecture). This group has conceived and evaluated several alternative measures of urbanization. The third objective is to identify relationships between the physical and geomorphic stream conditions and these more comprehensive measures of urbanization.

METHODS

Study Streams

I conducted this study on four streams in the Puget Sound Lowland region (Figure 1) that were chosen based on similarities in watershed size, surface geology, and relief ratio. The watersheds fall within a size range of 15 to 60 km^2, and they are predominantly underlain by glacial till. The relief ratios, defined as the difference in elevation between the highest and lowest points of the watershed divided by the length of the watershed measured roughly parallel to the major drainage (Dunne and Leopold, 1978), range from 11 to 23 m/km among the study watersheds.

The study watersheds were also selected to explore differences in land cover. Thorndyke Creek, on the western side of the Olympic Peninsula, served as a reference stream. Its watershed has very little development and is predominantly forested. Juanita Creek, which flows into the northwest side of Lake Washington, was chosen because its watershed is highly urbanized. Little Bear Creek and Swamp Creek both have intermediate levels of urbanization.

Figure 1.
Regional map with study

Field Methods

The study streams were sampled using a rapid assessment during the summer of 2000. The assessments were

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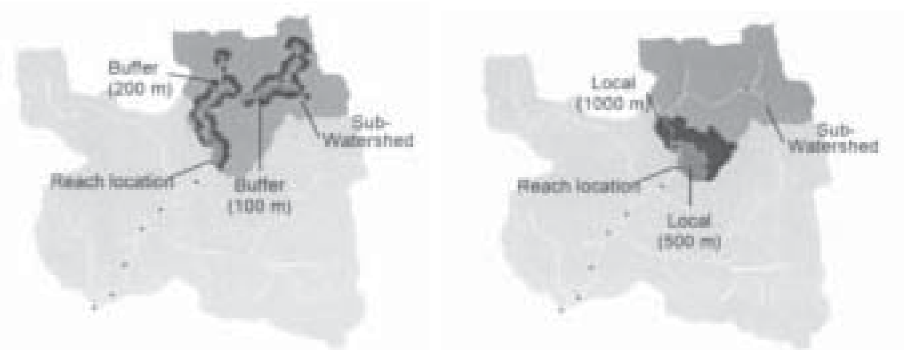

Figure 2.
Map of Juanita Creek illustrating two sizes of buffer and local zones for one site.

based on average conditions within 100-m reaches; they were completed every 300 to 500 m along the mainstem channel, except where access was prohibited, in wetlands, or in non-alluvial reaches (e.g., reaches constrained by bank armoring). Each site was located using a Garmin 12XL global positioning system (GPS) unit. I created a custom stream assessment to focus on physical stream changes typically found in urban streams. I measured a range of physical attributes borrowing methods from various stream assessment techniques most suitable to this region. Both quantitative and qualitative measures were taken to describe channel morphology, estimate channel dimensions, describe channel structure, characterize the substrate, and classify riparian conditions.

Spatial Methods

The intent of the GIS-based spatial analyses was to characterize the landscape contributing to each sampled site via quantitative metrics. Several spatial data sources were needed to characterize the study watersheds including land cover, elevation, and roads. This characterization took on two aspects. First, I partitioned the landscape into different zones. Second, I calculated a variety of landscape metrics within these zones. These metrics are quantitative descriptions of the landscape, which focus on the magnitude and connectivity of urban land cover. Connectivity is defined as "how spatially or functionally continuous a patch, corridor, network or matrix of concern is" (Zipperer et al., 2000).

Landscape zones

The first portion of the spatial analysis involved the creation of three landscape zones for each sampled site in order to evaluate their relative influence on physical stream conditions. Often, the primary zone of interest is the watershed, the total contributing area of the landscape. Sub-watersheds were delineated for each sampled site using the hydrologic functions in Arc/INFO's GRID extension. Another delineated zone was the "buffer." The buffer zone for any one site is the total riparian area upstream from the site location (Figure 2). I created two buffer zones of different widths, 100 m and 200 m. The third zone of interest was the "local." I defined a local zone as that portion of the total watershed uphill from the site location and within a specified distance(Figure 2). I created two local zones of different sizes, 500 m and 1000 m. Both buffer and local zone boundaries were determined along topographic flow paths, in order to delineate the most proximal, hydrologically significant area to each site. These methodologies for buffer and local zones were adapted from Morley (2000; see also the Spring 2000 issue of the Newsletter) and are similar to other spatial analyses (Lammert, 1995; Roth et al., 1996; Allan et al., 1997; Schuft et al., 1999).

Landscape metrics

The purpose of creating these three types of zones (sub-watershed, buffer, and local) was to calculate various landscape metrics within each zone. Landscape metrics provide quantitative measures of two aspects of urbanization: its magnitude and the connectivity of urban land. Table 1 lists and describes the metrics investigated.

Type	Name	Description
Magnitude	Paved urban land (%)	Proportion of paved urban land determined within each zone
	Paved and grass urban land (%)	Proportion of paved and grass urban land determined within each zone
	Total urban land (%)	Proportion of all urban land (paved, grass, and forest) within each zone
Connectivity	Road density (km/km^2)	Total road length within each zone divided by the area of the zone
	Median flow path length (m)	Median value of all flow path distances from each pixel of urban land to the closest stream channel within each sub-watershed
	Upstream distance to road (m)	Distance between site and closest upstream road crossing

Table 1
Landscape metrics.

Analytical Methods

Initial analysis involved: 1) the evaluation of the data collected during the rapid stream assessment, 2) exploration of the results from the spatial analysis by assessing the landscape metrics and determining interrelationships among them, and 3) testing the response of individual physical attributes to increasing urbanization.

