REDMOND PAIRED WATERSHED STUDY

MONITORING LITERATURE REVIEW SUMMARY REPORT

Prepared for
City of Redmond

Public Works Natural Resources Division

Prepared by
Herrera Environmental Consultants, Inc.

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Prepared for
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Public Works Natural Resources Division
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April 23, 2015

CONTENTS

APPENDICES

TABLES

1. INTRODUCTION

The Redmond Paired Watershed Study (RPWS) is one of four effectiveness monitoring studies that was selected for implementation starting in 2014 for the Regional Stormwater Monitoring Program (RSMP) for Puget Sound. The goal of effectiveness monitoring under the RSMP is to provide widely applicable information for improving stormwater management in the region. This monitoring is being funded by contributions from Municipal Stormwater National Pollutant Discharge Elimination System (NPDES) permittees to a Pooled Stormwater Resources Fund. Selection of the RPWS for implementation under the RSMP was made based on a monitoring proposal that was presented to permittee representatives at workshops that were held on March 20, 2014 and May 6, 2014. The specific study question to be addressed through the RPWS is as follows:

> *How effective are watershed rehabilitation efforts at improving receiving water conditions at the watershed scale?*

In this context, rehabilitation efforts could include any of the following practices:

- Stormwater retrofits in upland areas that would include facilities for on-site stormwater management (e.g., low impact development [LID] practices), runoff treatment, and flow control.
- Riparian and in-stream habitat improvements.
- Programmatic practices for stormwater management.

To address this study question, the monitoring proposal indicated improvements in receiving water conditions would be evaluated based on routine and continuous measurements of various hydrologic, chemical, physical habitat, and biological indicators. Furthermore, the study would use a "paired watershed" experimental design that would involve the collection of these measurements in seven different watersheds categorized as follows:

- Three "Application" watersheds that are moderately impacted by urbanization and prioritized for rehabilitation efforts.
- Two "Reference" watersheds that are relatively pristine and not subject to rehabilitation efforts.
- Two "Control" watersheds that are heavily impacted by urbanization and also not subject to rehabilitation efforts.

To further refine the experimental design from the monitoring proposal for the RPWS, Herrera Environmental Consultants (Herrera) was retained to conduct a literature review to obtain information on past studies that have been implemented to achieve similar objectives. The specific goal of this literature review was to identify indicators from these studies that appear useful for quantifying long-term changes in receiving water conditions in response to increased watershed urbanization and/or the implementation of stormwater controls.

This document summarizes the results from this literature review. It begins with a short description of the methods used for the review. Detailed descriptions of the most relevant studies are then presented followed by broader synthesis of information on the effectiveness of specific indicators for receiving water conditions. Conclusions and recommendations for improving the experimental design of the RPWS are then presented in a final section.

2. METHODS

This literature review involved searches of the following databases to identify published journals and proceedings for studies with similar objectives to the RPWS: Web of Science, ScienceDirect, and ProQuest. In addition, Google searches were also performed to identify these types of studies in the gray literature. When performing these searches, the following broad categories of studies were specifically sought using different combinations of search terms:

- Studies to quantify trends (5 years +) in receiving water conditions following implementation of stormwater controls and/or habitat improvements.
- Paired watershed studies looking at the effectiveness of stormwater controls for improving receiving water conditions.
- Studies to quantify changes in receiving water conditions in response to increased watershed urbanization.
- General references on sampling strategies/methodologies for detecting change in receiving water conditions.

These searches yielded 123 study references which are presented as an annotated bibliography in Appendix A of this report. Each study was then reviewed in detail to identify a subset of 11 priority studies that were found to be the most relevant for informing the experimental design of the RPWS. Detailed descriptions of these studies are provided in a subsequent section of this report.

In addition, all the studies were reviewed to determine if they utilized specific indicators for receiving water conditions in any of the following categories: hydrologic, chemical, physical habitat, and biological. Results from this review are summarized in Appendix B. These results were subsequently used to synthesize information on the effectiveness of specific indicators in these categories for assessing change in receiving water conditions.

3. PRIORITY STUDIES

In general, a large volume of literature has been amassed documenting the effectiveness of stormwater management practices at the site and parcel scale. These studies have consistently shown beneficial effects from these practices for removing stormwater pollutants and reducing peak flows at this scale. However, relatively few studies have examined the potential benefits of these practices for improving receiving water conditions. As noted above, a subset of 11 priority studies were identified as being most relevant for informing the experimental design of the RPWS. The citations and titles for these studies are as follows:

> Ahiablame, L. M., et al. (2013) – Effectiveness of low impact development practices in two urbanized watersheds: Retrofitting with rain barrel/cistern and porous pavement
>
> Clausen, J. C. (2007) – Jordan Cove Watershed Project: Final Report
>
> DeGasperi, C.L., et al. (2009) – Linking Hydrologic Alteration to Biological Impairment in Urbanizing Streams of the Puget Lowland, Washington, USA.
>
> Dietz, M. E., et al. (2004) – Education and changes in residential nonpoint source pollution
>
> King, K. W., et al. (2008) – Validation of paired watersheds for assessing conservation practices in the Upper Big Walnut Creek watershed, Ohio
>
> Line, D. E., et al. (2012) – Effectiveness of LID for Commercial Development in North Carolina
>
> Pitt, R., et al. (2013) – Performance Results from Small- and Large-Scale System Monitoring and Modeling of Intensive Applications of Green Infrastructure In Kansas City
>
> Roy, A. H., et al. (2014) – How Much Is Enough? Minimal Responses of Water Quality and Stream Biota to Partial Retrofit Stormwater Management in a Suburban Neighborhood
>
> Selbig, W. R., et al. (2008) – A comparison of runoff quantity and quality from two small basins undergoing implementation of conventional and low-impact-development (LID) strategies: Cross Plains, Wisconsin, water years 1999–2005.
>
> Smucker, N. J. and N. E. Detenbeck (2014) – Meta-Analysis of Lost Ecosystem Attributes in Urban Streams and the Effectiveness of Out-of-Channel Management Practices
>
> Stranko, S. A., et al. (2012) – Comparing the Fish and Benthic Macroinvertebrate Diversity of Restored Urban Streams to Reference Streams

The following information is provided below for each study under separate subsections that are identified using the associated citation:

- Study Overview
- Indicators Measured, Frequency of Measurement, and Sampling Locations
- Statistical Analysis
- Results

3.1. Ahiablame, L.M., et al. (2013)

3.1.1. Study Overview

This study used modeling to simulate the performance of rain barrel/cistern and porous pavement as retrofitting technologies in two urbanized watersheds of 70 and 40km(2) near Indianapolis, Indiana. The objective of the study was to document the effectiveness of these LID practices in managing urban water at the watershed scale by simulating watershed level impacts of rainwater harvesting systems and porous pavement, on runoff, baseflow, total streamflow and pollutant loads. The study period was 19 years, which included a 9-year calibration period, and a 10-year validation period. Six scenarios consisting of the watershed existing condition, 25 percent and 50 percent implementation of rain barrel/cistern and porous pavement, and 25 percent rain barrel/cistern combined with 25 percent porous pavement were evaluated using a proposed LID modeling framework and the Long-Term Hydrologic Impact Assessment (L-THIA)-LID model. The various application levels of barrel/cistern and porous pavement resulted in a small (2 to 12 percent) reduction in runoff and pollutant loads for the two watersheds. Baseflow and associated pollutant loads increased slightly; however, overall pollutant loading was reduced.

3.1.2. Indicators Measured, Frequency of Measurement, and Sampling Locations

3.1.2.1. Hydrologic

Over the study period, daily rainfall depths for each watershed, and daily streamflow volumes were measured at the watersheds' outlets and used for model calibration and validation purposes. Total runoff was the only hydrologic indicator used.

