THE IMPACTS OF IMPERVIOUSNESS ON AQUATIC ECOSYSTEMS:

An annotated bibliography on the effects of a key stressor of urbanization on the aquatic ecosystem

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Introduction

As the population of California continues to grow, new communities emerge and existing ones expand. Impervious surfaces, including roads, houses, and commercial buildings, are a hallmark of this urban expansion. These impervious surfaces have significant impacts on local watersheds. Impervious cover (IC) affects the hydrology, chemistry, and biotic integrity of aquatic ecosystems. Many of the effects are interrelated and can often be difficult to pinpoint and assess. Schueler (1997) described the impacts of increasing watershed IC on stream conditions as occurring in three primary stages: a) non-impacted streams when IC was less than 10%, b) impacted when IC was between 10 and 25%, and c) degraded waterways when IC exceeded 25%. Questions have been raised regarding the applicability of these thresholds to California's arid and semi-arid climates. Some studies suggest that the thresholds are actually lower in the arid Southwest (Coleman et al., 2005). Others suggest that total watershed IC is less relevant than connected IC or the IC within the riparian corridor, floodplain, or upstream portions of the watershed. Climate, geomorphology, and historical flow regimes of the watershed can also affect the threshold values. The validity of any threshold value is also a question that is under consideration. The literature reviewed in this annotated bibliography touches on these and other factors relevant to assessing the impacts of impervious cover on the aquatic ecosystem. The review is divided into four main sections as follows:

Overview of Contents

I. Impacts of Imperviousness on Biological Conditions

1. **Bowles, B., M. Sanders and R. Hansen (2006). Ecology of the Jollyville Plateau Salamander (Eurycea tonkawae: Plethodontidae) with an Assessment of the Potential Effects of Urbanization. *Hydrobiologia* 553(1): 111-120.**

Keywords: salamander; urban development; habitat; stream quality impairment; biological indicators

Background/Purpose: The purpose of this paper is to document the abundance and distribution of the Jollyville Plateau salamander, and to identify its habitat requirements and factors that may regulate the abundance and distribution of the species. The Jollyville Plateau salamander is a lungless salamander whose range is limited to six small drainages on the Edwards Plateau, Texas. The species was first described in 2000 and status of its population is not well understood. Most of the range of the species is potentially threatened by impairment from urban development.

Methods: Six sites known to provide habitat for salamanders were monitored for a two year period. Based on total impervious cover (TIA), sites were labeled as either developed (TIA>10%) or undeveloped (TIA<10%). Impervious cover was estimated from GIS maps of roads and buildings developed using 1997 aerial photos. Salamanders were surveyed each month and the habitat characteristics, including potential predators, were noted. The surface water chemistry was also sampled to determine temperature, pH, and dissolved oxygen.

Results: Salamander densities were lower in the developed sites than in the undeveloped ones, and were higher where water temperature was relatively stable. Mean salamander densities were higher where water temperature was stable and where cobble and rocks were abundant in the waterway. Salamander densities were much higher in the spring and summer than in the fall and winter, while the majority of gravid females were observed between November and February. The fact that there was no significant correlation between imperviousness and water temperature, embeddedness, or baseflow suggests that these factors were not responsible for the relationship between urbanization and salamander densities. Higher specific conductance, a measure of the concentration of charged particles at 20 °C, was strongly correlated (p=0.001) with areas with a greater degree of imperviousness. This could be an indicator of the presence of charged particles such as contaminants (ie., heavy metals or pesticides) that were not measured in this study.

Conclusions: Amphibians are very sensitive to environmental changes. Increased imperviousness was associated with two key habitat changes: 1) reduced cobble and rocks, and 2) higher conductivity possibly due to contaminants such as metals. These habitat changes may have contributed to lower densities of the Jollyville Plateau salamander.

2. **Chadwick, M., D. Dobberfuhl, A. Benke, A. Huryn, K. Suberkropp and J. Thiele (2006). Urbanization affects stream ecosystem function by altering hydrology, chemistry, and biotic richness. *Ecological Applications* 16(5): 1796-1807.**

Keywords: decomposition; impervious surface area; litter shredders; snails; stream catchment; urbanization; stream ecosystem function; urban streams Florida, leaf litter

Background/Purpose: This study was designed to explore the effects of impervious area on leaf litter decomposition and on the macroinvertebrate assemblage in 18 streams in the lower St. John's River Basin in Jacksonville, Florida. The purpose was to examine the impact of catchment urbanization on ecosystem functions by studying how biotic and abiotic factors interact and influence downstream decomposition.

Methods: Bags of either red maple or sweetgum leaves were placed in 18 streams that were picked based upon a hierarchical, stream-order procedure and accessibility. The authors compared total impervious area (TIA) of the catchment with mass loss, fungal biomass, and macroinvertebrate biomass within the leaf-litter bags. TIA was estimated using remote sensing techniques. All non-vegetated, non-wetted areas were assumed to be impervious. Water samples were taken each month for three months and analyzed for several chemical parameters. Litter bags were placed in the stream and analyzed 2, 4, 8, and 12 weeks later. The macroinvertebrate populations in the bags were analyzed based on five functional feeding groups: predators, collector-gatherers, filterers, snails, and shredders. Those findings were then analyzed using analysis of variance and principal component analysis.

Results: The highest rate of leaf litter breakdown (highest mass loss), the highest level of fungal biomass in the litter bags, and the highest flow rates occurred at sites with an intermediate level of TIA (30-40% imperviousness). The rate of breakdown of biomass was positively correlated with macroinvertebrate abundance and taxa richness. The concentration of nutrients and metals, commonly associated with increased urbanization and imperviousness, were inversely related to taxa richness.

Conclusions: Biomass and invertebrate species richness were positively correlated with litter breakdown rates. The highest leaf litter breakdown rates were observed at intermediate levels of TIA. The sites where litter breakdown rates were greatest were those with the highest base flow rates, which suggested that mechanical abrasion by the water was a major contributor to decomposition rates.

3. **Fend, S., J. Carter and F. Kearns (2005). Relationships of Field Habitat Measurements, Visual Habitat Indices, and Land Cover to Benthic Macroinvertebrates in Urbanized Streams of the Santa Clara Valley, California. *American Fisheries Society Symposium* 47: 193-212.**

Keywords: macroinvertebrate assemblage; habitat assessment; water quality; land use

Background/Purpose: The purpose of this paper was to determine which habitat features and measurement techniques are the most useful for predicting biological conditions in streams in the Santa Clara Valley. Many of the streams are historically ephemeral, but now are effluent dominated, so have become perennial streams. The streams drain north into the San Francisco Bay and are divided into two ecoregions; the valley floor and the upland sites.

Methods: In May of 1997, the macroinvertebrate communities were sampled at 85 stream sites. The organisms were identified to the lowest practical taxonomic level. Ephemeroptera, Plecoptera, and Trichoptera (EPT) richness was calculated, since those groups are pollution intolerant and are good indicators of stream conditions. Water quality and habitat data were taken concurrently, and a fairly simplistic analysis of land use was conducted. The impervious area was calculated based on four land use categories (low intensity residential, high intensity residential, commercial/industrial/transportation, and quarries/strip mines/gravel pits). The habitat, land use, and invertebrate data were analyzed using principal components analysis and correlation analyses.

Results: The total impervious area (TIA) in the subwatersheds ranged from 1-40% with a median of 4% for all of the sites. The analysis suggested that longitudinal stream features like stream slope and elevation were strongly correlated with stream biota. Channel slope and particle size were associated with higher elevation sites, while urban land use, canopy opening, and habitat modification were associated with the low elevation sites. The analysis of the lowland sub-watershed indicated an association between urban land cover and habitat modification variables, but habitat indices and water chemistry were both weakly correlated with invertebrate scores. In the entire watershed, EPT richness was associated with elevation, slope, and distance to the nearest upstream dam; however in the valley, distance to the nearest dam was negatively correlated with the same measures. In the entire watershed and the upland sites, the macroinvertebrate diversity was more closely related to percent of non-urban land than measures of urbanization (total urban land, impervious area). This contrasted with the lowland sites where watershed cover was a strong correlate with invertebrate diversity. Because the overall correlation between the biotic integrity of the macroinvertebrate community and watershed imperviousness was fairly small, as was the difference in TIA between urban and non-urban sites, it is difficult to draw convincing conclusions regarding the impact of imperviousness on the invertebrates.

Conclusions: The diversity of aquatic macroinvertebrates was closely related to both longitudinal stream features and to urban land use in both the buffer and watershed area in the Santa Clara Valley.

4. **Klein, R. D. (1979). Urbanization and Stream Quality Impairment. *Water Resources Bulletin* 15(4): 948-963.**

Keywords: urbanization; impervious surfaces; benthos; fish; toxic substances; stream quality impairment; sediment; migration barriers; base flow; storm water; temperature

Background/Purpose: This was one of the first papers to address imperviousness based on a dose-response relationship, and was the first to release a tested threshold value for imperviousness. The study was conducted in the Piedmont province of Maryland to determine the effects of impervious area on stream quality. The benthic community was sampled to determine the effects on the stream biota. From those results, the author presented possible ways to reduce the impacts of urban development on stream quality.

Methods: Percent impervious area was determined from 1973 land use maps that were created from satellite images. Land use impervious coefficients were obtained form the Soil Conservation Service (1975) and Graham et al (1974). Twenty-three small watersheds were selected, based on their size and degree of urbanization, to determine changes in base flow, alteration of the stream bed, changes in temperature, toxic substances, and nutrient input. The benthic organisms were sampled at three points on a single riffle at each site using a Surber square foot sampler. Fish were collected using a rectangular dip nets in a 100 m section of each small stream.