A multi-metric index was created in order to compile the

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measurements of the physical attributes into a single, general score of physical stream condition. Six attributes were chosen to be components of the physical stream conditions index (PSCI). Table 2 lists the attributes, their descriptions, and their scoring criteria. These attributes were selected because they varied systematically through a gradient of human influence and because they account for the diversity of responses to urbanization commonly reported in the literature. Lacking any conceptual basis to favor one attribute over another, all attributes are ranked with equal weighting, using a numerical scale of 1 to 4, and their individual scores totaled for the index score. Scores increase as the physical quality of the stream increases.

Parameter	Description	Scoring			
		1	2	3	4
Channel size	Rank based on enlargement above an expected channel size given the watershed size	> 90% larger	50 - 90% larger	15 - 50% larger	< 15% larger
Bank stability	Qualitative rank (Henshaw and Booth, 2000)	Unstable	Moderately unstable	Slightly unstable	Stable
LWD abundance	Rank based on quantity of LWD pieces in the 100m reach	< 5	5 - 9	10 - 14	> 14
Complexity	Qualitative rank (McBride, 2001)	Poor	Fair	Good	Excellent
Embeddedness	Qualitative rank	75 - 100%	50 - 75%	25 - 50%	< 25%
Cementation	Qualitative rank (Comings et al., 2000)	Poor	Fair	Good	Excellent

Table 2

Componenents of PSCI.

The PSCI was analyzed via simple and multiple regressions with landscape metrics. Longitudinal trends in the PSCI were also explored. The change in the PSCI score (Δ PSCI) was calculated as the difference in PSCI score between consecutive sites along the stream's longitude. Δ PSCI was compared to the intactness of the riparian buffer between the two sites. "Intactness" was quantified with two items, the proportion of forested land and wetland remaining in the 100-m buffer and the number of road crossings between sites. Finally, the PSCI scores were compared to B-IBI scores (the Benthic index of biotic integrity, a measure of instream biological health) using regression techniques.

RESULTS

Physical stream conditions

In total, 87 sites were sampled: nine in Juanita Creek, 31 in Swamp Creek, 34 in Little Bear Creek, and 13 in Thorndyke Creek. Channel morphology at all sites is similar in many, but not all, respects, including gradient, morphologic classification, planform, and storage features. Channel dimensions show a characteristic relationship with watershed size; as watershed size increases, the channel's cross-sectional area at bankfull increases. Channel structure, as measured by pool abundance, bank stability, complexity, and LWD abundance, showed variable results. Pool counts showed the least amount of variability among all of these measures of channel structure. Pool frequency simply did not vary much from site to site, and more than half of the sampled sites had an average of four pools per 100 m. The other three channel structure attributes displayed considerably more variability among the sampled sites.

Pebble counts revealed similar substrate size distributions at many of the sampled sites with d_{50} in the range of 20 to 40 mm. Riffles were evaluated for embeddedness and cementation of the substrate, and results indicate that these attributes were more disparate among different sites. The prevalence of fine sediment had variable results as well. Percent fines ranged from 20% to 100% among the sampled sites. Percent fines was not correlated with local slope but was significantly correlated with the presence or absence of storage features (alternate bars or point bars).

Landscape metrics

Magnitude of urbanization

The land cover of the four watersheds spans a broad range from largely urbanized to overwhelmingly forested (Figure 3). As classified, total urban land represents approximately 80%, 65%, 50%, and 20% of the watersheds of Juanita, Swamp, Little Bear, and Thorndyke creeks, respectively. Although the land cover analysis indicates that Thorndyke Creek has 20% total urban land, its watershed in fact has no urban development with the exception of a few paved roads. Portions of the watershed are actively logged; clearcuts were locally misclassified as urban land cover.

Land cover in the sub-watershed shows very different relationships with that of the smaller zones. Even though the 100-m buffer zone occupies only 16% of the sub-watershed zone on average, its land cover is nearly indistinguishable from that of the sub-watershed (Figures 4; $R^2 = 0.98$). Because the quantity of urban land in the buffer zones was so closely correlated with that in the sub-watershed zone, the buffer-zone metrics were

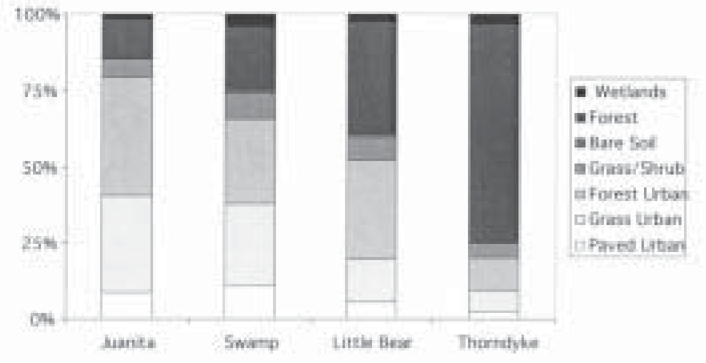

Figure 3.

Land cover distribution of each study watershed.

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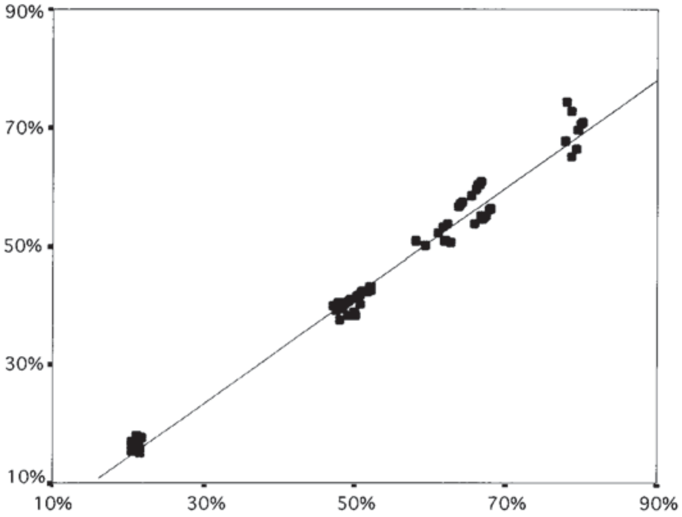

Figure 4.
Comparison of urban land within the sub-watershed and 100-m buffer zones.