3.1.2.2. Chemical

Simulated event mean concentrations (EMCs) and baseflow pollutant coefficients (BPCs) for total nitrogen and total phosphorus were derived from regional mean values reported by the Indiana Department of Environmental Management. No water quality sampling occurred.

3.1.3. Statistical Analysis

The L-THIA-LID model that was used is a modification of the L-THIA model (Engel and Hunter, 2009) that incorporates modeling capabilities of LID practices. The L-THIA-LID model estimates runoff using the Curve Number (CN) method from daily rainfall depth, land use, and hydrologic soil group data. To evaluate the impacts of LID practices on streamflow at the watershed scale, an empirical equation was developed for the study region to estimate baseflow from watershed characteristics based on calibration data from 18 adjacent watersheds. The model assumes that changes in runoff and baseflow under the application of LID practices would lead to changes in pollutant loads.

3.1.4. Results

Modeled results showed minimal to moderate effects of LID on runoff and pollutant loading at the levels tested. The two tested watersheds showed between a 1 and 12 percent reduction in runoff, and between a 1 and 9 percent reduction in total nitrogen and total phosphorus loads. The results also indicated that the treatments of either rain barrel/cistern, or porous pavement at the 50 percent implementation level performed better than the combination of both strategies at the 25 percent implementation level.

3.2. Clausen, J.C. (2007)

3.2.1. Study Overview

The Jordan Cove Urban Watershed Project was a ten year study that used a paired watershed approach to determine the water quantity and quality benefits of pollution prevention best management practices (BMPs) during the development of an urban subdivision. The project area was located in the town of Waterford, Connecticut. Stormwater runoff from three watersheds; control (5.5 hectares), traditional (2.0 hectares), and BMP (1.7 hectares) were monitored as part of the study. The traditional watershed was developed using “traditional” subdivision requirements. The BMP watershed was developed using a BMP approach before, during, and after construction. The runoff from these two watersheds was compared to the existing control watershed. The control and traditional watersheds had approximately 30 percent impervious surface, whereas the BMP watershed had only 22 percent impervious surface. The traditional and BMP treatment watersheds were monitored for about 1 and 3 years, respectively, before development for calibration purposes, and the control watershed was monitored for the project duration. The study also monitored the performance of specific BMPs, and resident behavioral practices.

3.2.2. Indicators Measured, Frequency of Measurement, and Sampling Locations

3.2.2.1. Hydrologic

Precipitation and flow were both monitored continuously for the study duration. Precipitation was monitored in one location and was presumed representative for all three watersheds. Flow was monitored at the terminus of each watershed. The hydrologic indicators assessed were:

- Stormflow volume
- Peak Discharge

3.2.2.2. Chemical

Water quality was sampled based on flow volume (i.e., sampled every 500 cubic feet of discharge) so the number of samples likely differed between sites. The specific number of samples from each location was not mentioned in the paper; however, sampling appeared to occur on approximately a weekly basis based on figures. Samples were analyzed for the following parameters and used to characterize concentrations and loading rates:

- Total suspended solids (TSS)
- NO3-N
- NH3-N
- Total Kjeldahl nitrogen (TKN)
- TP
- Biological oxygen demand (BOD)
- Fecal coliform bacteria
- Cu
- Pb
- Zn
- Statistical Analysis

Analysis of Variance (ANOVA) was used to test the significance of regressions for the calibration and test periods. Analysis of Covariance (ANCOVA) was used to test the differences between slopes and intercepts. Percent change in flow, concentration, and export was calculated by comparing mean predicted values from the calibration regression equations to observed values.

3.2.3. Results

In the BMP watershed, runoff was lower during the construction and post construction period than in the calibration period, 97 percent and 74 percent respectively. This result was attributed to landform changes that retained water on-site and allowed infiltration to occur after storm events. Conversely, runoff increased during and after construction in the traditional watershed by 894 percent and 102,800 percent respectively. This result was likely caused by the creation of asphalt roadway connected to a traditional curb and gutter stormwater collection system.

Water quality results were mixed relative to runoff results. In general, TSS concentrations and export increased in the BMP watershed both during and after construction. For most nitrogen species, concentrations increased in the BMP watershed during construction and remained higher than pre-construction conditions. Though nitrogen concentrations were higher, export remained stable during construction, and decreased following construction. Phosphorus concentrations and export increased in the BMP watershed during construction and remained high following construction. Concentrations of some metals within the BMP watershed increased during construction and decreased following construction. There was no net change in metals export in the BMP watershed.

In the traditional watershed, TSS concentrations and export decreased during and following construction. Most nitrogen species were unchanged before and after construction with the exception of TKN which increased. Export of all nitrogen species increased during and following construction in the traditional watershed. Phosphorus concentrations decreased during and following construction, but exports increased due to higher flow volumes. Metals concentrations remained the same in the traditional watershed during and following construction; but again, exports increased because of increased flow volumes.

3.3. DeGasperi, C.L., et al. (2009)

3.3.1. Study Overview

This study used a retrospective approach to identify hydrologic metrics with the greatest potential for ecological relevance for use as resource management tools (i.e., hydrologic indicators) in rapidly urbanizing basins of the Puget Lowland. Four criteria were proposed for identifying useful hydrologic indicators: (1) sensitive to urbanization consistent with expected hydrologic response, (2) demonstrate statistically significant trends in urbanizing basins (and not in undeveloped basins), (3) be correlated with measures of biological response to urbanization, and (4) be relatively insensitive to potentially confounding variables like basin area. Data utilized in the analysis included gauged flow and benthic macroinvertebrate data collected at 16 locations in 11 King County stream basins. Fifteen hydrologic metrics were calculated from daily average flow data and the Pacific Northwest Benthic Index of Biological Integrity (B-IBI) was used to represent the gradient of response of stream macroinvertebrates to urbanization.

3.3.2. Indicators Measured, Frequency of Measurement, and Sampling Locations

3.3.2.1. Hydrologic

Flow data were evaluated from 16 Puget Sound streams that were selected using a “space-for-time” approach that assumed spatial variation in the degree of urbanization of subcatchments captures the historical temporal trend in urbanization in the study area. Urbanization was represented by percent Total Impervious Area and percent urban land cover. Fifteen hydrologic metrics were calculated that captured the major flow regime categories of magnitude, duration, timing, frequency, rate of change, and flashiness/variability.

3.3.2.2. Biological

The 10-metric Pacific Northwest Benthic Index of Biotic Integrity (B-IBI) was used for this study.

3.3.3. Statistical Analysis

The relationship among the various hydrologic metrics, land cover, and B-IBI scores of study streams were evaluated by constructing bivariate correlation tables (Pearson's r). Principal components analysis (PCA) was conducted on the correlation matrix of the metrics with a significant correlation with B-IBI.

3.3.4. Results

Eight hydrologic indicators were significantly correlated with B-IBI scores (Low Pulse Count and Duration; High Pulse Count, Duration, and Range; Flow Reversals, TQmean, and R-B Index). Only two of the metrics tested – High Pulse Count and High Pulse Range – best met all four criteria for selecting hydrologic indicators. The increase in these high pulse metrics with respect to urbanization was the result of an increase in winter high pulses and the occurrence of high pulse events during summer (increasing the frequency and range of high pulses), when practically none would have occurred prior to development. An initial evaluation of the usefulness of the hydrologic indicators by calculating and comparing hydrologic metrics derived from continuous hydrologic simulations of selected basin management alternatives for Miller Creek, one of the most highly urbanized basins in the study was conducted. The preferred basin management alternative (75 percent forest/15 percent grass/10 percent impervious) appeared to be effective in restoring some flow metrics close to simulated fully forested conditions (e.g., TQmean), but less effective in restoring other metrics such as High Pulse Count and Range.