Results: There was a negative linear relationship between watershed imperviousness and base flow, or the portion of stream discharge that is not attributable to runoff or storm water (r =0.65). There were so few fish at the sites with the highest impervious area that a diversity index could not be calculated. Despite this challenge, the three sites with the highest benthic diversity were the wooded control sites, indicating that they were better suited to support fish populations. The sampling sites were too small to obtain representative samples from the benthic community, so diversity indices were not calculated. Therefore, based on the fish and benthos communities, the results could only be analyzed qualitatively. The blacknose dace, a species of fish tolerant of adverse habitat conditions, was the dominant species at three of the four urban sites. Most of the changes that were noted occurred at around 12 % imperviousness, but the author recommends developing restrictions on development to keep watershed imperviousness below 10%.

Conclusions: Stream quality degradation, determined by changes in base flow and the diversity of fish and invertebrates, was first noticeable at approximately 10% watershed imperviousness and became severe once watershed imperviousness reached 30%.

5. **May, C., R. Horner, J. Karr, B. Mar and E. Welch (1997). Effects of Urbanization on Small Streams in the Puget Sound Ecoregion. *Watershed Protection Techniques* 2(4): 483-494.**

Keywords: stream habitats; impervious area; fish habitat; urbanization; habitat change

Background/Purpose: This study examined the effects of urbanization on 22 small streams in the Puget Sound lowland region, known for the presence of native salmonids. Recently, the decline in salmon populations has been attributed, at least in part, to the land use practices of the region. The author focused on linking the overall landscape conditions with the habitat characteristics in the stream, and in turn, with the biological integrity of the stream community.

Methods: The author used GIS, aerial photographs, basin plans, and field surveys to determine total impervious area. The authors applied a regression relationship between impervious area and road density that had been established from a previous study to determine impervious cover for this project. Riparian integrity, chemical and physical characteristics of the stream, stream flow, and aquatic biota were sampled and analyzed on both watershed and stream segment scales. Salmonid abundance estimates were obtained from several sources including surveys of the instream habitat and riparian zone.

Results:
As imperviousness increased above 10% , the road density and drainage density also increased. Drainage density refers to the length of waterways, natural and articifical, relative to the total land mass. Both parameters were highly correlated with % total impervious area (TIA).
Several relationships between imperviousness and stream quality were also identified. As TIA increased, stream corridor widths decreased. Riparian encroachment and the number of interruptions along the length of the buffer both increased proportionally with TIA. None of the urbanized streams retained more than 25% of the natural floodplain.
Exceedance of chemical water quality criteria did not occurred until % TIA was greater than approximately 45%. At this point, habitat degradation was significant. Important habitat attributes for salmonids, such as pools and the presence of woody debris, were lacking as urbanization increased. Degradation of this streambed substrate as a result of sedimentation occurred in all of the streams with TIA>30%. Lastly, as TIA increased, the benthic index of biotic integrity and the ratio of coho salmon to cutthroat trout decreased substantially indicating that the coho salmon were being competitively excluded in streams where the TIA exceeded 5%.

Conclusions: The impacts of imperviousness on aquatic systems increased proportional to urbanization and adversely affected the habitat of native salmonid populations. In the streams investigated, changes in stream morphology detrimental to the protection of salmon occurred at levels of imperviousness much below the levels associated with reduced water quality. Changes in habitat appear to be the first signs of stress associated with urbanization.

6. **Maxted, J. (2000). Effects of Urbanization on the Macroinvertebrate Communities of Small Rocky Mountain Streams, and the Benefits of Riparian Vegetation. U.S. EPA Cooperative Agreement No. 82444601.**

Keywords: macroinvertebrate assemblage; physical habitat; rocky mountain streams; urbanization; riparian integrity

Background/Purpose: This paper examined the impact of urban development on small streams in and around Vail, CO and the importance of riparian vegetation in the buffer area as a non-structural control mechanism for mitigating the impacts of urbanization. The study watersheds had relatively low levels of imperviousness due to their small residential populations (most of the urban effects were from ski resorts) and innovative planning strategies (preservation of buffers and road designs that drained into grass swales rather than storm drains).

Methods: Twenty-eight sites were selected in the communities of Vail, Copper Mountain, and Beaver Creek in the Rocky Mountains. They were placed into three reference groups based on their impervious area (IA) and the proportion of the watershed that was in the lowlands, where most of the urban development was occurring. Six sites were considered reference sites (<0.2% IA, <7% lowlands), ten sites were good cover sites (0-1% IA, 3-25% lowlands), and twelve sites were poor cover sites (0-3% IA, 4-45% lowlands). Because of the low amount of urbanization, there was some overlap between the groups. For each watershed, IA was determined by using 12 land use categories and their respective amounts of imperviousness. Stream measurements, including macroinvertebrates, physical habitat, flow, velocity, width, depth, and water quality (pH, temperature, conductivity, and dissolved oxygen) were determined. Estimates of riparian protection were recorded in three width classes in the entire stream network above each sampling site. The width classes were <1 meter, 1-5 m, and >5 m.

Results: The study watersheds had low TIA (0 -3%). The poor cover sites had a significantly lower % EPT abundance (the relative proportion of the pollution sensitive orders, Ephemeroptera, Plecoptera, and Trichoptera, in the invertebrate sample) than the reference sites. For all of the other biological measures, there was no significant difference between the urban sites and the reference sites. The amount of riparian cover did not play a significant role in any of the endpoints. This may be because all of the urban watersheds had >92% of their stream length in the lowlands with good riparian cover.

Conclusions: Local, natural factors may cause rocky mountain streams to be more resistant to urbanization. Even with low TIA, urbanization had a significant adverse effect on benthic macroinvertebrates. Results suggest that stormwater and riparian management efforts are effective in ecological protection of urban streams. Further study of periphyton richness and biomass is recommended.

7. **Maxted, J. and M. Scoggins (2004). The Ecological Response of Small Streams to Stormwater and Stormwater Controls in Austin, Texas USA. U.S. EPA Cooperative Agreement No. 9701.**

Keywords: Stormwater; macroinvertebrate assemblage; land use; impervious area; stream hydrology

Background/Purpose: This paper addressed two questions: a) What were the impacts of urbanization and watershed imperviousness on small streams in Austin, Texas; and b) How effective were stormwater mitigation ponds in protecting streams from the impacts associated with imperviousness.

Methods: Macroinvertebrates, flow, physical habitat, water quality, channel dimensions, and habitat quality were measured in 43 small streams with varying degrees of urban land cover using the US EPA's

Rapid Bioassessment Protocol. The streams were categorized as either having low impervious area (<13% IA), medium-low (14-23% IA), medium-high (24-40% IA), or high impervious cover (>40% IA). Through the analysis of aerial photographs, two sets of 10 imperviousness coefficients were developed by the City of Austin, one set for urban areas and a second for rural areas. Topographic maps were analyzed to determine the areal extent of each land use type for each subwatershed. The urban sites were further classified based on the presence or absence of stormwater control ponds and compared with non-urban reference sites (5.6-7.7% imperviousness). EPT taxa richness and overall % EPT were employed as measures of species richness and relative proportion of the pollution sensitive orders, *Ephemeroptera*, *Plecoptera*, and *Trichoptera*.

Results: In general, % EPT declined as imperviousness increased. However, the use of stormwater retention partially offset this decline. The presence of stormwater control ponds significantly increased EPT taxa richness and % EPT in high IA (>40%) streams relative to those without stormwater ponds. The linear regression of the invertebrate data and percent imperviousness was not significant for a variety of macroinvertebrate metrics except %EPT (r^2=0.22); even in this case, the regression relationship was weak. Most of the invertebrate species observed in the study were pollution tolerant, including those at the reference sites. The authors speculated that the results may have been confounded as a result of dessication of riffles in the months just prior to the sampling period.

Conclusions: In general, the authors found the % EPT taxa was the most sensitive biological indicator of impervious cover in streams sampled in the Austin, TX area. However, the results of this study are inconclusive due to possible confounding by drought, which likely affected the population of macroinvertebrates in the streams studied.

8. **Miltner, R., D. White and C. Yoder (2004). The biotic integrity of Streams in urban and suburbanizing landscapes. *Landscape and Urban Planning* 69(1): 87-100.**

Keywords: biological integrity; fish; land use; streams; rivers; urbanization

Background/Purpose: This paper addressed the impacts of urban and suburban development and allied stressors, including combined or sanitary sewer overflows, waste water treatment plants, dumping, spills, etc, on streams in Columbus and five other cities in Ohio in the context of the Clean Water Act and the guidelines of the Ohio EPA.

Methods: Fish community and habitat data were obtained from the Ohio EPA statewide biological and habitat database for 267 sites in small watersheds in the major metropolitan areas statewide. The fish community attributes were represented by IBI and the habitat quality was assessed using a qualitative habitat evaluation index (QHEI). The number of highly sensitive species that were found at a site at the beginning and end of the decade was compared using a two sample t-test. Urban land use for each site was determined from Landsat Thematic Mapper satellite imagery and qualitatively classified by predominant impact type. IBI scores were initially regressed against percent urban land use, and diagnostic plots were used to evaluate model assumptions. An analysis of covariance was used to further identify relationships between the IBI and % land use; IBI data response to TIA was divided into quartiles. Fourteen sites in three streams in and near Columbus were chosen for in-depth sampling. The land use changes from 1990 to 2000 were estimated based on census data. Population density was used as a surrogate for urban land use for the drainage areas for each of the three streams. Several stressors (modifications to physical habitat, combined or sanitary sewer overflows (CSO/SSO), past land use for industry, sites downstream from wastewater treatment plants (WWTP), and the presence of sewer lines beneath the stream bed) were examined to determine their impacts of in-stream biota.