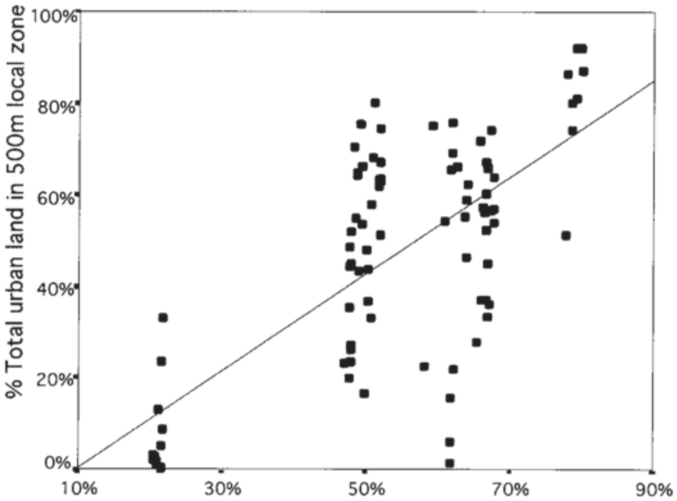

Figure 5.
Comparison of urban land within the sub-watershed and 500-m local zones.

abandoned in the subsequent analysis. In contrast, the percentage of total urban land is often considerably different between the 500-m local zone and the sub-watershed zone (Figure 5; $R^2 = 0.48$).

Connectivity of urban land

Connectivity was quantified with various landscape metrics including road density, median flow path length, and distance to road crossings. In sum, these metrics showed that urban land becomes more connected with the stream network as it becomes more prevalent. Generally, watersheds with "disconnected" urban land did not exist, at least in the way I quantified connectivity. Road density was strongly correlated with the amount of urban land, and median flow path length had little variability among the urban watersheds.

In contrast, the third connectivity metric (upstream distance to a road) varied considerably, ranging from about 100 m to 1800 m for the three urban streams. This metric varies more in Swamp Creek and Little Bear creeks, as compared to the more urbanized Juanita Creek. The upstream distance values for Thorndyke Creek are considerably larger because it has only two road crossings along its mainstem.

Physical attributes and landscape metrics

Several individual physical stream attributes, including bank stability, bankfull cross-sectional area, complexity, LWD counts, riffle embeddedness, and riffle cementation respond to a gradient of urbanization. The bank stability results provide an example of this relationship. Bank stability is significantly different among the study watersheds, as seen in the box-plot (Figure 6; $\chi^2 = 20.4$, $p < 0.0005$). The most stable banks were found in Thorndyke Creek, whereas the most unstable banks were found in Juanita Creek.

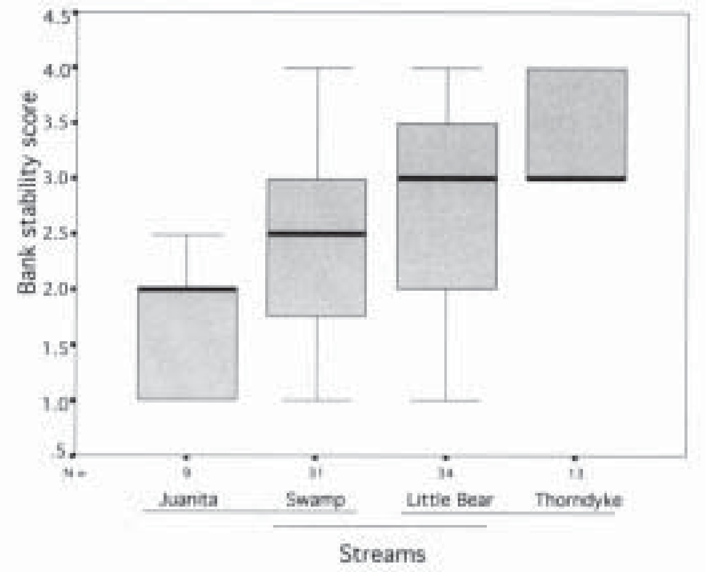

Figure 6.
Comparison of bank stability scores by study stream
(N is number of sites, lines show stream pairs not significantly different by Dunn's test, $\alpha = 0.05$)

Box plot description:

solid line = median
box = 50% of values
whiskers = highest and lowest values excluding outliers
open circles = outliers with values 1.5 to 3 box lengths beyond the upper or lower edge of the box
asterisks = outliers, with values more than 3 box lengths beyond the upper or lower edge of the box

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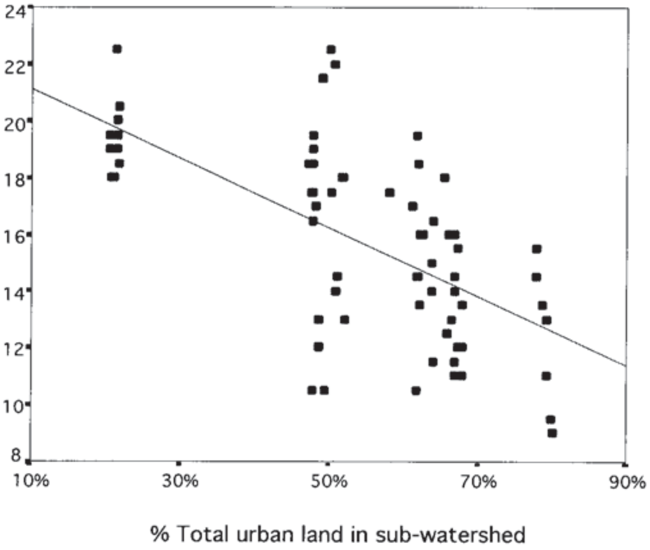

Figure 7.
Regression of PSCI against percent total urban land in the sub-watershed zone.