3.4. Dietz, M.E., et al. (2004)

3.4.1. Study Overview

The objective of this study was to determine if stormwater quality could be improved by educating homeowners in a residential neighborhood near Long Island Sound in the town of Branford Connecticut. A paired watershed design was used where a control and treatment watershed were monitored during a calibration and treatment period. The control and treatment watersheds were relatively small; 5.4 and 6.1-hectares, respectively. The total study duration was 47-months, which was divided into a 25-month calibration period and a 22-month treatment period. Trained volunteers worked with homeowners in the treatment watershed to help improve yard and garden care, and pet waste management with the specific intent of reccomending actions that would help reduce runoff, nitrogen, and bacteria. Residents were also surveyed prior and after the education was conducted to determine the effect of education on homeowner actions.

3.4.2. Indicators Measured, Frequency of Measurement, and Sampling Locations

3.4.2.1. Hydrologic

Flow was continually monitored at the base of each watershed for the study duration. Precipitation was also monitored continuously.

3.4.2.2. Chemical

Water quality samples were collected at the bottom of each watershed. The sampling frequency was not specifically reported; but 104 samples were collected during the 47-month study period, which equates to approximately 2 samples per month. Samples were analyzed for the following parameters:

- Nitrite + nitrate-N
- Ammonia-N
- Total Kjeldahl-N
- Total Phosphorus

3.4.3. Statistical Analysis

Statistical analysis was performed during the calibration period to enumerate significant regressions between paired observations from both watersheds for the constituents measured. Regressions were performed on paired flow and concentration values, and the slopes and intercepts of the two regressions were compared using ANCOVA. Survey results (before and after education) were also analyzed using a Chi-square test to identify significant changes in behavior.

3.4.4. Results

The main findings of this study were two-fold. First, the analysis of survey results indicated intensive education efforts in the form of workshops and one-on-one consulting resulted in significant adoption of BMPs. Second, it appeared that education, and the subsequent adoption of homeowner BMPs, decreased runoff, nitrite + nitrate-N and bacteria. However, ammonia nitrogen and TKN did not decrease relative to the control watershed.

3.5. King, K.W., et al. (2008)

3.5.1. Study Overview

This method paper examined the suitability of selected paired watersheds to quantify hydrologic, chemical, and ecological effects of conservation practice implementation for channelized and unchannelized watershed in the predominately agricultural Upper Big Walnut Creek Watershed (UBWC), Ohio. The assessment of suitability was based on the following considerations: correlations of response variables between the channelized and unchannelized watersheds; the minimum percent change in response variables to detect significant differences; and lack of temporal trends in response variables for each watershed pair.

Four headwater watersheds (two channelized, two unchannelized) were selected based on qualitative assessments of size and physical characteristics (e.g., land use, topography, dominant hydrologic processes). The watersheds ranged in size from 389 to 454 hectares. Biological and water quality monitoring occurred at the bottom of each watershed for a period of 2 years.

3.5.2. Indicators Measured, Frequency of Measurement, and Sampling Locations

3.5.2.1. Hydrologic

Flow was measured continuously at the outlet of each watershed. Precipitation was also measured continuously.

3.5.2.2. Chemical

Grab samples and weekly composite samples were collected at the outlet of each watershed. The water quality parameters measured were:

- Total nitrogen
- Nitrate + nitrite-N
- Total phosphorus
- Soluble reactive phosphorus
- Pesticides (atrazine, simazine metolachlor residues)

3.5.2.3. Biological

Fish communities were sampled from two sites within each watershed at a frequency of three times per year. One site was located at the watershed outlet and the second site was at least 150 meters upstream. Sampling reaches were 150 meters long.

3.5.3. Statistical Analysis

Several different statistical analyses were used in this study. Similarity in watershed characteristics was determined using a qualitative assessment of descriptive statistics (e.g., percent forest cover, percent soil type). Relationships between hydrology, water chemistry, and fish communities were assessed using simple linear regression. Temporal trends in the differences between paired watersheds in hydrology, water chemistry, and fish community response variables were analyzed using the Daniels Test for trend. The minimum percent change required to detect a significant difference in hydrology, water chemistry, and fish community response variables before and after the implementation was calculated using formulas presented in Clausen and Spooner (1993).

3.5.4. Results

The methods and tests used in this study were sufficient for determining that the selected watersheds were sufficient for a paired watershed study that was likely to yield statistically sound results. Combined hydrology, water chemistry, and ecological assessments are needed to provide a comprehensive understanding of the impact of soil and water conservation practices on agricultural watersheds. Effective use of paired watershed design requires that paired watersheds should (1) be similar in physical characteristics, (2) have moderate correlations (i.e., greater than 0.6) in response variables between paired watersheds, (3) lack the presence of a temporal trend in the difference in response variables between control and impact watersheds prior to the impact, and (4) exhibit minimal effect sizes needed to detect a significant change.

3.6. Line, D.E., et al. (2012

3.6.1. Study Overview

The purpose of this study was to characterize runoff and pollutant export from three commercial sites in east central North Carolina. Each site represented different stormwater control measure (SCM) treatments. The NoTreat site had no SCMs in place, the WetBasin site had a traditional wet detention basin, and the LID site had bioretention cells, pervious concrete, and stormwater wetlands. Rainfall, runoff, and pollutant concentrations were monitored at each site simultaneously for a period of one year. Hydrologic and chemistry data was compared between the sites to determine the relative effectiveness of the SCMs.

3.6.2. Indicators Measured, Frequency of Measurement, and Sampling Locations

3.6.2.1. Hydrologic

Flow was monitored continuously at each of the water quality sampling sites for the project duration. Precipitation was monitored continuously at one location, however there were likely differences in precipitation between sites, and this inaccuracy may have confounded predicted runoff estimates. The hydrologic indicators assessed were:

- Flow Volume
- Rainfall to runoff relationship

3.6.2.2. Chemical

At the No Treat and Wetbasin sites, water quality was sampled at the outlet of each site. The LID site had four monitoring stations located at the inlet and the outlet to the site, as well as at individual features (pervious concrete parking area, and bioretention cell). At all of the monitoring stations, flow proportional samples were collected during 30 storm events over a 1-year period. The samples from each site were analyzed for the following parameters:

- TSS
- Total phosphorus
- Orthophosphorus
- TKN
- Ammonia nitrogen
- Nitrate + nitrite nitrogen
- Total nitrogen

3.6.3. Statistical Analysis

Annual rainfall, runoff, and pollutant export rates were computed for each site and compared. The LS mean test was used to compare rainfall vs runoff and pollutant load relationships for each site.

3.6.4. Results

The storm runoff to rainfall ratio was greatest for the NoTreat site and least for the WetBasin site, which was anticipated because the NoTreat site had no detention/storage. The WetBasin site had the greatest detention/storage. Export of TKN, ammonia nitrogen, total phosphorus, and TSS was lowest for the LID site, whereas export of nitrate + nitrite nitrogen and total nitrogen was lowest for the WetBasin site.

3.7. Pitt, R., et al. (2013)

3.7.1. Study Overview

The US EPA's Green Infrastructure Demonstration project in Kansas City, MO, incorporates both small-scale individual biofiltration device monitoring, along with large-scale watershed monitoring. The test watershed (40 ha, 100 acres) has as many green infrastructure components (including curb-cut biofilters with extra subsurface storage, rain gardens, cascading biofilters, and porous concrete sidewalks). An adjacent 35 ha (87 acre) control watershed is also being monitored for comparison and to track effects of different rains affecting the watershed responses. A locally calibrated version of the WinSLAMM stormwater model was used to evaluation specific design options of these stormwater controls and for analyses of green infrastructure alternatives at other areas of the city. SWMM and SUSTAIN are also being used in this demonstration project to obtain insights in applying the lessons learned to larger city-wide applications.