Results: The analysis revealed that the impacts of CSO/SSO, WWTP and physical habitat degradation were independent of the impacts due to urban land use. The authors divided the IBI data into quartiles the response to catchment imperviousness. The mean IBI response in the first quartile of urbanization (<4.4% watershed impervious cover) was significantly higher than in the third quartile (13.8-27.1% IA). The strongest negative impacts were CSO/SSO, past land use, and habitat. Based on the census data, it was clear that the urban influence in some of the streams had more than doubled over the course of ten years, and the fish communities in these streams has been impacted by the change.

Conclusions: The IBI was significantly impacted when imperviousness exceeded 13.8% and was severely degraded when imperviousness exceeded 27.1%.

9. **Ourso, R. and S. Frenzel (2003). Identification of Linear and Threshold Responses in Streams Along a Gradient of Urbanization in Anchorage, Alaska. *Hydrobiologia* 501(1-3): 117-131.**

Keywords: impervious area; stream biota; hydrology; water quality; habitat

Background/Purpose: This experiment was designed to determine the main factors that are affected by impervious cover in streams near the Anchorage area. The authors examined 86 variables that relate to various aspects of the habitat, biota, chemistry, and hydrology to make this determination.

Methods: Numerous variables, including macroinvertebrate diversity, water chemistry, and habitat structure, were analyzed during two consecutive summers to assess their relationship to impervious cover. One complete set of data were taken for each of 12 sites. The land use descriptors and impervious areas were calculated using USGS land use data and IKONOS satellite imagery. The imperviousness was determined directly from 1 meter grayscale imagery. The data was analyzed for significant correlations using Spearman rank correlation coefficients. The variables that were correlated with impervious area were further analyzed to identify a quantitative response to imperviousness.

Results: Eighteen of 86 variables were found to be significantly correlated with impervious area, including riparian and instream habitat, macroinvertebrate communities, water chemistry, and sediment chemistry. Eight of the variables had a threshold response (very little impact up to a certain threshold, at which point effects become significant) to impervious area. Each of the study sites had a mean threshold value between 4.4% and 5.8%, which was determined by combining the response curves of physical, biological, and chemical endpoints. Some of the variables used in the analysis were bank erosion, percent reach greater than 20% embeddedness, concentrations of selenium, zinc, lead and cadmium in the sediment, and percent EPT (Ephemeroptera, Plecoptera, and Trichoptera in the invertebrate samples) taxa at the site .

Conclusions: Impervious area was significantly linked with 18 of the 86 variables. Sinuosity, EPT family richness, EPT abundance, and sediment selenium had a strong negative correlation with imperviousness, while manganese, chloride, and iron in the water and zinc in the sediment had a strong positive correlation with imperviousness. Eight of the variables were significantly affected at 5% imperviousness. This threshold is lower than what has been cited in other studies.

10. **Paul, M., J. Meyer and C. Couch (2006). Leaf breakdown in streams differing in catchment land use. *Freshwater Biology* 51(9): 1684-1695.**

Note: This article does not discuss impervious cover however we decided to include it because the authors analyzed effects of urbanization on the ecosystem as a whole, not simply on fish and invertebrate populations.

Keywords: litter breakdown; woodland stream; aquatic insects; Georgia; ecosystem; leaves; decomposition

Background/Purpose: This purpose of this paper was to analyze the effects of urbanization on the ecology of aquatic systems. The authors tested the hypothesis that leaf litter decomposition rates would vary in catchments with different land uses. They compared breakdown rates in catchments with four predominant types of land use (forested, agricultural, suburban, and urban) in the Piedmont region near Atlanta, Georgia.

Methods: The authors observed the breakdown rates of chalk maple leaves in 100-200 meter study reaches in a total of 12 third and fourth order streams. Leaf litter decomposition has been used as a variable that integrates various aspects of ecological functions. The land use, base flow, chemistry, pesticide, and sediment metal data were obtained from a USGS survey. Eight grams of leaves were placed into each of 40 bags at each site and were removed at regular intervals. Invertebrates from two of the bags were identified and classified as shredding or non-shredding. Breakdown rates were calculated and analyzed to identify relationships with the USGS data.

Results: In the urban streams, the leaf decomposition rates were as much as four times higher than in reference sites due primarily to increased flow from urban runoff. Mean shredder abundances were significantly higher in forested and agricultural streams than in urban and suburban streams, which could be attributable to the fact that usable biomass remains in streams longer where the rate of physical decomposition is lower. There was no significant difference in the temperature of the streams, but the storm runoff and total phosphorus concentrations were significant predictors of breakdown rates (R^2=0.64). Total phosphorus was the best predictor of decomposition rates in agricultural or forested watersheds (R^2=0.92), while for urban streams, storm runoff alone was the best indicator (R^2=0.78). Two different mechanisms the increase in breakdown rates between urban and agricultural land were suggested. In the agricultural streams, increased nutrients stimulated the decomposition of the leaf litter by stimulating growth of the microbial and fungal populations. In the urban streams, the elevated leaf degradation rates could be the result of increased physical breakdown from runoff.

Conclusions: It was suggested that higher decomposition rates in agricultural streams are due to high nutrient inputs that stimulate invertebrate and fungal growth, and that ncreased rates in urban streams are due increased stormwater flows that cause mechanical decomposition. The results imply that increased urbanization will continue to alter organic matter processing and insect survival and secondary production.

11. **Pedersen, E. R. and M. A. Perkins (1986). The Use of Benthic Invertebrate Data for Evaluating Impacts of Urban Runoff. *Hydrobiologia* 139(1): 13-22.**

Keywords: benthos; urbanization; runoff; cluster analysis

Background/Purpose: This is one of the first papers to examine the impacts of urban runoff on aquatic biota. The benthic invertebrate fauna can be a valuable indicator of the health of urban streams. The increase in peak flow in storm conditions can modify the physical habitat and influence the presence of a food source for benthic fauna due to increased flow rates. This paper compares the variation in benthic fauna between an urban and a rural creek in Bellevue, Washington.

Methods: Two sites were chosen on Bear Creek, a watershed that is 15% developed, and three sites were chosen on Kelsey Creek, a watershed that is 78% developed. The benthic macroinvertebrate fauna was sampled using buried sampling bottles. The collected organisms were identified to the family level and placed into one of 13 functional and taxonomic groups.

Results: The abundance of organisms collected from the urban and rural creeks did not significantly differ, but the number of different species and relative proportions of functional groups were significantly different. The collection of organisms from the sites at Bear Creek had a relatively even distribution of groups. The sites on Kelsey Creek had an abundance of amphipods, worms, and chironomids, which are more tolerant of unstable habitats than other macroinvertebrates. Kelsey Creek also lacked the trophic groups that could utilize large particulate organic matter, suggesting low availability of organic materials.

Conclusions: The benthic macroinvertebrate community shifted from one dominated by pollution sensitive species in rural streams to a community dominated by worms, amphipods and midges in urban streams. This shift suggested the absence of available food and good quality habitat for sensitive species.

12. **Roth, N. E., J. D. Allan and D. L. Erickson (1996). Landscape influences on stream biotic integrity assessed at multiple spatial scales. *Landscape Ecology* 11(3): 141-156.**

Keywords: fish communities; agricultural watersheds; riparian forest; management; habitat quality

Background/Purpose: The goal was to determine whether land use/cover was an effective predictor of stream integrity in small streams dominated by agricultural and urban landscapes in the upper River Raisin basin of southeastern Michigan, and if so, at what spatial scale.

Methods: The authors investigated the advantages and disadvantages of using different techniques and different spatial scales for estimating the significant land uses in a riparian buffer. They compared the effects of land use at three different spatial scales as well as the effects of various buffer widths on indices of aquatic habitat quality. They looked at 23 small watersheds with a wide variety of land uses that were dominated by agriculture and urbanizing land use. The land use estimates were compared with habitat indices and a fish index of biotic integrity (IBI).The land use in each watershed was quantified at local (150 meter), reach (1500 meter) and catchment (15000 meter) scales. Land use within the buffer area was quantified using aerial photographs. Buffer widths were 50, 125, and 250 meters on each side of the waterway. Electrofishing surveys were conducted and the IBI calculated. The habitat index was based on field observations of nine features: stable substrate, embeddedness, velocity and depth variability, flow stability, bottom deposition, pools/riffles/runs/bends, bank stability, bank vegetative stability, and streamside cover. Two other measures of fish diversity (number of species and proportional representation by sensitive species) were evaluated as possible alternatives to IBI.

Results: IBI and HI scores ranged from poor to very good among the 23 sites, and habitat and fish assemblage measures were highly correlated. Stream biotic integrity and habitat quality were negatively correlated with the extent of agriculture and positively correlated with the extent of wetlands and forests. Correlations were strongest at the catchment scale and weak and non-significant at the local scale. Species richness was higher at sites where wetlands were the predominant land cover. The riparian measures, such as the width of the buffer covered by woody vegetation, did not correlate strongly with habitat index scores. The best evaluation of the riparian system was offered by the field surveys, which were very labor intensive. The use of a previously digitized database was relatively simple, but it was limited by the accuracy of the database.

Conclusions: Destruction of riparian vegetation to agricultural and urban land uses resulted in the degradation of stream habitats and a reduction of fish diversity. The use of multiple spatial scales allowed for the assessment of different portions of the riparian ecosystem. The land use in the largest spatial scale tended to have the strongest link with stream biotic integrity.

13. **Roy, A. H., A. D. Rosemond, M. J. Paul, D. S. Leigh and J. B. Wallace (2003). Stream macroinvertebrate response to catchment urbanisation (Georgia, USA). *Freshwater Biology* 48(2): 329-346.**

Keywords: anthropogenic disturbance; biotic indices; land cover change; macroinvertebrates; streams; urbanization; water quality

Background/Purpose: This study examined the effects of urbanization on water quality and biotic integrity in thirty small steams in the Etowah River basin in north central Georgia. The area has had a long history of agricultural land use and has recently undergone increased urbanization from the Atlanta area. The goals of this study were to identify factors (i.e. water chemistry, habitat types) that were affected by land cover and to examine the relationships between macroinvertebrate assemblage characteristics and watershed land cover. A further aspect of the study focused on an evaluation of the role of drainage size on land use impact analysis.