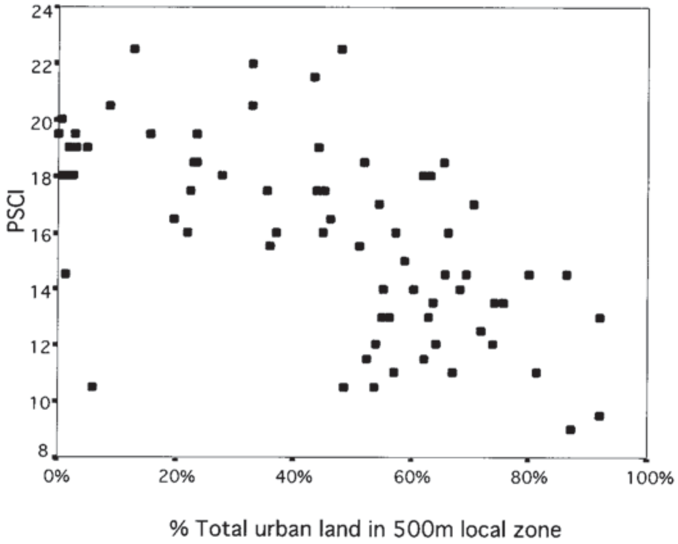

Figure 8.
Regression of PSCI against percent total urban land in the 500-m local zone.

PSCI

Measured PSCI values range from 9 to 22.5 out of a total possible range of 6 to 24. Simple and multiple regression analysis techniques were used to find the best relationships between the PSCI and the landscape metrics that quantify the magnitude and connectivity of urban land. The PSCI shows a decline with increasing percent total urban land in the sub-watershed zone, though the regression relationship is not compelling (Figure 7; $R^2 = 0.42$). When PSCI is regressed with the total urban land within the 500-m local zone, the relationship provides slightly less explanation of the variability (Figure 8; $R^2 = 0.36$).

In an attempt to further explain the PSCI, the connectivity metrics were added to the regression model. The sites from Thorndyke Creek were excluded from this set of regressions, because the connectivity metrics (as defined) were not applicable in a watershed without urban land. Of all connectivity metrics, only one, upstream distance to a road crossing, added further explanatory power to the regression model, which is:

$$PSCI = 20.1 - 11.8\,U_S - 9.4\,U_L + 1.7\,D \qquad (1)$$

where U_S is percent paved and grass urban land in the sub-watershed, U_L is percent paved and grass urban land in the 500-m local zone, and D is the upstream distance (km) to the closest road crossing. This model illustrates that urbanization at the sub-watershed and local zones has an additive effect in degrading urban streams and that the influence of urbanization at the sub-watershed and local zones is nearly equivalent. This significance of D as a predictor variable is consistent with the physical stream conditions associated with road crossings, which are key points of disruption in urban streams. Road crossings interrupt the riparian zone and can alter a stream's fluvial processes. Furthermore, they are commonly locations of stormwater discharge to the channel in urban watersheds.

The PSCI was also analyzed for longitudinal trends. The sites sampled in Thorndyke Creek were again excluded from this portion of the analysis, because this analysis was not applicable to a non-urban watershed. To explain the longitudinal change in the PSCI score, I considered the riparian conditions between

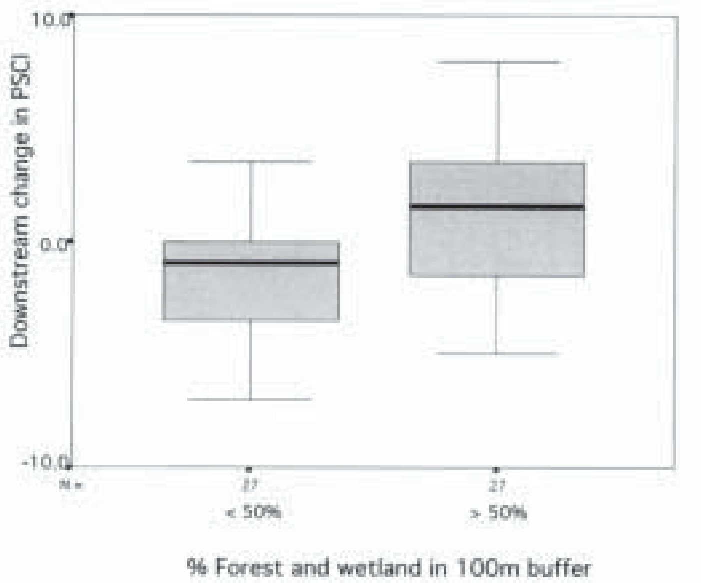

Figure 9.
Comparison of ΔPSCI and percent forested buffer between consecutive sites (Significantly different by t test, unequal variance, $p = 0.002$; see Figure 6. for box plot description).

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% Forest and wetland land in buffer[1]	< 20%	> 20%	< 35%	> 35%	< 50%	> 50%	< 65%	> 65%	< 80%	> 80%
n	5	49	17	37	27	27	37	17	44	10
Mean D PSCI	-0.2	-0.2	-1.7	0.5	-1.5	1.2	-0.5	0.7	-0.3	0.6
p value[2]	0.973		0.015		0.002		0.224		0.510	

1: Buffer zone is 100-m wide and the portion between consecutive sites
2: T test results, unequal variance

Table 3
Comparison of Δ PSCI using various thresholds of percent forest land in the buffer.