Performance plots were prepared using the calibrated WinSLAMM model relating the size of green infrastructure components with expected flow reductions considering local design approaches and site conditions. As an example, the curb-cut biofilters being used are about 1.5 to 2 percent of their drainage areas (containing substantial surface and subsurface storage) and are expected to provide about 90 percent long-term reductions in stormwater runoff to the combined sewer. During the monitoring period, none of the rain gardens on private property had any surface overflows, and the monitored biofilters contained well over 90 percent of their flows.

More than half of the 100-acre pilot area is directly treated by about 135 individual green infrastructure control installations. The remaining areas were not treated as they drained to private property yard drains or had no suitable locations due to interferences (large trees, driveways, etc.). The area treated was associated with the largest flow portion of the whole site (mostly being along the roads). The large system flow monitoring at the test and control locations in the combined sewer indicated significant and large flow reductions. The period of construction was associated with continuously decreasing runoff yields, stabilizing to about 50 to 70 percent runoff volume reductions after all the controls were completed. The EPA-sponsored monitoring program will continue through the summer of 2013.

3.7.2. Indicators Measured, Frequency of Measurement, and Sampling Locations

No information provided.

3.7.3. Statistical Analysis

No information provided.

3.7.4. Results

No information provided.

3.8. Roy, A.H., et al. (2014).

3.8.1. Study Overview

This study used a paired watershed approach to determine if the adoption of parcel scale LID components (rain gardens and rain barrels) in 5 subbasins would illicit a positive response in a range of hydrology, water quality, habitat, morphology, and biological indicators. The study was conducted in the 1.8 km^2 Shepherd Creek catchment in Cincinnati, Ohio. The study design used a modified before-after-control intervention (BACI) model, where the intervention was the installation of treatments (rain barrels and rain gardens) on select parcels. There were two control subbasins and four treatment subbasins. No new development took place in either the control or treatment subbasins during the 7 year study duration.

3.8.2. Indicators Measured, Frequency of Measurement, and Sampling Locations

Basic morphometric, geometric, and water quality parameters were measured five times a year within 6 study reaches when biotic samples were collected. Monthly grab samples were collected and analyzed for a suite of water quality constituents. Sampling parameters are listed below

3.8.2.1. Chemical

- Conductivity
- Temperature
- Turbidity
- Dissolved Oxygen
- pH
- Alkalinity
- Chloride
- Calcium

- Dissolved organic carbon
- Suspended sediment concentration
- Total organic carbon
- Sulfate
- Iron
- Magnesium
- Nitrate + nitrite nitrogen
- TKN
- Total phosphorus
- Ortho-phosphate
- Total dissolved phosphorus
- Oxidation reducton potential
- Dissolved Metals (Al, Fe, Mn, Cu, Zn)
- Base cations (Na, Mg, K, Ca)

3.8.2.2. *Physical Habitat*

- Headwater Habitat Evaluation Index
- Closed Canopy (percent)
- Mean depth
- Filamentous algae
- Wetted reach area
- Riffle Habitat
- Quantitative Habitat Assessment Index

3.8.2.3. *Biological*

- Periphyton (percent dominant diatom, percent motile diatom, Periphyton Index of Biotic Integrity, Shannon diversity, percent eutraphenetic diatom)
- Macroinvetibrates (abundance, taxa richness, biomass)

3.8.3. *Statistical Analysis*

ANOVA was used to compare the difference between responses of control and experimental subcatchments for three periods to determine if signiicant treatment efects were present. One of the effects tested was the effect of treatment period (i.e., they accounted for time since installation as a factor in their model). While this method wasn't intended, or capable, of describing long-term trends, it was unique compared to the majority of other studies describing LID effects, because it examined the change periods. Most other studies either use a paired basin approach, comparing similar basins, one witih LID, one with conventional stormwater infrastructure, or simply compare before and after conditions.

3.8.4. Results

The results of this study showed few practical differences between the treatment and control watersheds for many of the above listed indicators. There was an apparent increase in conductivity and sulfate through time within the control watersheds, but no change within the treatment sites. Calcium concentrations were constant at the control sites, but decreased at the treatment sites through time. Filamentous algae counts fluctuated at the control sites, but were stable over time at the treatment sites. There were few significant effects related to treatment on macroinvertebrates. This study represents a sizeable effort to control stormwater runoff on private properties, but the stream responses to the retrofit management were limited to localized responses of a few variables.

3.9. Selbig, W.R., et al. (2008)

3.9.1. Study Overview

The US Geological Survey, in cooperation with the Wisconsin Department of Natural Resources, studied two residential basins in Cross Plains, Wis., during water years 1999–2005. A paired-basin study design was used to compare runoff quantity and quality from the two basins, one of which was developed in a conventional way and the other was developed with LID. The two study basins were relatively small with drainage areas of 137 acres for the conventional basin, and 192 acres for the LID basin. Only about 35 acres of each basin is developed, and the rest of the drainage area is wooded hills.The conventional basin was monitored in its developed state, but the LID basin was monitored pre, during, and post construction.

3.9.2. Indicators Measured, Freuency of Measurement, and Sampling Locations

3.9.2.1. Hydrologic

Precipitation and flow were monitored continuously for the study duration. Redundant flow monitoring stations (i.e., two stations per site) were established in pipes at the bottom of each basin. Precipitation was measured at a single location, but the basins were located one quarter mile from eachother so there should not have been climatic differences between the two basins. The hydrologic indicators used for evaluation were:

- Mean storm event volume
- Annual discharge volume
- Peak flow rate
- Cumulative-discharge volume as a percentage of total discharge volume, compared to rainfall depth

3.9.2.2. Chemical

Water quality samples were collected at the bottom of both study basins. Flow paced composite samples were collected during storm events. Samples were analyzed, and pollutant loads were calculated for the following parameters:

- Total Solids
- Total Suspended Solids
- Total Phosphorus

Temperature was also measured continuously at each site.

3.9.3. Statistical Analysis

Precipitation data was analyzed for trends using the method described in Helsel and Hirsch (1992). Stepwise multivariate linear-regressin analysis incorporating precipitiation depth, precipitation intensity, and antecedent dry period was used to test whether a relation existed between percent runoff volume reduction and climatic variables. Descriptive statistics were used for comparing peak-flow and discharge volumes. Runoff water quality and storm loads were compared using descriptive statistics and linear regression.

3.9.4. Results

The study results showed that runoff volumes from the LID basin remained low before and during development, and continued to remain low following development. Ninety-five percent or more of precipitation in the LID basin was retained during each year of construction from predevelopment through near-complete build-out. Smaller, more frequent precipitation events that produced stormwater discharge from the conventional basin were retained in the LID basin. Only six events with precipitation depths less than or equal to 0.4 inch produced measurable discharge from the LID basin. However, pollutant load export for some parameters was higher in the LID basin compared to the conventional basin.

3.10. Smucker, N.J. and N.E. Detenbeck (2014)

3.10.1. Study Overview

This paper summarizes results from a meta-analysis of literature that used response reatios to examine how ecosystem attributes (water quality, habitat/hydrology, ecological structure, and ecological function) responded to development and restoration by comparing (1) restored to unrestored urban streams (or postto pre-management), (2) restored to less impacted reference streams, and (3) unrestored urban to reference streams.

3.10.2. Indicators Measured, Freuency of Measurement, and Sampling Locations

A wide range of indicators was used in this assessment, and not all indicators were used for every comparision. For example, a water quality response ratio was calculated for unrestored watersheds/reference watershed; whereas water quality was not used for comparing restored urban watersheds to reference streams. Some indicators that were used in response ratio calculations such as “hydrology” were not defined. To examine broad trends, attributes were grouped into the following attribute categories: ecological structure, ecological function, and physical habitat.