Methods: At each of the sites, macroinvertebrate samples were collected from various locations such as riffles, pools, and the streambank, within each reach of the selected waterways. The benthic index of biotic integrity (B-IBI) and the invertebrate community index (ICI) values from each site were compared following Ohio EPA methods. Sediment was also analyzed for various characteristics including benthic organic matter, coarse particulate organic matter, dry mass, and algal biomass. Conventional water quality parameters and contaminants were measured monthly for a year during base flow conditions. Stream morphology of each site was mapped. The type of land cover/use was assessed in each catchment from satellite images based on eight land use categories. Correlation analyses and principle component analysis were used to identify uncorrelated variables. Multiple regression analyses were used to identify relationships between macroinvertebrate indices, water quality and land use/cover. The catchment area was placed into one of three size classes (15, 50 and 100 km^2 ± 25%).
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Results: Increased land cover and decreased forested land were associated with decreased biotic integrity. The percent of the riparian buffer that was forested was positively correlated with total richness and with two biotic indexes, the North Carolina biotic Index and Hilsenhoff's Family Biotic Index. Percent urban land cover was negatively correlated with these same indices. Stream biota began to change when percent urban land reached 15-20%. Different sized catchment areas did not seem to impact the results. Environmental variables were more predictive of changes in macroinvertebrate structure than land cover/use variables.

The Invertebrate Community Index was positively correlated with riffle bed sediment size, specific conductivity, and bedded sediment size variability; all of which declined as urbanization increased. Increased nitrogen concentration, conductivity, and suspended solids were identified as important chemical constituents linked to pollution-tolerant macroinvertebrate assemblages such as dipterans.

Total richness and EPT (ephemeroptera, plecoptea, and trichoptera) richness were the two metrics most strongly correlated with in-stream variables (habitat conditions).

Conclusions: Urban land cover negatively affected macroinvertebrate diversity at a threshold of 15 to 20 percent urban land use. Management strategies that reduce sediment and other nonpoint source contamination are needed to maintain healthy stream biota..

14. **Schueler, T. (1994). The Importance of Imperviousness. *Watershed Protection Techniques* 1(3): 100-111.**

Keywords: impervious area; stream quality impairment; macroinvertebrate assemblage; fish assemblage; sensitivity levels; indicators

Background/Purpose: This paper is among the first papers to describe how imperviousness affects stream quality using measures such as macroinvertebrate and fish assemblages. The goal of the article is to present a guide for understanding and limiting the effects of imperviousness on aquatic ecosystem integrity.

Significant Content:
As imperviousness within a watershed increases, the conditions and functions that aquatic ecosystems perform are compromised. The author reported that when the total impervious area (TIA) is less than 10% impervious, most functions are protected. Between 10-25% imperviousness, changes in critical stream elements, such as bank stability, canopy cover, and channel morphology, can be observed. Watersheds with more than 25% TIA are "non-supporting streams" and their pre-development state will not be manageable even with intense restoration measures. These ranges have been supported in many studies of perennial streams in temperate and maritime climates, primarily in the eastern United States, and represent the response of several biological indicators to increasing levels of watershed imperviousness.

Fish and macroinvertebrates are useful for determining the severity of stream quality degradation. The assemblage of aquatic invertebrates is an excellent indicator of stream health and is directly related to the TIA. The abundance and diversity in the fish community is also a good indicator of ecosystem health. At high levels of imperviousness, there is a decrease in the abundance and diversity of the fish community that shifts from sensitive to tolerant species. Increased amounts of runoff also result in the widening and deepening of stream channels at relatively low levels of imperviousness (10%). The water temperature and the amount of pollutants entering aquatic systems increase with imperviousness. These factors interact to influence the ability of fish and invertebrates to survive.

Conclusions: General thresholds for stream integrity impacted by urbanization were described in this article: 10% TIA or less usually does not negatively impact waterways; between 10-25%, degradation of varying degrees occurs; above 25% TIA, beneficial uses are significantly compromised. These thresholds were developed from streams in the eastern US and might not be applicable to California waterways.

15. **Stranko, S., M. Hurd and R. Klauda (2005). Applying a Large, Statewide Database to the Assessment, Stressor Diagnosis, and Restoration of Stream Fish Communities. *Environmental Monitoring and Assessment* 108(1-3): 99-121.**

Keywords: bioassessment; biological monitoring; fishes; predictions; streams; stressors; restoration

Background/Purpose: The purpose of this report was to develop a method for predicting what types of fish are likely to inhabit streams in different areas that have had no human influences, and to identify the stressors that could alter the predictive model. The authors used their predictions of natural stream conditions to develop a model of the impacts of human influences on stream ecosystems in Maryland.

Methods: The Maryland Department of Natural Resources provided a database of 1656 stream sites with varying degrees of urban influence that were sampled for fish and environmental variables. Over 800 sites were sampled from 1995 to 1997 and 761 sites were sampled from 2000 to 2002. Fish were collected, identified, and counted, and an index of biotic integrity (IBI) was calculated at each site. The water, pH, nitrogen, dissolved organic carbon, dissolved oxygen, and temperature were characterized. Physical habitat was described using five metrics: in-stream habitat, epifaunal substrate, velocity/depth diversity, pool/glide/eddy quality, and riffle quality. The land use data were derived from USGS topographic maps. From the 895 sites, the fish prediction and diagnosis model (PDM) was created to be able to predict what species of fish would be found in a particular stream, given its climactic and geomorphologic conditions. The model was applied to streams with varying degrees of urban intensity. Based on the actual composition of the fish assemblage in those streams with a high level of urban influences, the primary stressors that resulted in deviations from the predictions were identified. Ninety representative sites were chosen based on their urban intensity and fish assemblage for the data analysis. Reference sites were those that had little deviation from the predictions of the PDM.

Results: Reference sites had more predicted species than the sites that were influenced by urban stressors. Out of the 761 sites sampled from 200 to 2002, 113 received good scores, and 206 received poor scores. The rest received intermediate scores. Within those 206 sites a subsample of 90 were selected for stressor diagnosis. The most common stressor identified was impervious land cover (69 sites), followed by acidity, lack of physical habitat structure, and agricultural land use.

Conclusions: Impervious land cover was the most common stressor for fish communities in Maryland streams. The PDM can be used independently or in conjunction with IBI scores to assess and manage stream fish assemblage.

16. **Walsh, C. J., K. A. Waller, J. Gehling and R. Mac Nally (2007). Riverine invertebrate assemblages are degraded more by catchment urbanisation than by riparian deforestation. *Freshwater Biology* 52(3): 574-587.**

Keywords: biological integrity; impervious area; macroinvertebrate assemblage; riparian forest; stream habitats

Background/Purpose: It has been thought that the amount of riparian forest is strongly correlated with the macroinvertebrate assemblage. The goal was to test the effectiveness of riparian vegetation restoration as an urbanization mitigation measure for in-stream biotic health. The study site was the Yarra River near Melbourne, Australia that has seasonal patterns of high winter-spring and low summer-fall flows and a predominantly agricultural land use.

Methods: The study was designed to compare the composition of the benthos to total impervious area (TIA), riparian forest cover (RF), and canopy cover (CC). Transects were made along the lowland portion of the Yarra River near Melbourne, Australia, and 44 sites were randomly selected. Macroinvertebrates (MI) in sediment and in snags were the indicators of biotic health, and were collected in the spring and fall. Samples were pooled and counted to the 400 individual taxa. Taxon richness, mean richness, EPT (Ephemeroptera, Plecoptera, and Trichoptera) richness, and a sensitivity index were used to describe the MI assemblage. TIA was measured at the catchment scale using digital aerial orthophotography, the local scale using GIS to delineate a riparian buffer from digital aerial orthophotos, and the site scale using field surveys. Among other statistical analyses, a best-fit linear regression model was used to find the relationships between the MI composition and TIA, RF and CC.

Results: TIA was most closely correlated with all of the macroinvertebrate descriptors (autumn and spring snags and benthos species richness had $R^2>0.65$, $P<0.001$). Forest cover and canopy cover were much weaker correlates with the macroinvertebrate species richness descriptors. Some of the macroinvertebrate species that are typical of degraded urban Melbourne streams were positively correlated with total imperviousness. Hence the best fit model for total species richness was a model with riparian forest cover and total imperviousness independently impacting the aquatic ecosystem. The data also suggested that 4% total watershed imperviousness was the level at which impacts on the invertebrate assemblage were noticeable. Since Melbourne's climate is similar to that of California, the results may also be applicable to California's rivers.

Conclusions: The macroinvertebrate assemblage in aquatic systems was more closely correlated to catchment imperviousness than it is to the amount of forest cover. Imperviousness above 4% affected invertebrate assemblages.

17. **Wang, L., J. Lyons and P. Kanehl (2003). Impacts of Urban Land Cover on Trout Streams in Wisconsin and Minnesota. *Transactions of the American Fisheries Society* 132(5): 825-839.**

Keywords: biotic indicators; urban land cover; impervious area; fish assemblage

Background/Purpose: This paper examined the relationship between urban land cover and fish diversity, base flow, habitat quality, and water temperature in 33 coldwater streams in Wisconsin and

Minnesota. The goal was to understand the impacts of urban development on stream ecosystems, and to identify biotic indicators that could be used to assess stream quality.