The presence of an intact forested riparian buffer promotes downstream improvement in physical stream conditions, as measured by the PSCI. More significant improvements in the PSCI score resulted when the riparian buffer was more than 50% forested (p = 0.002; Figure 9). The sites were grouped using the median value (50% forested buffer) in order to facilitate a simple 2-sample t-test with equal sample sizes. Similar t tests were performed by separating sites by other proportions of forested buffer (20%, 35%, 65%, and 80%). Only the groups separated by the 35% and 50% thresholds were significantly different from each other (Table 3). Further results suggest that the absence of road crossings promotes downstream recovery of physical conditions (see McBride, 2001).

The PSCI was significantly correlated with the B-IBI. B-IBI scores were only available for 14 of the 87 sites and were only from sites in Swamp and Little Bear creeks. A regression analysis of the two indices illustrates that B-IBI scores are fairly well predicted by PSCI scores ($R^2 = 0.63$, F = 20.7, p = 0.001; Figure 10), indicating that physical attributes are an important, but by no means the sole, determinant of biological health.

DISCUSSION

The results can be summarized into six key points:

- Local in-stream physical attributes are heterogeneous and are a function of the geomorphic context, the urbanization of the watershed, and the landscape conditions at the local scale.
- The PSCI functions well as a general measure of the physical integrity in streams, responding in an intuitively reasonable and statistically significant manner to gradients of urbanization.
- The quantity, location, and distribution of urbanization can be successfully quantified with relatively simple, GIS-based landscape metrics.
- Landscape metrics provide explanatory power for physical stream conditions.
- Longitudinal trends in the PSCI scores show that partial recovery of physical conditions is possible when a degraded stream flows through an intact forested riparian buffer.
- Both watershed land use planning and the preservation of uninterrupted forested riparian zones are crucial to maintain functioning stream ecosystems.

Heterogeneity in physical stream conditions

Several of the evaluated physical attributes varied considerably between and within each study stream. Variability in physical stream conditions was greatest for Little Bear Creek and Swamp Creek, suggesting that factors functioning at a local scale can influence the ecosystem of streams within moderately urbanized watersheds. The geomorphic context strongly influenced some of the physical attributes of these four streams. Their similar bed morphology, local channel gradient, median sediment size, and longitudinal profile shape were partly a consequence of the initial criteria used for the selection of watersheds and are also due to the shared geologic history across the entire Puget Sound Lowland region.

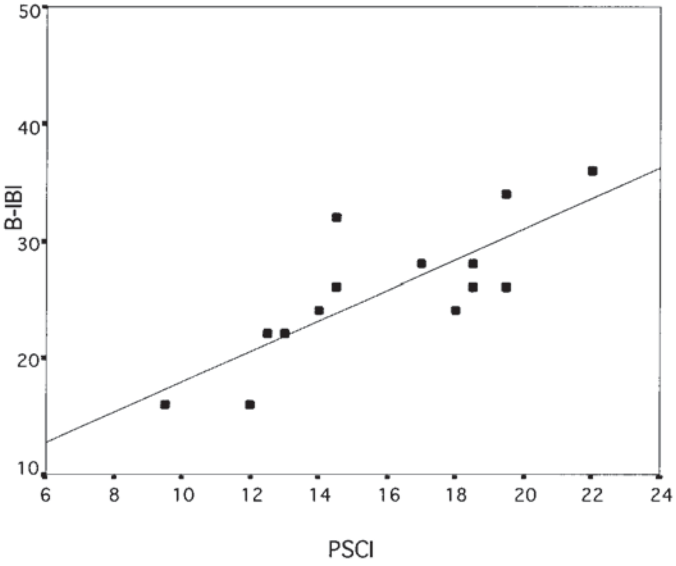

Figure 10.
Regression of B-IBI against PSCI.

Physical Stream Conditions Index

The PSCI effectively integrates a variety of qualitative attributes that are strongly influenced by urbanization into a meaningful, quantitative score. It correlates well with the B-IBI, an index that has been proven to respond to a gradient of urbanization, indicating levels of degradation to aquatic biota (Figure 10; Karr and Chu, 1999; Morley, 2000). Perfect correlation between these two indices should not be expected because the B-IBI responds to changes in multiple factors that affect aquatic systems, whereas the PSCI is only a measure of physical condition. The PSCI also correlates well with the proportion of urban land in the sub-watershed and local zones (Figures 7, 8). The PSCI appears to be a useful index, responsive to the effects of urbanization; to further evaluate the utility and robustness of the PSCI, it should be validated with another sampling effort.

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The applicability of the PSCI may be limited, however, by the stream sampling and geographic scope of this study. This index could be used in most other Puget Sound Lowland small-order (1st – 3rd order) streams without much hesitation. Applying the PSCI beyond this region or in larger order streams would not be recommended without first testing its applicability. That said, most of the PSCI's components are physical attributes that show a common response to urbanization in other parts of this country and the world (Neller, 1988; Galli,1996; Roth et al., 1996; Trimble, 1997; Pizzuto et al., 2000).

Measuring urbanization

In some instances, the variety of landscape metrics explored in this study provided a more robust characterization of the urbanized landscape than more commonly used gross measures of urbanization, such as "percent total impervious area in the contributing watershed." The urbanization of the local zone (another "magnitude" metric) and the proximity to road crossings (a "connectivity" metric) provided further explanation of the physical stream conditions of each site. However, some landscape metrics are so closely related that they cannot help decipher stream conditions (i.e. urban land in the buffer zone and sub-watershed, road density and urban land). Although not useful for better understanding of stream conditions, these relationships between landscape metrics do provide insight to the nature of the urban landscape.

"Connectivity," as measured by two of the three metrics (road density and median flow path length) is not an independent variable in the urban landscape. Increasing urbanization leads to an increasing number of pathways (*i.e.* roads) connecting stormwater to urban streams, and urban land is fairly evenly spread throughout the study watersheds, not clustered near or far from the stream channel.