3.10.3. Hydrologic

- Indicators not defined

3.10.3.1. Chemical

- Nutrients
- Conductivity
- Turbidity

3.10.3.2. Physical Habitat

- In-stream habitat
- Geomorphology

3.10.3.3. Biological

- Biodiversity
- Indicies of Biotic Condition
- Macroinverrtebrates
- Fungi
- Periphyton
- Indicies of biologic condition

3.10.3.4. Other

- Organic matter breakdown/retention
- Element Cycling

3.10.4. Statistical Analysis

Wilcoxon signed rank tests were used to examine whether median response ratios were signficantly different than zero. A significant difference would indicate a negative or positive response. When data were avaialbe, Spearman rank correlations were used for determining whether ecological structure and function were related to water quality and habitat response ratios. Spearman rank correlations were also used to examine relationships between mean response ratios and watershed attributes such as watershed area, percent impervious cover and time since restoration.

3.10.5. Results

Mean measures of ecosystem attributes in restored streams were significantly greater than those in unrestored urban streams. Measures of biodiversity in restored streams were 132 percent of those in unrestored urban streams, and indices of biotic condition, community structure, and nutrient cycling significantly improved. However, ecosystem attributes and biodiversity at restored sites were significantly less than, and only 60 percent and 45 percent of, those in reference streams, respectively. Out-of-stream management practices improved ecological conditions in urban streams but still failed to restore reference stream conditions. Despite statistically significant improvements, the study concludes assessments of restoration success remains difficult because there are few comparisons to reference sites or to clearly defined targets. These findings can inform future monitoring, management, and development strategies and highlight the need for preventative actions in a watershed context.

3.11. Stranko, S.A., et al. (2012)

3.11.1. Study Overview

This study examined the efficacy of urban stream restorations for improving biological diversity. The study compared the biological diversity and condition of four stream categoriess: (1) urban restored; (2)urban non-restored; (3) nonurban and (4) reference (minimally restored). These four categories of streams were compared using measures of fish and benthic macroinvertebrate diversity. The study aimed to answer the question, are restored sites more similar to reference sites and less like other urban sites as a result of restoration practices?

The study took place in the Eastern Piedmont Ecoregion off Maryland within three large river basins; the Gunpowder, Patapsco, and Middle Patomic River basins. Collected or compiled data were analyzed for 15 restored reaches on three different streams. The number of years of ecological data varied by site. One reference reach on three diferent streams were selected for comparison. Sampling of the reference reaches occurred annualy for a period of 10 years. An additional 334 sites within the region were sampled once over a 14-year time-span to place the reference and restored stream sites within a regional context. Sites were selected using a stratified random design.

3.11.2. Indicators Measured, Freuency of Measurement, and Sampling Locations

3.11.2.1. Biological

The following biological indicators were sampled once per year on reference and restored streams:

- Fish (fish IBI, species, intolerant fish species, species density)
- Benthic macroinvertebrates (abundance, taxa, intolerant genera, IBI)

3.11.3. Statistical Analysis

Nonmetric multidimensional scaling (NMS) was used to summarize and provide a graphical representation of the biological data patterns. Bray Curtis distance was used to measure the similarity of sites. The focus of the analysis was on patterns in the diversity metrics among streams rather than on individual taxa, which can differ substantially from site to site, yet still have high diversity ratings due to taxa substitutions. Multiresolution permutation procedure (MRPP) was used to test for significant differences among the four site categories (i.e., urban, restored, nonurban, and reference). ANOVA with a Tukey's studentized range test was used to determine which biological diversity metrics differed across the sites.

3.11.4. Results

Biodiversity metrics differed substantially among the land use classes. Both multivariate and univariate statistical analyses show biological diversity of restored urban streams to be similar to nonrestored urban streams and lower than nonurban and reference streams. Restored urban sites showed no apparent increase in biological diversity through time, while diversity decreased at two of the reference streams coincident with increased urban development within their catchments.

4. INDICATORS

This section synthesizes information obtained through this literature review on the effectiveness of specific indicators for assessing change in receiving water conditions. It is organized to present this information under separate subsections for the following indicator categories: hydrologic, chemical, physical habitat, and biological.

4.1. Hydrologic

The flow regimes (e.g., flashy hydrograph, higher peak flows, and lower base flows) typical of urban watersheds have been demonstrated to be one of the root causes of declining receiving conditions, particularly as measured by integrative indicators such as benthic invertebrate communities (Booth 2005; King County 2014). As such, flow is commonly used as a primary indicator for changing watershed conditions. Flow is also being used as a primary indicator for documenting the effectiveness of urban development practices and watershed restoration efforts that incorporate flow control technologies and practices (e.g., LID).

Most of the studies reviewed used one of three monitoring approaches for assessing hydrologic alterations (Table 1). Each approach was intended to quantify the hydrologic impacts of watershed alterations (urbanization or rehabilitation). In Before/After studies, the same watershed or basin may be monitored before and after alteration (e.g., conventional stormwater management measures replaced by LID; before and after urbanization). In this approach, the “before” conditions effectively serve as the “control,” and the “after” conditions effectively serve as the “treatment.” In paired watershed studies, two or more similar basins, or watersheds, are monitored concurrently during and after watershed alteration. Using this approach, differences between the “treatment” and “control” watersheds are assumed to result from the respective alterations within the treatment watershed. Finally, modelling studies using standard watershed hydrologic models (e.g., HSPF, SWMM) that account for variables that affect runoff (e.g., permeability) are used to simulate the impacts of watershed alterations.

Table 1. Monitoring Approaches for Assessing Hydrologic Alterations.

Monitoring Approach	Study Reference
Before/After	Archer and Newson (2002); Klein et al. (2007); Roy et al. (2014); Selbig et al. (2008)
Paired Watershed	Ahiablame et al. (2013); Bedan and Clausen (2009); Dietz and Clausen (2008); Hood et al. (2007); King et al. (2008); Line et al. (2012); Pitt et al. (2013); Selbig et al. (2008)
Modelling	Ahiablame et al. (2013); King County (2014); Pitt et al. (2013)

A host of hydrologic recovery indicators have been used and proposed for gauging watershed health. DeGasperi et al. (2009) identified hydrologic indicators which impacted BIBI scores within the Puget Sound Basin. These indicators were, low pulse (frequency and duration), high pulse count (frequency and duration), rate of change of rise, and fall rate, fall count, rise count, flow reversals, flashiness (TQmean, R-B index), seven-day minimum, and date of annual minimum. Clausen and Biggs (2000) grouped 35 hydrologic recovery indicators to represent different aspects of the flow regime, and classified the ecological relevance of these groups. These groups were: size of the river, the overall variability of flow, the volume of high flows, and the frequency of high flow events. Few studies monitored or reported all of these flow variables and the majority used just a small subset that generally included peak flow, annual flow volume, and metrics for "flashiness" (e.g., high pulse count). Table 2 lists the most commonly used metrics and the corresponding studies.

Table 2. Hydrologic Indicators.

Indicator	Study Reference
Annual Runoff or Flow Volume	Ahiablame et al. (2013); Bedan and Clausen (2009); Clausen (2007; Hood et al. (2007); King et al. (2008); Line et al. (2012); Pitt et al. (2013); Selbig et al. (2008); Stillwater Sciences (2015)
Flow Variability	Archer and Newson (2002); Hood et al. (2007)
Peak Flow	Archer and Newson (2002); Bedan and Clausen (2009); Hood et al. (2007)
Rainfall : Runoff	Dietz and Clausen (2008); King et al. (2008); Klein et al. (2007)

The majority of papers reviewed showed some positive effect of LID, adoption of stormwater BMPs, and other watershed improvement actions on hydrologic recovery indicators. The literature revealed that the magnitude of response is related to the magnitude of actions taken. Ahiablame et al. (2013) found that modeled runoff volume changed only slightly (2 to 12 percent) under various combinations of 50 percent application levels of rain barrels and porous pavement. They posited that more widespread adoption of stormwater BMPs at the watershed scale would have a larger impact.