Methods: Thirty-nine sites in the 33 streams were chosen to represent a gradient of agricultural and urban land use. The length of each site was approximately 35 times the mean stream width, ranging from 103 to 272 m. The sites were electrofished and the fish assemblage was quantified using an index of biotic integrity (IBI), species distributions, total catch, and the number of species and catch per 100 m. These variables were calculated for all fish, all trout, coldwater, coolwater, and eurythermal fish. The physical and habitat characteristics of each site were recorded within a day of the fish sampling and included the lengths of riffles, pools, and runs; bottom substrates; cover for fish; bank conditions; riparian vegetation; and land cover. The watershed cover by impervious surfaces was estimated for the watershed as a whole and for streamside buffers within 30 meters upstream of the study area. Connected impervious area was calculated using ARC/VIEW and orthophotography counting only streets, sidewalks, parking lots, and rooftops with common connections.

Results: Nine fish variables were compared with the land use variables: cold water index of biotic integrity, catch per 100 m of cool- and coldwater fish species, percentage cool- and coldwater individuals, percentage tolerant individuals, percentage intolerant individuals, number of fish species, catch per 100 m for all fish, catch per 100 m for trout, and the percentage of top carnivore individuals. The percentage of the connected imperviousness was significantly correlated with eight of the nine fish variables. The percent of urban land cover in the watersheds was correlated with six of the same nine variables. Both imperviousness and urban land cover were negatively correlated with IBI score, catch and percentage of cool and coldwater fish, percent intolerants and top carnivores, and catch of trout. They were positively correlated with the percent of tolerant species and the number of species. Total species richness and EPT richness, among other parameters, were impacted significantly between 6 and 11 % total imperviousness. Connected imperviousness was significantly correlated with adjusted base flow and maximum daily mean water temperature; hence at high levels of imperviousness, most of the species present were eurythermal species. Using a linear regression model, the authors found that a 1% increase in connected imperviousness was associated with a 0.25 °C increase in water temperature.

Correlation coefficients for connected imperviousness and urban land cover

Fish variable	Connected imperviousness	Urban land
Cold water index of biotic integrity	-0.64	-0.59
Catch per 100 m cool and coldwater fish	-0.62	-0.60
Percentage cool and coldwater individuals	-0.60	-0.60
Percentage tolerant individuals	0.33	
Percentage intolerant individuals	-0.54	-0.52
Number of fish species	0.32	
Catch per 100 m all fish		
Catch per 100 m trout	-0.55	-0.44

Conclusions: There was a strong negative relationship between watershed imperviousness and the quality of fish assemblages in Wisconsin and Minnesota coldwater streams.

18. **Wang, L. Z., J. Lyons and P. Kanehl (2001). Impacts of urbanization on stream habitat and fish across multiple spatial scales. *Environmental Management* 28(2): 255-266.**

Keywords: urbanization; spatial analysis of land cover; imperviousness; habitat; fish community; base flow

Purpose/Background: The purpose of this study was to examine the relationship between several urban land use types, including landscape imperviousness, and a variety of ecological parameters and to assess the spatial distribution of impervious cover (IC) and its effect on stream health. The parameters or endpoints examined include fish density, species richness, index of biotic integrity (IBI), the Shannon diversity index, bank erosion, base flow, habitat score, population of pollution-tolerant fish and the total number of fish.

Methods: The analysis was performed in a relatively small area in southeastern Wisconsin. It consisted of 47 small watersheds with sites chosen to minimize the differences in stream size, slope, soil type, and natural biological characteristics, while maximizing the variation in the amount of urbanization. Land use data was collected at each sampling site and within a 50 meter wide region upstream from the site, and within the 100 meters surrounding the sampling site. Watershed imperviousness was determined using an existing database from the Southeastern Wisconsin Regional Planning Commission that was overlayed with topographic maps and analyzed with ARC/INFO. The land use, fish habitat, and fish community data were analyzed to identify correlations between the parameters.

Results: Connected imperviousness was negatively correlated with the number of fish species (r^2=0.55) and the index of biotic integrity (r^2=0.32), while it was positively correlated with stream bank erosion (r^2=0.27). The aerial extent of highways, streets, parking lots, commercial, and government land use categories had a high negative correlation with the selected indicators of aquatic life. The authors developed models explaining the effect of connected imperviousness on the abundance of fish, IBI, and adjusted base flow. They noted that there was a sharp decline in all three parameters between 8-12% connected imperviousness. Imperviousness below 8% did not seem to impact the system, while imperviousness above 12% had a large effect on these parameters. Values between 8 and 12% showed consistently decreasing values for all three parameters. They found that when IC occurred close to the waterway that the aquatic life impacts were greater than in those areas where impervious areas were farther away from the water.

Conclusions: Imperviousness is a good indicator of urban impacts on three important parameters: the number of fish species, IBI, and adjusted base flow. The threshold value for impacts was between 8-

12% connected imperviousness. Imperviousness upstream of the sampling sites or within the riparian buffer had an increased effect on stream health compared to IC farther from the waterway.

19. **Weber, D. and R. Bannerman (2004). Relationships between Impervious Surfaces within a Watershed and Measures of Reproduction in Fathead Minnows (*Pimephales promelas*). *Hydrobiologia* 525(1-3): 215-228.**

Keywords: fish; impervious surfaces; land use patterns; reproduction; storm water; urban streams; watersheds

Background/Purpose: This study examined the impact of urbanization on the reproductive success of the fathead minnow (*Pimephales promelas*) in five small streams in the Milwaukee area in order to identify critical measures of reproductive success that could explain some of the mechanisms involved in the loss of fish populations in urban streams.

Methods: Five watersheds were classified as low (<10% impervious cover (IC)), intermediate (15-35% IC), or high (65-90%) impact. The IC was calculated using ten land use categories, with data provided by the Southeastern Wisconsin Regional Planning Commission. Mobile field stations were set up to contain twelve mating pairs of fathead minnow that allowed for control of the temperature and ration size. The mating pairs were placed in cages inside of the stream that each contained four mating pairs separated by netting. Their reproductive characteristics and behavior, including male nip-chase behavior (a behavior intended to initiate mating), secondary sexual characteristics, egg production, and time spent in the nest, were closely monitored and compared with land use data.

Results: The time spent in the nest and egg care activities were significantly different between fish residing in the different impact categories. There was significantly more parental care in the low impact streams than the intermediate and high impact streams. Imperviousness was negatively correlated with male nip-chasing activity, male secondary sexual development, and average daily egg count. The data suggested that reproductive development and success of the fathead minnow was lower in streams with high levels of impervious area. Only three mating pairs of fishes produced eggs in the most highly developed watershed, and they each spawned only once. In the intermediate and low impact sites, a minimum of 10 mating pairs produced eggs and they spawned repeatedly, the normal spawning pattern in fathead minnows. The authors speculated that endocrine disrupting chemicals, which were not measured in the waterways, might have been responsible for the apparent lack of male behavior among the fish in high impact areas.

Conclusions: The reproductive behavior, parental care, egg production, and development of fathead minnows were negatively affected when watershed imperviousness exceeded 15%. The authors speculated that the presence of endocrine disruptors might have been responsible for the altered reproductive behavior.

20. **White, M. and K. Grier (2006). The Effects of Watershed Urbanization on the Stream Hydrology and Riparian Vegetation of Los Peñasquitos Creek, California. *Landscape and Urban Planning* 74: 125-138.**

Keywords: urbanization; stream; watershed; riparian vegetation; hydrology; runoff; California

Background/Purpose: This paper examined the effects of urbanization on riparian vegetation and hydrological changes in Los Peñasquitos Creek, located in San Diego County. The two main objectives of the study were to a) quantify the changes in the urban land use and the hydrograph, and b) identify associated changes in the riparian vegetation.

Methods: The land use was determined using aerial photographs from 1928 to 2000 and historic land use maps from the California Department of Water Resources. Flow data were obtained from the USGS. Using these values and the precipitation data from the Western Regional Climate Center, the annual rainfall and runoff for the entire water year and for the dry season alone were determined. Flood recurrence estimates were calculated based on the flood and flow data from 1965 to 2000. The flood recurrence intervals were estimated fro three time intervals in order to compare past and present flood frequency and magnitude. The distribution and density of the riparian vegetation were estimated based on the aerial photos for two reaches of the creek from 1928 to 2000.

Results: From 1966 to 2000 urbanization increased from 9% to 37%. Annual minimum and median flows increased significantly from 1973 to 2000, as runoff increased by about 4% per year. Floods with return intervals greater than five years increased significantly in magnitude from 1965 to 2000. The patterns observed in the riparian community were not clear since there were no historical data that documented past abundance and distribution of plant species. The aerial photography showed an increase in the total area of the riparian forest. The total area increased by 164% at one site and by 71% at another, although the riparian community shifted from a mixture of many different trees to a community dominated by willows.

Conclusions: The increase in urbanization in the Los Peñasquitos Creek watershed has resulted in increased flow and dry season runoff, increases in flood magnitude, and a shift toward willow-dominated riparian vegetation.

II. Impacts of Imperviousness on Chemical Conditions

21. Hatt, B. E., T. D. Fletcher, C. J. Walsh and S. L. Taylor (2004). The influence of urban density and drainage infrastructure on the concentrations and loads of pollutants in small streams. *Environmental Management* 34(1): 112-124.

Keywords: urbanization; stormwater runoff; impervious area; drainage connection; catchment; water quality

Background/Purpose: The authors examined several chemical endpoints to evaluate their hypothesis that drainage connection (the percent of all impervious surfaces that are directly connected to waterways via pipes or lined channels) might be a more suitable indicator of risks to the aquatic ecosystem than total impervious area.