In contrast, other studies have found connectivity to be a more important and influential factor. Bledsoe and Watson (2000) have studied the change in stream power associated with increased impervious areas and have found it to be sensitive to the connectedness of those impervious areas. These researchers have also demonstrated the importance of connectivity in a modeling effort of the Goodwin Creek watershed in Mississippi (Bledsoe and Watson, 2001). Two watershed scenarios were simulated, one with connected impervious areas and one with disconnected impervious areas. The results showed that connected impervious areas clearly increased peak flow magnitude (Bledsoe and Watson, 2001). The land cover distribution was imposed in this study, however, and not based on actual land cover from urban areas.

Landscape metrics as predictor variables

The results suggest that physical stream conditions are impacted by urbanization in both the sub-watershed and local zones to nearly equivalent degrees. Most of the individual physical attributes degraded with increasing urbanization in the local zone, and they also tended to be more degraded in the more urbanized watersheds. The regression of PSCI against sub-watershed and local zone urban land revealed that these independent landscape metrics were equally important predictor variables. Given no urbanization in the local zone, physical condition is primarily dictated by urbanization of the sub-watershed. With an increasingly greater proportion of urban land in the local zone for a set level of sub-watershed urbanization, physical conditions progressively degrade.

Many studies have tried to determine what portion of the landscape is most influential to stream integrity. Identifying the most influential zone is important, so that managers can strategize and prioritize efforts that aim to rehabilitate or protect stream systems. Although watershed conditions are undeniably influential, many studies have identified a disproportionate influence of the local or riparian zone (Steedman, 1988; Lammert, 1995; Davis, 1998; Naiman et al., 1998). Similar to my findings, the B-IBI scores of several Puget Sound streams were equally well predicted by urbanization in the watershed and by urbanization in the local area (Morley, 2000). In contrast to my findings, however, another study using indices of habitat quality and biological integrity attributed significantly greater importance to watershed land use than the local or riparian land use (Allan et al., 1997).

In sum, GIS-based analysis of urban watersheds provides some but not all of the explanation of the physical and biological conditions in streams. The R^2 values of the various regression models tested suggest that approximately half of the variability in conditions can be explained by various landscape metrics. Therefore, landscape metrics should not be expected to adequately predict stream conditions, and they cannot be used as a surrogate to in-stream assessments. Both GIS-based analysis and in-stream assessments of physical or biological conditions are required to best understand any particular stream system.

Downstream recovery

Where the segment of stream between consecutively sampled sites had an uninterrupted forested buffer, a larger improvement in PSCI score occurred than for those without such a buffer. Sites with roads and developed land between them tended to decrease in PSCI score. The results from the series of t tests of the effect various proportions of forested land in the riparian buffer on Δ PSCI suggest that the buffer must be at least 35% to 50% forested to be beneficial to physical conditions (Table 3).

There are several possible recovery processes acting along a stream channel that have effects on a stream's physical components. Undeveloped riparian zones in the Puget Sound Lowlands typically have active floodplains and stream-side wetlands. The roughness of a forested riparian zone and wetland areas can attenuate peak storm flows and reduce specific stream power (Bledsoe and Watson, 2000). If the erosive force of peak flows can be successfully diminished, stream reaches will experience less enlargement of their channels, resulting in more stable stream beds and banks. If forested riparian zones and wetlands can significantly slow peak flows and temporarily store stormwater, fine sediment suspended or carried in the water col-

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umn has the potential to filter out and remain deposited in wetlands or on floodplains or within the channel in bars. An intact forested riparian zone also allows the recruitment of LWD and inhibits direct anthropogenic impacts, such as channel straightening or stream bank armoring, efforts often used in developed areas to protect stream-side land or structures.

Management implications

The results of this study have specific management implications. The amount of development in a watershed is extremely influential to the physical and biological conditions in streams, which necessitates watershed-wide land use planning for successful protection of streams. Watershed land use is not the sole determinant of stream conditions, however, and a strategy that imposes only a watershed-wide limit on development will be inadequate. Local land cover is extremely important to physical stream conditions, and therefore this zone of the watershed should also have high priority and considerable attention in planning and regulations. Finally, the results suggest hope for degraded urban streams. If riparian buffers can be reforested and road crossings eliminated in certain reaches of streams, partial but still substantive recovery of a stream's physical integrity is possible.

CONCLUSION

Urbanization of both the entire contributing watershed and the part of the watershed closest to the stream appear to have approximately equal weight in influencing a stream's physical conditions. This result has important management implications. If development is restricted in areas adjacent to streams and road crossings (and any other point sources of stormwater discharge) are limited, a stream's physical attributes can achieve the best condition for a given level of watershed urbanization. Otherwise, progressively greater degradation is possible.

Physical conditions can improve downstream from degraded stream reaches if the riparian zone is substantially forested and devoid of road crossings. Stream rehabilitation efforts that reforest the riparian buffer, even along short reaches, and remove the physical and hydraulic connections to urban disturbance via road crossings have the potential to significantly improve physical conditions in *moderately* urbanized streams. With greater amounts of urbanization in a watershed, the beneficial influence of the local riparian zone apparently diminishes.

The results also highlight the usefulness of several methodologies utilized in this study. The PSCI effectively integrates a set of physical attributes, responding in an intuitively reasonable and statistically significant manner to gradients of urbanization. The GIS-based analysis generated several landscape metrics that better described the quantity, location, and distribution of urban land in the study watersheds and explained much of the variability in physical stream conditions.

In sum, with better information on the interaction of urbanization and stream ecosystems, we should be able to improve policies and management strategies for protecting stream integrity in developing areas. Hopefully with more robust knowledge, like that provided by this study, we can mold our landscapes to preserve those streams or stream segments that still function, and we can target rehabilitation to those degraded portions of streams that have realistic chances for improvement.