Many of the studies showing a positive benefit of LID adoption on flow were located in fairly small watersheds. For example, Clausen (2007) compared a 5.6 hectare "control" watershed which was developed conventionally to a 1.7 hectare BMP watershed, and documented a 97 percent decrease in runoff during construction and a 74 percent decrease post-construction when compared to the conventionally developed watershed. Selbig et al. (2008) documented similar positive effects in somewhat larger developed watersheds (approximately 35 developed acres). However, studies looking for these benefits across relatively large watersheds were not identified from this literature review.

The duration of monitoring was highly variable in the literature. Some studies, particularly those located in very small catchments, were able to document statistical differences in hydrology indicators in as few as 22 months using a paired basin approach (Dietz et al. 2004). Studies which monitored before and after conditions were typically much longer, often spanning more than a decade. For example, Clausen et al. (2007) monitored watersheds for 3 years to establish baseline hydrologic characteristics before development, and then continued monitoring the watersheds for an additional 7 years. Ahiablame et al (2013) used flow data from a 19-year record for the purposes of model calibration and validation.

Monitoring strategies (e.g., equipment choices, location within watershed, etc.) were relatively uniform among the studies. In general, monitoring stations were selected at the terminus of the study watersheds to be able to measure runoff from the entire watershed area. Monitoring frequency was on a 5 to 15-minute time step.

King County (2014) modeled the combined effect of geology and land cover on high pulse counts to develop a high pulse count score. The modeled high pulse count scores were subsequently used as one component in a more holistic hydrologic condition index. Ahiablame et al. (2014) used the Long-Term Hydrologic Impact Assessment (L-THIA)-LID model to estimate direct runoff given various treatment levels of rain barrel/cistern and porous pavement applications (maximum treatment level 25 percent porous pavement, 50 percent rain barrel/cistern). Pitt et al (2013) used the WINSLAMM for developing pollutant load estimations. The WINSLAMM model calculates flow and pollutant discharges that reflect a broad variety of development conditions and many combinations of common urban runoff control practices.

4.2. Chemical

Numerous studies have indicated structural and nonstructural BMPs can reduce pollutant concentrations in stormwater at the site scale (Barrett 2008; BES 2006; Dietz 2007; Herrera 2011); however, few have assessed whether the broad application of treatment BMPs across a basin will result in reduced pollutant concentrations and loadings in local receiving waters. Water quality indicators are commonly used in assessing the effectiveness of watershed improvement projects and application of water treatment BMPs. Of the compiled studies, most evaluated the same parameter groups (nutrients, sediments, metals). Of the 120 studies reviewed, 35 (29 percent) had a water quality monitoring component. However, only three long-term studies (Ahiablame et al. 2013; Clausen 2007; Roy et al. 2014) were identified that quantified water quality responses to watershed wide stormwater management efforts. Two of these studies relied solely on monitoring data to support their conclusions (Clausen et. al 2007; Roy et al. 2014); the other study (Ahiablame et. al. 2013) used a modeling approach. Summaries of these three studies are presented in the preceding section and discussed briefly below.

The Jordan Cove Project in Waterford, Connecticut (Bedan and Clausen 2009; Clausen 2007; Hood et al. 2007) monitored conventional water quality parameters (nutrients, bacteria, sediments) and metals, at the bottom of three small watersheds (5.5, 2.0, and 1.7 hectares) for a 10-year period. During this 10-year period, two of the watersheds were developed; one conventionally and one with stormwater BMPs, which resulted in an 8 percent lower proportion of impervious surface in the watershed with the BMPs. The third watershed was not developed and served as a control. In general, pollutant concentrations within the BMP watershed were higher than the control watershed, and not markedly different than in the conventionally developed watershed. However, pollutant exports from the BMP watershed were generally less than those in the conventionally developed watershed due to reduced flow volumes.

The Shepherds Creek Project in Cincinnati, Ohio (Roy et al. 2014) used a before-after-control-intervention (BACI) design to monitor five subbasins (three treatment, two control) within the

1.8 km^2 Shepherds creek watershed. Small parcel scale stormwater controls (rain-barrels and rain gardens) were installed throughout the 5 subbasins. Conventional water quality parameters were measured at the base of each of the subbasins before the installation of the stormwater controls, and for several years after installation. The results of this study showed few practical differences in water quality between the treatment and control watersheds indicating that small scale stormwater retrofits have little impact on water quality at the watershed scale.

Ahiablame et al. (2013) used the Long-Term Hydrologic Impact Assessment (L-THIA)-LID model to evaluate the water quality impacts of various treatment levels of rain barrel/cistern and porous pavement applications (maximum treatment level 25 percent porous pavement, 50 percent rain barrel/cistern). The model was calibrated for a period of 9 years and validated for a period of 10 years. Results showed that nutrient loads were only reduced by 1 to 9 percent under any of the treatment level scenarios.

Stillwater sciences (Stillwater Sciences 2015) designed a long-term status and trends monitoring project for the Lower Columbia Evolutionary Significance Unit (ESU) that incorporates a substantial water quality monitoring effort. A stratified site selection procedure was used to identify sampling sites based on the coefficient of variation of targeted parameters and site selection attributes. A fairly basic set of water quality parameters (temperature, sediment metals, conductivity, chloride, and total nitrogen) were selected for monitoring. Monitoring has not initiated on this project to date.

There are a large number of other studies that have used water quality indicators to quantify the effects of urbanization and document responses to restoration or other management strategies (Kaushal et al. 2008; Selbig et al. 2008); however, most evaluate responses at the small catchment level. In general, these studies detected a beneficial impacts from management actions more frequently than studies implemented at the watershed scale.

4.3. Physical Habitat

This literature review indicated the effectiveness of physical habitat indicators for assessing improvements in receiving water conditions may be limited depending on the scale that rehabilitation efforts are applied. For example, numerous studies have indicated the likelihood of aquatic habitat recovery is low if in-channel habitat is simply improved without addressing basin-wide issues (Booth 2005; Frissell and Nawa 1992; Haase et al. 2013; Hilderbrand et al. 1997; Jahnig et al. 2010; Kail et al. 2012; Lorenz and Feld 2013; Selvakumar et al. 2010; Stewart et al. 2009; Suren and McMurtrie 2005; Thompson 2002). Suren and McMurtrie (2005) suggest that in-channel restoration efforts should focus on watersheds which have a natural hydrograph and minimal sediment loading. They argue that external drivers will dictate reach scale dynamics and that without a watershed-based approach reach-scale restoration will be useless. In a separate study, Frissell and Nawa (1992) monitored 161 in-stream structures and found that 60 percent of the structures had had the opposite of the intended effect on the stream. They attributed the high failure rate to the fact that structures were placed in both high velocity and sediment laden reaches.

Other studies have found in-stream structures placed in Pacific Northwest streams to be more durable, with only a 20 percent failure rate after 5-year recurrence interval flood events (Roper et al. 1998). Regardless, most research indicates that in-stream structures are more likely to fail in high energy environments (Frissell and Nawa 1992) and when sediment loading is elevated (Frissell and Nawa 1992; Suren and McMurtrie 2005). In addition, studies have shown that benthic community reestablishment may be a function of proximity to existing pristine watersheds or reaches (Brederveld et al. 2011; Sundermann et al. 2011; Suren and McMurtrie 2005), so obviously multiple factors outside the channel restoration site will be important for project success.

Indicators for assessing physical habitat alteration in streams have been assessed in multiple studies. The most common physical habitat indicators are listed in Table 3.