Methods: Fifteen first- or second-order stream sites of primarily urban and forested land uses were chosen near Melbourne, Australia. Impervious areas (IA) were mapped using digital road data, local building infrastructure data, and orthorectified aerial photographs. The connectivity of the IA was estimated based on proximity to stormwater drains. Water quality data were collected every two weeks from September 2001 to November 2002; additional samples were taken during peak flow events. The data set was analyzed using multiple regression analysis to determine the relationship between base flow and chemical concentrations so that the chemical loads could be directly compared with impervious area, drainage connection, and other land use variables.

Results: Impervious area was positively correlated with water temperature (R=0.63), conductivity (R=0.77), and concentrations of dissolved organic carbon, (R=0.77), dissolved phosphorus (R=0.48), total phosphorus (R=0.37), and ammonium (NH_4^+) (R=0.66). Percent drainage connection was more closely correlated with several water quality endpoints. Percent drainage connection was positively correlated with temperature (R=0.71), conductivity (R=0.91), and concentrations of dissolved organic carbon, (R=0.77), dissolved phosphorus (R=0.71), total phosphorus (R=0.55), and ammonium (NH_4^+) (R=0.71). The correlations between water quality variables and drainage connection were significant for two more base flow water quality parameters and three more storm event parameters than impervious area. This indicates, at least for low to moderate levels of imperviousness, directly connected impervious areas are better indicators of water quality conditions that total impervious area.

Conclusions: Percent drainage connection, also referred to as effective impervious area, was more strongly correlated to some water quality parameters than total impervious cover. The authors recommend widespread application of Low Impact Development across basins for reduction in pollutant concentrations and loads.

22. **Wollheim, W., B. Pellerin, C. Voeroesmarty and C. Hopkinson (2005). Nitrogen Retention in Urbanizing Headwater Catchments. *Ecosystems* 8(8): 871-884.**

Keywords: watershed; nitrogen retention; nitrogen loading; location: MA

Background/Purpose: This study examined the impacts of imperviousness in a watershed on nitrogen retention, stormwater runoff, and nitrogen loading in two headwater catchments with contrasting land use (urban vs. forested).

Methods: Runoff volumes and nitrogen exports during a wet and a dry year from two catchments in northeastern Massachusetts with different land use were studied. The Sawmill Brook watershed had about 25% impervious cover (IC) while the Cart Creek watershed was primarily forest and wetland, contained a major interstate, and had about 8% IC. Several other catchments were studied less intensively in an effort to characterize mean annual concentrations of dissolved inorganic nitrogen (DIN). Impervious areas were calculated for six land use types: residential, agricultural/open field, industrial/commercial, forest, wetlands, and water using data defined by MASSGIS, a database maintained by the state of Massachusetts along with coefficients provided by NEMO, (the Non-Point Source Education for Municipal Officials program). Nitrogen loading from atmospheric deposition, septic systems, and fertilizer applications was assessed by measuring various forms of nitrogen in water samples collected every two weeks. The authors also assessed whether impervious surfaces control nitrogen retention in aquatic ecosystems. The annual and daily runoff was calculated using measurements of stream depth, discharge rate, and precipitation volume. Water samples were collected at the discharge monitoring sites. Automated samples were collected every two weeks, while grab samples were taken monthly. From those samples, total dissolved nitrogen (TDN), dissolved inorganic nitrogen (DIN), and dissolved organic nitrogen (DON) were determined for a dry and a wet year. High and a low nitrogen loading estimates were calculated based on estimated per capita loading rates for comparison with nitrogen retention and concentrations.

Results: The annual runoff volume and dissolved inorganic nitrogen were higher in the urban catchment than in the forested catchment, due to the higher percent of IC. The dissolved organic nitrogen concentration was slightly higher in the dry year for the forested watershed, but in the wet year there was no significant difference between the two watersheds. In the forested watershed, the main constituent of the inorganic nitrogen was NO_3 whereas in the urbanized watershed, it was NH_4. The ability of the systems to maintain relatively stable nitrogen levels declined with urbanization, and small changes in retention resulted in dramatic increases in nitrogen concentration. Increased IC resulted in increases in TDN and DIN in the waterway. Nitrogen loading was greatest at about 10% IC. As more and more land is covered with hardscape, nitrogen from septic systems declines, fertilizer applications decrease, leaving atmospheric deposition as the sole source of loading.

Conclusions: In response to urbanization, runoff and nitrogen loading increased, causing a major increase in the nitrogen exports. Nitrogen loading is highest at modest levels of impervious cover.

III. Impacts of Imperviousness on Physical Conditions

23. Coleman, D., C. MacRae and E. D. Stein (2005). Effect of Increases in Peak Flows and Imperviousness on the Morphology of Southern California Streams. *Southern California Coastal Water Research Project* Technical Report 450.

Keywords: impervious area; hydrology; ephemeral streams

Background/Purpose: This paper investigated the effects of imperviousness in 11 southern California streams that are either currently or historically ephemeral. The study addressed the impacts of imperviousness on channel morphology, bed material, bank material, and stream flow, and other physical characteristics of each waterway. The purpose was to present information that would ultimately lead to the development of sustainable management practices in the region.

Methods: The study area included watersheds from a region that spans six counties from Ventura County to San Diego County. Geomorphologic changes were analyzed and compared to historical data in order to determine the changes that occurred in the stream as imperviousness increased in the surrounding areas. The channels were classified on three levels: watershed characteristics, stream channel characteristics, and stream channel resistance. The total impervious area (TIA) was calculated from aerial photographs from 1949 to 1983, land use maps from 1990, 1993, and 2001, and satellite imagery. Coefficients for the major land use categories (roads, residential, etc.) were provided by the agencies that developed them.

Results: Sites ranged from 0.15% to 26.7% TIA. The changes that occurred in channels in response to increased dominant discharge due to increased impervious surfaces began with stream widening and eventually proceeded towards deepening of the channel. Additionally, the response of these ephemeral streams was more dramatic than streams in other parts of the nation. The threshold value at which impacts begin to be significant for stream channel impairment was approximately 2-3% total impervious area. Since this value was lower than the suggested threshold value from studies in other parts of the country (approximately 10% impervious area), the authors suggested that semi-arid ephemeral streams are much more sensitive to changes impervious cover.

Conclusions: Ephemeral southern California streams were very sensitive to imperviousness, and followed a predictable pattern of physical degradation. Stream channel erosion proceeded from widening to deepening of the channel and was noticeable around 2-3% imperviousness.

24. Denault, C., R. Millar and B. Lence (2006). Assessment of possible impacts of climate change in an urban catchment. *Journal of the American Water Resources Association* 42(3): 685-697.

Keywords: climate change; runoff; urban streams; rainfall intensity

Background/Purpose: This paper examined the impacts of climate change on streams that were already showing the impacts of urbanization. Climate change has generally been analyzed from a large scale or global perspective. Since there had been so much recent attention devoted to assessing the impacts of imperviousness on stream ecosystems, the authors investigated whether the predicted increases in runoff associated with urbanization would change if the observed climate change patterns were to continue.

Methods: Precipitation data, collected at the Vancouver Airport between 1940 and 2000, were analyzed to reveal trends in precipitation that might be associated with climate change. Estimates of future climate change scenarios were developed, and the possible alternative causes of the change in precipitation were assessed. Maximum rainfall intensities (for 5 minute to 24 hour events) were compared for rainfall between 1960 and 1990; rainfall from 1975 was used as a baseline for climatic predictions. Rainfall estimates were predicted for 2020 and 2050, based on past trends. In order to combine climatic predictions with forecasted changes in impervious area, the normalized channel stability index (NCSI) and equivalent percent total impervious area (TIA) were calculated. NCSI is an index that compares a difference in the flow between a 2- and a 10-year storm, pre- and post-development. It was calculated using the following formula:

$$NCSI = \frac{Q_{2\,post} - Q_{2\,pre}}{Q_{10\,pre} - Q_{2\,pre}}$$

where Q is flow rate pre- and post-development for 2- and 10-year floods. Equivalent % TIA represents the impervious area that would be expected to generate future predicted peak runoff under the predicted potential climate change patterns with baseline (1975) rainfall intensities.

Results: There was a 20% increase in annual rainfall between 1940 until 2000. The rainfall intensity for 5-minute, 15-minute, 30-minute, 1-hour and 2-hour peak rainfall events also increased significantly from 1960 to 1990. There was a slight decrease in the 24 hour peak rainfall over the thirty-year period analyzed. The predicted effects of climate change on rainfall intensity were very similar to the effects of imperviousness on runoff, ie., amplification of the existing runoff problems. With the 1975 rainfall intensity, a two-year peak runoff event at the level predicted for 2020 rainfall would be equivalent to that which would be associated with 87 % TIA. A similar storm event with 2050 rainfall would have the effects equivalent of 100 % TIA. The predicted NCSI values were 1.1 in 2020 and 1.9 in 2050. NCSI values of 1 are the maximum known to support salmonid populations. This means that under the current climate change predictions, Vancouver streams would be seriously degraded and unable to support salmonid populations by 2020 even with no additional urban development.

Conclusions: The predicted effects of climate change on Vancouver streams suggest that there will be increased runoff due to probable increases in total and peak rainfall. By 2020, the amount of runoff is predicted to be equivalent to the runoff associated with a watershed that is 87% impervious. Impervious area and climate change together are likely to significantly increase peak flow and stormwater runoff volume, threatening the ability of these waterways to support aquatic life. This indicates that sthe same planning strategies that can reduce the impacts of imperviousness may also help to reduce the effects of climate change.