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LITERATURE REVIEW ON SUBSTANCES OF POTENTIAL CONCERN IN RECLAIMED WATER

By Ruth Douzinas, Research Associate, Center for Urban Water Resources Management

Water resources management has become more complex in western Washington in the past decade as pressure for a limited water supply has increased due to population growth, needs to protect dwindling aquatic habitat for endangered species, increased recreational demands, and continual agricultural and industrial requirements. There are no longer simple solutions such as exploiting surface water supplies or resorting to increased pumping of groundwater. The stresses on both surface water and groundwater are linked, and additional draining of underground water supplies may cause surface water levels to fall. Such a disturbance could endanger the habitats of aquatic species protected under the Endangered Species Act. These conditions provide an incentive to include reclaimed water as part of a water resources management program.

The use of reclaimed water is already becoming a more important alternative for water resources management in western Washington. Common uses of reclaimed water elsewhere in the U.S. include irrigation, industrial uses, groundwater recharge, stream flow augmentation for fish habitat, and indirect potable reuse via augmentation of groundwater and/or surface supplies. General guidelines on water reuse quality have been established by state agencies for public health and environmental protection.

The purpose of this study was to identify specific substances and classes of substances that may be of potential concern to human and environmental health that are not being addressed by current broad-based parameters (such as BOD5, TSS, turbidity, and total coliforms) contained in current state guidelines to regulate reclaimed water quality. The main intent behind reclaimed water quality guidelines is the protection of human health against the risks of exposure to viable pathogens. Removal of chemicals from reclaimed water has not been a leading consideration, with the possible exception of some general guidelines for removal of nutrients and organic matter.

A comprehensive literature review that pursued journal articles, conference proceedings, and current books was used to identify and evaluate specific chemicals of potential concern. This review summarizes the literature that discusses the occurrence, fate, and transport of these compounds in the environment and their possible effects at low doses. The groups of substances covered in this review include disinfection byproducts, cyanide, endocrine disruptors, pharmaceutical byproducts, and nutrients.

Reclaimed water is defined as "effluent derived in any part from sewage from a wastewater treatment system that has been adequately and reliably treated, so that it is suitable for a beneficial use or a controlled use that would not otherwise occur. It is no longer considered wastewater" (Washington State Department of Ecology 1997). To produce reclaimed water, wastewater effluent must undergo advanced treatment beyond secondary, the extent of which depends on the water's final purpose. Advanced treatment refers to additional removal of colloidal and suspended solids by chemical coagulation and granular medium filtration, and possibly dissolved inorganic solids by reverse osmosis and ion exchange processes (Asano 1998). It achieves reduced concentrations of inorganic and/or organic constituents below what is possible with only primary and secondary treatment.

Though there are EPA guidelines (EPA/625/R-92/004, September 1992) for water reuse, no national standards exist, nor are any being planned. Individual states are reliant on themselves for regulation, and various regulatory formats are in use. The different approaches involve one or two state agencies. Washington, along with California and Oregon, uses two agencies. The Washington Department of Health regulates potable water use, establishes criteria for recycled water, and grants permits for and enforces any recycled water use that may involve human health matters. The Washington Department of Ecology regulates wastewater use and grants permits for and enforces all non-health related use of recycled water (Alexander 2000).

Multiple processes are used in treatment systems to produce reclaimed water. These typically consist of biological treatment, filtration, and disinfection, depending on the treatment requirements and the likelihood of humans coming into contact with the water. The Washington State Water Reclama-

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tion and Reuse Standards are a compilation of guidelines and regulations that require assessment of the concentration of certain parameters, such as BOD and total coliforms, in reclaimed water. These constituents are indicative of the biological components of the water and, in turn, pathogen survival. Though these standards are explicit, the Department of Ecology uses them only as guidelines. Each project has to be inspected on a case-by-case basis for exact effluent goals to be set.

With technology today providing the capability to clean water to almost any quality, reclaimed water can serve both potable and nonpotable functions, from recharging groundwater supplies to irrigating landscapes and agriculture. Table 1 lists all of the possible applications of reclaimed water for Washington State.

Type of Reuse	Treatment and Reclaimed Water Quality	Comments
Irrigation Nonfood Crops Food Crops Landscape	Class C-D water acceptable.Class A or better.Class C (freeway landscapes) to Class A or better (residential).	Class depends on human and animal direct exposure to crop products.Varies with restricted vs. open access areas.
Misc. Commercial and Industrial Uses	Varies between Class D and Class A or better.	Includes fish hatchery basins, decorative fountains, flushing of sanitary sewers, street cleaning, washing of yards and lots, dust control, damping of soil, water jetting for consolidation of backfill, firefighting, ship ballast, making concrete, industrial cooling, industrial process water, toilet flushing.
Discharge to Effluent Streams/ Receiving Waters	Must meet requirements of federal water pollution control act, chapter 90.48 RCW.	Must demonstrate beneficial purpose for stream flow augmentation.
Use in Wetlands	Depends on wetland type.	No discharge to Category I wetlands. Lesser standards for lower category wetlands if beneficial use.
Groundwater Surface Recharge	Minimum Class A treatment with Nitrogen removal in secondary treatment process.	Must be of a quality that "fully protects public health" and meets groundwater recharge and DW criteria.
Groundwater Injection Potable Aquifers Nonpotable Aquifers	Class A water and Reverse Osmosis treatmentClass A	Pilot study required. 12-month retention time underground.Monitoring of wells required as specified by DOH and DOE.

Table 1.
Types of water reuse and applicable water quality classes (adapted from Washington State Water Reclamation and Reuse Standards #97-23).