The duration and intensity of monitoring used in the studies presented in Table 3 is highly variable, but in general physical habitat monitoring occurred on an annual basis for the few studies designed to detect a trend (Stillwater Sciences 2015). An exception to this is a paired basin study by Roy et al (2014) that measured physical habitat five times annually for 7 years. Despite the high-intensity monitoring, the study was only able to detect a difference in canopy cover due to invasives removal in the treatment basin. Bryant (1995) proposed a pulsed monitoring approach to assess stream restoration that involved an initial intensive sampling before treatment that is paired with an intensive sampling after treatment; at the same time, a low-intensity synoptic sampling regime would be implemented across the entire study period.

Spatial site selection is frequently opportunistic, that is sites are selected based on convenience (e.g., near a road crossing) and a judgment regarding the representativeness of the site. A pseudorandom sampling site selection approach is currently being proposed for monitoring in the Lower Columbia Basin (Stillwater Sciences 2015) based on stratified sampling criteria.

4.4. Biological

Biological indicators range across scales from populations, to guilds, to the entire community of selected organisms. These indicators may also address different attributes of an ecosystem, ranging from ecosystem composition (e.g., species abundance or biomass) to ecosystem functions that reflect important ecological processes (e.g., dispersal or nutrient cycling) (Weber et al. 2011). Biological indicators are integrative variables (i.e., they are impacted by a number of watershed factors) and, as such, are useful for holistic assessments of watershed health; however, this may also make it difficult to attribute specific causes to changes in biological indicators.

Numerous studies indicate that while biological indicators are an important assessment tool, the results must be carefully interpreted to reach appropriate conclusions. The majority of the time, restoration success is considered on a reach scale, outside of the context of the larger watershed. Populations, both fish and invertebrate, often respond to factors exogenous to restoration treatments. These factors may include fishing pressure, environmental effects (e.g., drought, severe winters), or habitat disruption outside the treatment area.

Table 3. Physical Habitat Indicators.	
Indicator	**Study Reference**
Permeability of river bed	Buchanan et al. (2012); Doll et al. (2014); Stillwater Sciences (2015); Woolsey et al. (2007)
Grain size	Boavida et al. (2012); Doll et al. (2014); Henshaw and Booth (2000); King County (2014); Kristensen et al. (2011); Larson et al. (2001); Lepori et al. (2005); Levell and Chang (2008); Luderitz et al. (2011); Pizzuto et al. (2000); Pretty et al. (2003); Selvakumar et al. (2010); Violin et al. (2011)
Bed mobility	Luderitz et al. (2011); Stillwater Sciences (2015)
Longitudinal profile	Bain et al. (2014); Boavida et al. (2012); Buchanan et al. (2012); Frissell and Nawa (1992); King County (2014); Klein et al. (2007); Larson et al. (2001); Lepori et al. (2005); Levell and Chang (2008); Luderitz et al. (2011); Pizzuto et al. (2000); Stillwater Sciences (2015); Violin et al. (2011)
Leaf packs	Doll et al. (2014)
LWD	Bryant (1995); Buchanan et al. (2012); Doll et al. (2014); Hilderbrand et al. (1997); King County (2014); Larson et al. (2001); Moerke and Lamberti (2004); Stillwater Sciences 2015)
Width	Bain et al. (2014); Boavida et al. (2012); Bryant (1995); Buchanan et al. (2012); Doll et al. (2014); Frissell and Nawa (1992); Henshaw and Booth (2000); King County (2014); Klein et al. (2007); Kristensen et al. (2011); Larson et al. (2001); Lepori et al. (2005); Levell and Chang (2008); Luderitz et al. (2011); Moerke and Lamberti (2004); Pizzuto et al. (2000); Selvakumar et al. (2010); Stillwater Sciences (2015)
Depth	Bain et al. (2014); Boavida et al. (2012); Bryant (1995); Buchanan et al. (2012); Doll et al. (2014); Frissell and Nawa (1992); Henshaw and Booth (2000); Klein et al. (2007); Kristensen et al. (2011); Lepori et al. (2005); Levell and Chang (2008); Luderitz et al. (2011); Moerke and Lamberti (2004); Pizzuto et al. (2000); Selvakumar et al. (2010); Stillwater Sciences (2015)
Pool number	(Bryant 1995; Buchanan et al. 2012; Doll et al. 2014; Hilderbrand et al. 1997; King County 2014)
Pool length	Doll et al. (2014); Hilderbrand et al. (1997); King County (2014)
Pool area	Doll et al. (2014); Hilderbrand et al. (1997)
Riffle number	Doll et al. (2014); Hilderbrand et al. (1997)
Riffle length	Doll et al. (2014); Hilderbrand et al. (1997)
Riffle area	Doll et al. (2014); Hilderbrand et al. (1997)
Bank stability/ vegetation	Boavida et al. 2(012); Buchanan et al. (2012); Doll et al. (2014); Henshaw and Booth (2000); Luderitz et al. (2011); Stillwater Sciences (2015)
Sinuosity	Klein et al. (2007); Kristensen et al. (2011)
Bankfull distance to top of bank	Klein et al. (2007); Violin et al. (2011)
Percent canopy	Moerke and Lamberti (2004); Stillwater Sciences (2015); Violin et al. (2011)
Rankin Qualitative Habitat Evaluation index	Moerke and Lamberti (2004)

Further, the response may be carried through several life cycles (e.g., weak year classes) (Bryant et al. 1995). Additionally, factors affecting the biological assemblages must be clearly understood in order to target meaningful restoration measures. For example Kemp et al. (2014) discusses the importance of connecting the underrepresentation of fish taxa in impacted urban streams with the mechanisms responsible for their reduction or elimination; which can then be addressed with stream restoration. Numerous studies have also documented relationships between urbanization and resident fish assemblages; however, few have confirmed involved mechanisms for these relationships.

Specific methods for using biological indicators based on invertebrates and fish differed among the studies reviewed; however, there was some consistency in overall approach. For example, one of the indicators measured by Roy et al. (2014), and Bain et al. (2014) was ephemeroptera, tricoptera, plecoptera richness (EPT richness), whereas other studies such as Laasonen et al. (1998) more broadly described taxa richness. In general, the same basic indicators (i.e., taxa abundance, richness, and diversity,) were used for both macroinvertebrate and fish indicators. Heinrich et al (2014) took a more integrative approach and used the presence and diversity of insectivorous birds at restoration sites as a restoration success indicator. Table 4 lists the most common biologic (macroinvertebrate and fish) indicators. Several studies measured both individual biotic metrics but also combined metrics such as macroinvertebrate and fish indices of biotic integrity (IBI) (Table 4).

Table 4. Biological Indicators.

Indicator	Study Reference
Total macroinvertebrate abundance	Bain et al. (2014); Canobbio et al. (2013); Heinrich et al. (2014); Hilderbrand et al. (1997); Jahning et al. (2010); Laasonen et al. (1998); Luderitz et al. (2011); Miller et al. (2010); Nakano et al. (2006); Purcell et al. (2008); Roy et al. (2014); Stranko et al. (2012)
Specific taxa abundance	Bain et al. (2014); Hilderbrand et al. (1997); Jahning et al. (2010); Laasonen et al. (1998); Luderitz et al. (2011); Miller et al. (2010); Nakano et al. (2006); Purcell et al. (2008); Roy et al. (2014); Stranko et al. (2012)
Macroinvertebrate taxa richness (e.g., EPT)	Bain et al. (2014); Cannobio et al. (2013); Heinrich et al. (2014); Hilderbrand et al. (1997); Jahning et al. (2010); Laasonen et al. (1998); Luderitz et al. (2011); Miller et al. (2010); Nakano et al. (2006); Purcell et al. (2008); Roy et al. (2014); Stranko et al. (2012)
Macroinvertebrate biomass	Bain et al. (2014); Hilderbrand et al. (1997); Laasonen et al. (1998); Roy et al. (2014); Stranko et al. (2012)
IBI, EBI, or other multimetric indices	Cannobia et al. (2013); Heinrich et al. (2014); Jahning et al. (2010); Luderitz et al. (2011); Purcell et al. (2008); Roy et al. (2014); Stranko et al. (2012)
Fish abundance	Bain et al. (2014); King et al. (2008); Luderitz et al. (2011); Stranko et al. (2012); Whiteway et al. (2010)
Fish taxa richness	Bain et al. (2014); King et al. (2008); Luderitz et al. (2011); Stranko et al. (2012); Woolsey et al. 2007)
Fish biomass	Bain et al. (2014); Luderitz et al. (2011); Stranko et al. (2012); Whiteway et al. (2010)

Spatial site selection was often based on the location of specific restoration projects. For example Heinrich et al. (2011) measured macroinvertebrate emergence adjacent to instream rock weir structures placed for habitat creation; and Luderitz et al. (2011) monitored invertebrates in a restored reach and compared results to adjacent non-restored, and partially restored reaches.