25. **Finkenbine, J. K., J. W. Atwater and D. S. Mavinic (2000). Stream health after urbanization. *Journal of the American Water Resources Association* 36(5): 1149-1160.**

Keywords: stream rehabilitation; fish habitat; stormwater management; urban hydrology; erosion/sedimentation

Background/Purpose: This study was designed to determine the impacts of present and historic watershed urbanization on stream conditions. The 11 streams in the Fraser River lowland region near Vancouver, British Columbia ranged from 4-77% total impervious area (TIA), and were urbanized approximately 20 years prior to the study. For many of the sites, the pressures from rapid urban development, like construction and deforestation, had subsided. Hence a major benefit of this study site is that it can be used to investigate the effects of an urban presence rather than urban growth. Additionally, the study streams are important spawning habitat for salmonids. The study examined physical stream characteristics that have the potential to impact the fish habitat.

Methods: Surveys were conducted in the dry months to understand in-stream conditions during periods of low flow. Base flow, grain size, and sediment composition were measured at each stream reach. Using the pebble counts, the D_{84} (the 84^{th} percentile particle size) of each stream was calculated. Large woody debris and bank conditions were recorded and quantified as a percentage of the total length of the reach. The percent total impervious area was calculated for each watershed using orthorectified aerial photos; details of the calculation were not provided.

Results: The data showed no significant difference in the percent of fine-grained bedded particles between the urban and rural study sites. There was a significant positive correlation between TIA and D_{84} (R^2=0.66), indicating that the urban streams, with high TIA, have larger bedded sediment than the rural streams, where TIA is low. The authors suggest that this pattern is due to increased flow and the ability of urban streams to transport larger amounts of fine grained material. Increased impervious area was also related to a decrease in summer base flow and stream velocity (R^2=0.75), which tended to result in shallower water and reduced pool volume. The loss of large woody debris (LWD) was significant when TIA exceeded 10%. In a few sites, there was a very wide, wooded riparian buffer area and LWD was found up to 20% TIA. There was no significant relationship between TIA and bank erosion, but the streams with the highest percent of bank erosion had little or no LWD and had very reduced vegetation.

Conclusions: The urban streams studied reached a new urban equilibrium around 20 years after their watersheds were urbanized, during which stream water and habitat quality improved. The authors suggest that these streams should not be restored by changing the flow, but rather restoring the large woody debris and riparian forests.

26. **Paul, M. J. and J. L. Meyer (2001). Streams in the Urban Landscape. *Annual Review of Ecology and Systematics* 32: 333-365.**

Keywords: impervious surface cover; hydrology; fluvial geomorphology; contaminants; biological assessment; review article.

Purpose: This paper synthesizes information dating back to 1960.on the chemical, physical, and biological stressors associated with urbanization on the ecology of streams. One of the main changes caused by urbanization is an increase in imperviousness of the landscape, which dramatically increases the amount of runoff into urban streams. This review article includes a lengthy citation list.

Significant content:

The physical effects of imperviousness include a shorter lag time for runoff to reach waterways, resulting in changes in the hydrograph. Peak flows occur more quickly, known as stream flashiness, and are larger than in non-urban streams. There is also a loss of groundwater recharge. Increasing imperviousness from a natural condition up to 20% and 75% resulted in two-fold and five-fold increase respectively, in the volume of stormwater runoff.

The change in water flow from the land into the waterway has implications for the biology, chemistry, and physical characteristics of urban streams. The imperviousness of the upland areas causes runoff volume and rate to increase, carrying with it high quantity of sediment. The physical structure of the waterway changes to accommodate the pressure caused by increased volume in stormwater runoff. The banks of the waterway erode causing the stream to become wider and deeper, and resulting in the displacement sediment. Bank erosion not only contributes to incision, a widening and deepening of the channel, but also causes a loss of riparian cover and increases sedimentation. These changes cause increased turbidity and changes in sediment characteristics in the streambed. Bridges and culverts associated with increased road density alter in-stream flows, causing abrupt changes in stream depth which can act as barriers to fish passage.

Chemical contaminants in the runoff include phosphorus, heavy metals, nutrients, petroleum products, and pesticides. There is an increase in biological oxygen demand from the plants and algae stimulated by nutrients in the runoff. This in turn reduces dissolved oxygen available for invertebrates, fish, and other aquatic life. Frequently there is an increase in the density of bacteria in urban streams due to wastewater treatment plant and combined sewer overflow effluent. The overall effects of increased imperviousness on algal populations have not been well studied, but it is clear that increased nutrient concentrations from urban runoff increase the algal biomass. This increase is limited by increased turbidity and changes in the substrate that limits their ability to find attachment spots. Invertebrate diversity decreases in response to toxins, temperature change, and siltation, while the abundance of invertebrates increases in response to nutrients. The effects of urbanization on fish communities include the loss of sensitive species and diversity, the destruction of habitat, and the colonization by less sensitive species

Conclusions: Urbanization affects the physical, chemical, and biological conditions in urban streams, changing the ecology of the entire aquatic ecosystem.

27. **Trimble, S. (1997). Contribution of Stream Channel Erosion to Sediment Yield from an Urbanizing Watershed. *Science* 278: 1442-1444.**

Keywords: erosion/sedimentation; impervious area; urban hydrology

Background/Purpose: This was a study of channel changes in the San Diego Creek watershed in Orange County, California that identified channel erosion as the primary source of in-stream sediment. Sedimentation is a particular concern in this watershed because the creek drains into Newport Bay, which has important estuarine wildlife habitat that has been adversely affected by sediment loading from San Diego Creek. Previous studies suggested that the source of this sediment was primarily agricultural.

Methods: One hundred ninety-six channel cross sectional profiles were monitored starting in 1983, and sediment loads were concurrently measured downstream. After 10 years of monitoring, 108 usable profiles remained for the final analysis. Sediment loads were measured at downstream sampling locations, and a sediment budget was constructed to determine the proportion of sediment that came from erosion of the stream banks.

Results: The net average rate of channel erosion from 1983 to 1993 was determined to be 106×10^3 Mg/year. This amount of sediment accounted for about two-thirds of the total sediment loading measured downstream from the measurement sites. The analysis was the basis for concluding that the cause of sediment loading was bank erosion as a result of greater magnitudes and frequencies of peak stream flows in response to increasing imperviousness.

Conclusions: Sedimentation in urban watersheds is associated primarily with stream bank erosion, not with soil and other materials from upland areas. The likely cause of the erosion is runoff due to impervious surfaces.

IV. Overall Impacts of Imperviousness on the Aquatic Ecosytem

28. Center for Watershed Protection (2003). Impacts of Impervious Cover on Aquatic Systems. *Watershed Protection Research Monograph No. 1*.

Keywords: impervious cover model; hydrology; water quality; biological indicators; physical habitat; general trends

Purpose: This monograph is a comprehensive review of the effects of urbanization on streams and other aquatic ecosystems. It addresses the reasons why impervious cover is significant and reviews the use of the impervious cover model (ICM). The primary goal of the paper is to explain the impacts of impervious cover on hydrologic, physical, water quality, and biological endpoints based on the results of research studies.

Significant Content: The authors assesses the strengths and weakness of the thresholds relating impervious cover to stream habitat quality. They examine the impacts of imperviousness on hydrologic, physical, water quality, and biological endpoints. Some of the hydrologic effects of increasing imperviousness include increases in runoff volume, peak discharge rate, and bank-full flow, and decreased base flow. Physical responses to watershed imperviousness involve increased water temperature, changes in channel geometry, stream channel network, and stream habitat features including bank stability, embeddedness, large woody debris, and barriers to fish migration. Water quality endpoints examined include sediment and suspended solids, nutrients, trace metals, hydrocarbons, bacteria and other pathogens, organic carbon, pesticides, deicers, and MTBE (a fuel additive that can have harm wildlife and drinking water quality). These endpoints were analyzed based on their sources, impacts, and concentrations in urbanized aquatic ecosystems.

The discussion of the biological impacts of imperviousness evaluates the usefulness of various biological endpoints as indicators of ecosystem quality. The endpoints assessed were the diversities of aquatic insects, fish, amphibians, wetland species, and freshwater mussels. The authors discussed the effects of possible interactions between these endpoints, and how they can be used to better understand the impacts of imperviousness. With increasing watershed imperviousness, the % forested area, biotic integrity, species richness, number of sensitive species, flood recurrence interval, and base-flow all decrease , while nutrient loading and peak flows increase. Many of the biological and stream hydrology endpoints are affected very predictably by imperviousness, and can be reliable indicators of stream quality.

As imperviousness increases, high levels of riparian cover can partially offset the degradation and provides habitat for fish and wildlife. Several studies have shown that adverse effects on the fish and insect communities occurs at approximately 10 - 15 % impervious area, and that streams become seriously degraded, or "non-supporting" at about 25% imperviousness. The studies that contributed to the development of the impervious cover model have only been verified in some regions of the U.S., including the mid-Atlantic, northeast, southeast, upper Midwest, and the Pacific Northwest. Studies in other parts of the nation have shown degradation occurring at lower levels of impervious cover. The limitation of the ICM is that a single set of thresholds may not accurately represent the behavior of all aquatic ecosystems. Still, greater amounts of imperviousness are associated with adverse effects on watersheds. Despite its limitations, the ICM is very useful for developing strategies to limit the impacts of urbanization on streams by reducing the percent total impervious area to below the threshold. There is a distinct lack of information regarding the effects of imperviousness on community structure and on populations that rely more indirectly on the stream than fish and benthic invertebrates.

Conclusions: Imperviousness affects the hydrologic, physical, chemical, and biological aspects of stream health. In general, once imperviousness reaches 10% the stream begins to widen and deepen and valuable habitat is lost. At about 25% imperviousness the ecosystem is degraded to the point where it is no longer suitable for supporting aquatic life. There is a need for more research that analyzes the impacts of impervious cover on stream and riparian ecosystems and interactions.