Reclaimed water used for recharge to potable groundwater requires the additional step of reverse osmosis, and it must meet the water quality criteria for primary contaminants (except nitrate), secondary contaminants, radionuclides, and carcinogens listed in the Water Quality Standards for Groundwaters of the State of Washington (173-200 WAC and 246-290 WAC). Reclaimed water used for streamflow augmentation may also require special standards be met under chapter 90.48 RCW. The purpose of these regulations is to monitor pathogen removal to protect public health, and, secondarily, to ensure environmental protection (Alexander 2000).

Most of the chemicals of potential concern to be discussed are not specifically addressed by existing water reuse guidelines and regulatory programs (e.g., chlorination byproducts, cyanide). These chemicals are only considered hazardous when they reach certain concentrations, determined by traditional toxicological methodologies. In calculating the risks associated with these chemicals, concern must be given to the chemical's environmental fate and transport (e.g., does it bioaccumulate?) in addition to its acute and chronic toxicity. Assessing potential long-term low-level exposures may be important because lower concentrations of chemicals may cause chronic or harmful effects that are not observed until years later or in subsequent generations.

Disinfection byproducts (DBPs) consist of a wide variety of organic chemicals, created when chlorine, ozone or another oxidant is used to disable viable microbial pathogens in influent. The number and identity of all possible byproducts are not known. Trihalomethanes and haloacetic acids are the most extensively researched. Certain trihalomethanes such as chloroform, bromodichloromethane, and tribromomethane are of potential concern because they have been shown to cause cancer in rodents. There is some epidemiological data that suggests an association between the consumption of chlorinated drinking water and reproductive and developmental effects, though there remain critical data gaps. It is not known whether treated effluent contributes more precursors to the formation

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of DBPs than do conventional water sources, nor whether treated effluent provides precursors that lead to the formation of DBPs different from those formed in traditional water supplies.

Cyanide is less well studied than DBPs, but unexplained occurrences involving the sources and formation of cyanide in wastewater treatment facilities aroused concern as to its potential health and environmental effects. Multiple municipal treatment plants have reported elevated concentrations of cyanide after chlorination in secondary effluent (≥ 22 microgram/L). Insufficient data exist to determine if the effluent cyanide levels measured are a result of an analytical artifact, production of cyanide in biological treatment, or chlorine disinfection reactions. A 3-year study (currently underway) has been sponsored by the Water Environment Research Foundation (WERF) to look into these issues. Data are considered inadequate to accurately determine or predict the toxicity and environmental fate of three cyanide species (thiocyanate, cyanate, and cyanogen chloride) found in treated effluents. Still, reviews of WERF reports to date found that no significant problems have been identified involving the concentrations of cyanide species currently found in surface waters.

Endocrine disruptors are a large body of chemicals that have been shown to induce adverse reproductive and developmental effects in wildlife. Those found in treated effluents include natural and synthetic hormones, degradation products of nonionic surfactants (phenolic compounds), and plasticizers. Phenols are the degradation byproducts of ubiquitously used industrial detergents and surfactants. Various kinds, including alkylphenol ethoxycarboxylate, have been found to persist through tertiary treatment (filtration) processes. Alkylphenolic compounds have been found in rivers, estuaries, and tap water. They have been shown to cause endocrine disruption and altered reproductive physiology in fish, such as changes in the morphology of male gonads. Natural and synthetic hormones such as estradiol and ethinylestradiol have also been shown to persist through wastewater treatment processes and end up in low concentrations (microgram/L-ng/L range) in receiving waters. Hormones have been shown to induce the production of vitellogenin, a protein normally found in female fish, in male fish. While endocrine disrupting compounds may affect human, fish, and wildlife reproductive organs, there is not a sufficient basis of science to quantify the effects of long term exposure and concentration levels to biological responses. At this time, there is no direct evidence for reproductive disorders in humans induced by endocrine disrupting agents in the water supply, nor is there any proof of population level effects to wildlife organisms as a result of individual reproductive and developmental effects caused by hormones in the aquatic environment. However, the lack of proof so far does not mean no negative effects exist.

The primary route of drugs into the environment is through wastewater collection, treatment, and reuse or disposal, since most are ingested and excreted in urine or feces. Data exist to show that pharmaceutical byproducts are not completely removed in wastewater treatment plants. These excreted drugs, in either their original form or a mixture of metabolites, may still be biologically active, which arouses suspicion about their ability to affect receptor organisms. Many pharmaceutical compounds are polar, nonvolatile, lipophilic, and have low biodegradability. Classes that have shown up in treated effluent include hormones, antibiotics, lipid regulators, antineoplastics, and analgesics. The effect of pharmaceutical compounds on the natural ecosystems exposed to them is largely unknown. Practically no data are available from which to gage potential toxicity of chronic exposures to low doses of pharmaceuticals in the environment.

The last category of chemicals reviewed in this study was nutrients, particularly nitrogen and phosphorus. These chemicals are known contaminants, are commonly monitored at treatment facilities, and their impacts on eutrophication are well known. However other effects may be found with elevated nitrogen (nitrate level >10 mg/L) concentrations. Amphibians (e.g. frogs, salamanders) are thought to be some of the most sensitive aquatic organisms to elevated nitrate levels. Chronic effects such as depressed immune responses have been found to occur at concentrations of nitrate nitrogen below 10 mg/L.

Reclaimed water is being successfully used in several indirect potable reuse projects around the United States. Many of these projects meet or exceed the quality of the raw waters that would otherwise be used if reclaimed water were not available. However, it was the purpose of this paper to question those current standards by which reclaimed water is measured. There appear to be many unanswered questions regarding the use of reclaimed water, especially regarding substances such as endocrine disruptors, chlorination byproducts, and pharmaceutical byproducts. Work by the scientific and toxicological community should be continuously monitored to identify progress on understanding the fate and health effects of pharmaceutical and endocrine disrupting compounds.

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