29. Impervious Area Analysis. *SWRCB Contract # 05-309-550-0* (In Progress)

Keywords: impervious area; drainage connection; California; management

Background/Purpose: This paper is a review of the literature on impervious area (IA) and an analysis of how IA can be used locally as a tool for land use decision makers. The goals of the paper are to evaluate the usefulness of IA as an indicator of hydromodification, to explain the methods for determining IA, and to examine the problems related to the calculation and use of IA. The paper also provides local examples of the applied use of IA, with an assessment of its use in the Critical Coastal Areas program.

Significant Content: Total impervious area (TIA) has been used nationwide as a measure of urbanization and potential risks to the aquatic ecosystem. A large body of literature supports the idea that stream ecosystems are first impacted at about 10% IA and are degraded by about 25% IA. These values might not apply to streams in California. The use of IA as an indicator of ecosystem degradation due to human impacts is often useful, but there are many problems with its use and calculation that must be dealt with in order to make this information more useful. Most agencies use TIA because it is much easier to calculate than connected or effective impervious area (EIA). Some effort has been made to develop a way to determine EIA, however the results have not been verified in the field and were calculated based on whether a hard surface was connected to another one, without taking account surfaces that may be partially connected. The results of these problems are that calculations of EIA are often as inaccurate as calculations of TIA.

Only one method of calculating TIA has been used in California, and the precision of this method is still being tested. It is a major goal of the State to be able to provide a set of impervious surface coefficients that can be applied statewide, however local agencies define their land use categories differently.

Often even categories with the same name do not represent similar land use. Impervious surface analysis was performed in the Watsonville Sloughs, Sonoma Creek, and Fitzgerald Marine Reserve watersheds with some success, using coefficients developed for the Sacramento region. Results varied based on the use of current and predicted land use. For example, in the Sonoma Creek watershed, the Sonoma County Water Agency included a stipulation in its Stormwater Management plan that construction sites that create impervious areas greater than one acre would be required to develop stormwater mitigation structures. However, it did not address the effects of impervious areas created by many projects that are smaller than one acre. If impervious estimates are used responsibly in urban planning to predict impairment, then efforts to protect or restore beneficial uses of waterways need to be integrated with land development plans.

Conclusions: Although IA is a useful indicator of aquatic habitat degradation, it still has limited utility in California because the impacts of increasing urbanization on IA are variable, there are many methods of determining IA, and the impacts of imperviousness vary between systems. Effective impervious area has the potential to be a much better indicator, however it is more difficult to calculate and the methods for doing so are not standardized.

30. **Allan, J. D. (2004). Landscapes and Riverscapes: The Influence of Land Use on Stream Ecosystems. *Annual Review of Ecology Evolution and Systematics* 35: 257-284.**

Keywords: catchment; disturbance; stressor response; stream health; river

Purpose: This paper is a review of the literature on the effects of land use on stream and river ecosystems and landscapes. The author discusses the impact of scale on stream health and land use spatial scales, as well as the discontinuities in the literature regarding the threshold response to imperviousness. The author also examined the effects of past land use on present conditions and how that information can shape future research and best management practices.

Significant content: The author pointed out the various aspects of stream health that have been studied and how they relate to each other. Two land use indicators that have often been used to predict stream health are impervious area and total urban land. Which of these is a better indicator of stream health depends on what types of compounds are involved in the runoff and on the region in which the study is located. When impervious area is used as an indicator, adverse effects on waterways are observed between 8-20% imperviousness. However, the relationship between imperviousness and stream health is often too complex to assign a single threshold value that can have widespread application. In order to understand the complex relationships between urban development and stream quality, it is necessary to understand how anthropogenic and natural landscape factors interact with respect to their influence on stream biota. Some of the most significant interactions include climate change, invasive species, and dams. There is a need for more research on how land use at various spatial scales impacts stream quality, and how various stages of urban development can impact watersheds differently. Based on current information, it does not seem practical to try to return waterways to what we perceive to be their historical state. A better management plan is to use landscape characteristics like geomorphology and climate patterns to determine what types of conservation and restoration measures are appropriate for a particular watershed.

Conclusions: In order to adapt appropriate management practices, we need a better understanding of the mechanisms through which land use and impervious cover impact the health of streams. We must recognize issues such as the possible impacts of climate change, dams and dam removals, and future population growth and development in order for management efforts to be effective.

31. **Brabec, E., S. Schulte and P. L. Richards (2002). Impervious surfaces and water quality: A review of current literature and its implications for watershed planning. *Journal of Planning Literature* 16(4): 499-514.**

Keywords: land use; pollutant removal; biotic integrity; stream habitats; runoff; urbanization; stormwater; drainage; mitigation

Purpose: Stream hydrology and function are dependent on climate, geology, soils, land use, and vegetation; these in turn affect flows and sediment loads. Humans can affect land use and vegetation, therefore land use planning can have significant impacts on stream health. Tools and models used by engineers to evaluate these changes are not familiar to planners. This review addresses issues related to the ways in which impervious cover (IC) can be calculated, its effects on stream health, and mitigation strategies in the context of the planning process.

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Significant Content: The authors review some key issues relevant to the analysis of impervious cover and the application of that information as an indicator of watershed health.
1. Thresholds: Much of the literature suggests that IC above 10% caused some level of degradation in waterways. A few issues emerge here: a) there is variation in what is considered degraded, b) a threshold that might be applicable in one climate or geography might not be appropriate to another region of the country, and c) thresholds for IC vary depending on the endpoint used, be it a physical, chemical, or biological metric. Typically thresholds of impacts on biological metrics are lower, 3-15% IC, than that for chemicals measurements such as contaminant concentrations, which don't typically reach levels of concern until IC is 30-50%.
2. Issues with defining the percentage of impervious cover (also known as impervious surface coefficients). The authors identified three key problems with impervious surface coefficients (ISC) that have been developed: a) land use categories are aggregated to too high a degree, thereby introducing error into the calculations; b) a failure to properly account for the contribution of roads to total imperviousness, and c) most values have been developed from East Coast data, where the land use planning style varies from the approach used in the West. This results in inaccuracy in the ISCs.
3. Failure to differentiate between total and effective impervious cover (TIA vs. EIA). Almost all analysis of IC involves the analysis of TIA, not EIA. EIA are those areas that are directly connected either by concrete or other hardscape and/or pipes. This contrasts with TIA which is the total amount of hardscape regardless of its inter-connections. The result of the failure to differentiate between TIA and EIA can lead to an overestimation of the amount of storm water runoff that enters a waterway. Since it

is very challenging to measure EIA, which usually requires knowledge of the drainage system within a community, it is rarely evaluated.

4. Mitigating effects of forest, wetlands, and buffers. Forested areas can mitigate the effects of imperviousness by increasing infiltration and reducing evaporation. The authors suggest, based on research results, a minimum of 15% forest be retained in a watershed to reduce IC impacts. Buffers, if sizable, can reduce the impacts of IC. Forested buffers also contribute woody debris and leaf litter, both essential elements of a healthy aquatic ecosystem. However, above a certain level (one study suggested 45% IC), buffers cease to protect biological integrity. Wetlands, if located in appropriate areas within the stream network, reduce the effects of IC.

5. Location of IC within a watershed. High levels of IC in the upper watershed appear to exacerbate sedimentation problems. Some research suggested local riparian vegetation was a weak correlate of stream integrity. However, distance between IC and stream channel is very important, especially in areas where runoff is not piped into streams.

6. A brief review of a variety of best management practices is also contained in this article

Conclusions: It is well established that increased amounts of impervious cover degrade stream integrity. However, the exact threshold at which effects are evident, the role of riparian buffers, forests, and wetlands, the sometimes inaccurate methods by which IC is measured all contribute to uncertainty regarding the exact effects of any level of imperviousness.

32. **Morse, C. C., A. D. Huryn and C. Cronan (2003). Impervious surface area as a predictor of the effects of urbanization on stream insect communities in Maine, USA. *Environmental Monitoring and Assessment* 89(1): 95-127.**

Keywords: bioassessment; biomonitoring; urban land use; urban streams; stream insects

Background/Purpose: This paper examined the impacts of urbanization, represented by percent total impervious area (TIA), on streams in Maine. The goals of the study were twofold: to determine if a relationship existed between impervious area and stream quality (chemical, physical and biological) and to determine the threshold at which adverse impacts occur.

Methods: The sites were chosen from streams in four urban areas in Maine. The site selection requirements included the presence of cobble riffles, specified average stream width and depth, and a gradient less than or equal to 4%. The TIA was determined using aerial photographs taken from 1991 to 1998. An impervious surface factor was created from direct field measurements and used in the calculation of TIA. The impervious surface factors that were determined were considerably lower than the coefficients that have been used in other studies. The qualitative habitat index (QHI) and the stream reach inventory and channel stability index (SRICSI) were determined based on various habitat variables to represent the overall quality and stability of habitats for fish and insects. The water chemistry variables were measured during summer, fall, and spring. The insect community was sampled during the spring and the fall from randomly selected locations at each site, and identified to the lowest possible taxonomic level. Species density, number of unique species, total richness, and an Ephemeroptera, Plecoptera, Trichoptera (EPT) richness index were calculated for each site.

Results: The total richness and the EPT richness of the insect community both decreased significantly at 6% impervious area. Between 6% and 27% imperviousness, there were no measurable impacts on the insect community. As TIA increased, the riparian width decreased and bank erosion increased. QHI values were negatively related to TIA (r^2=0.40), while SRICSI values were positively related to TIA (r^2=0.29). There was an inverse exponential relationship between the D_{50} (median particle size) and TIA, which means that the particle size in urban streams was smaller than the particle size in non-urbanized streams. Specific conductance and nitrate concentration increased with impervious area, while dissolved oxygen concentrations decreased.

Conclusions: The species richness of insects in Maine streams was impacted by urbanization at where total impervious area exceeded 6%.

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