Results from this literature review showed biological indicators were not consistently correlated with watershed restoration efforts, with some studies showing a positive response to restoration while others showed little, none, or even a negative response. With exceptions, biological indicators have shown a positive response when reach scale restoration has been coupled with reach scale monitoring (Heinrich et al 2014; Hilderbrand et al. 1997; Whiteway et al. 2010). However, a meta-analysis of 22 publications relating river restoration to macroinvertebrate responses (Miller 2010) concluded that macroinvertebrate metrics can exhibit considerable variability at small spatial scales for reasons unrelated to restoration actions, their use to assess restoration effectiveness needs to be done with caution and rigorous study designs. Larger scale assessments aimed at studying the broader effects of river and watershed restoration have generally shown little to no response (Roy et al. 2014; Pretty et al. 2003; Stranko et al. 2011).

5. CONCLUSIONS AND RECOMMENDATIONS

Given the size and scope of the RPWS, careful consideration needs to be given to site selection and sampling frequency to ensure that monitoring results are representative of watershed conditions, and capable of detecting real environmental trends in the chosen indicators. In addition, indictor selection is important both for defining project scope and for characterizing environmental change. In this section recommendations for indicator selection as well as sampling site location and frequency are presented based on the information gathered in this literature review.

In general, the reviewed studies indicated that a large portion (e.g., >50 percent) of the basin must be treated in order to see a measureable difference in receiving water conditions (Ahiablame et al. 2013). In addition, it is apparent that in order for channel restoration to manifest sustainable environmental benefits, basin-wide issues (e.g., impervious surfaces, anthropogenic accelerated erosion) must be addressed (Booth 2005; Frissell and Nawa 1992; Haase et al. 2013; Hilderbrand et al. 1997; Jahnig et al. 2010; Kail et al. 2012; Lorenz and Feld 2013; Selvakumar et al. 2010; Stewart et al. 2009; Suren and McMurtrie 2005; Thompson 2002). These findings should guide the implementation and phasing of rehabilitation efforts in the Application watersheds for the RPWS.

In general, the scope and nature of the RPWS is unprecedented in the literature. Numerous studies have been conducted with similar goals, but they are generally conducted at the subbasin scale. In these studies a hydrologic monitoring station is typically located at the terminus of the study basin. Therefore, we recommend that stations be installed at the terminus of each of the seven study watersheds for the RPWS. However, because the watersheds are so large and because much of the rehabilitation will occur in the upper reaches of the Application watersheds, we also recommend establishing additional hydrologic monitoring stations at a mid-point location in each of the watersheds. Continuous flow data collection was used in each applicable study reviewed and is recommended for the RPWS. Finally, the most useful and pervasive hydrologic indicator appeared to be frequency and duration of high and low pulse count. At the least these indicators should be used to assess the success of rehabilitation efforts in the RPWS. Annual flow volume was also commonly used in the literature and should be considered when selecting indicators of hydrologic change. Modeling to quantify changes in hydrology as a function of land use changes and stormwater treatment applications has also been performed in a number of relevant studies. The RPWS provides an opportunity to validate the results from this modeling.

The literature indicated that most basin-scale studies have not been able to detect a difference in pollutant concentrations between basins with and without stormwater treatment facilities including LID practices. Load reductions were more easily quantified, but with concentration alone, natural variability tended to overwhelm any signal which could be associated with stormwater treatment applications. The majority of studies monitored water chemistry at the terminus of the study basins. Like flow, we recommend an additional station at the midpoint of each basin. This will improve the likelihood of detecting chemical changes given the proximity of the mid basin stations to the proposed treatment facilities. Water quality sampling frequency varied widely from study to study. We recommend that the frequency of water quality sampling for the RPWS be determined with power tests tailored to the specific parameters which will be selected for the study. The most common parameter groups measured in the literature of relevant studies where nutrients, suspended solids, and metals. The RPWS should select parameters from these groups at the very least.

The majority of studies which assessed physical habitat response to watershed rehabilitation were conducted in reaches in which channel rehabilitation measures were applied. Consequently, they were design to assess the localized effects of channel alterations. The RPWS will involve both channel rehabilitation and basin-wide BMP application. Consequently, we recommend a more synoptic approach to assessing physical habitat recovery. Stations should be selected in the Application watersheds in reaches which will be restored and in reaches where there will be no physical alterations to the channel. In this way, the RPWS can assess physical habitat response to both localized and basin-wide drivers. Annual monitoring of longitudinal profile, cross sectional area, grain size, incision, and riparian cover appear to be the most common in the literature and are recommended for the RPWS. If feasible, channel restoration should involve floodplain reconnection as the literature indicates that it is more effective at improving biologic conditions compared with in-channel work (e.g., installation of wood and rock weirs).

Studies linking macroinvertebrate and fish response to watershed restoration have primarily focused on responses to in-channel work. Macroinvertebrate metrics can show considerable variation across small spatial scales and will be sensitive to local conditions in the channel which may override influences from higher up in the watershed. Because an objective of the RPWS is to measure both localized and watershed effects on biologic recovery, it is recommended that the biologic monitoring program mirror the habitat monitoring program discussed above. Specifically, multiple monitoring locations should be located in both reaches where channel rehabilitation will occur and in reaches which will only be affected by upstream stormwater management activities in the Application watersheds. Annual monitoring coinciding with the collection of habitat data is recommended. Numerous studies have measured fish response to channel rehabilitation and many have seen a positive benefit, but it is not always clear if these results are due to redistribution of existing populations. Because fish are a key endpoint of the RPWS, adding a metric of fish abundance, diversity, or health should be considered.

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APPENDIX A

Annotated Bibliography

ANNOTATED BIBLIOGRAPHY

Ahiablame, L.M., et al. (2013). "Effectiveness of low impact development practices in two urbanized watersheds: Retrofitting with rain barrel/cistern and porous pavement." Journal of Environmental Management **119**:151–161.

> The impacts of urbanization on hydrology and water quality can be minimized with the use of low impact development (LID) practices in urban areas. **This study assessed the performance of rain barrel/cistern and porous pavement as retrofitting technologies in two urbanized watersheds of 70 and 40 km(2) near Indianapolis, Indiana**. Six scenarios consisting of the watershed existing condition, 25% and 50% implementation of rain barrel/cistern and porous pavement, and 25% rain barrel/cistern combined with 25% porous pavement were evaluated using a proposed LID modeling framework and the Long-Term Hydrologic Impact Assessment (L-THIA)-LID model. The model was calibrated for annual runoff from 1991 to 2000, and validated from 2001 to 2010 for the two watersheds. For the calibration period, R-2 and NSE values were greater than 0.60 and 0.50 for annual runoff and streamflow. Baseflow was not calibrated in this study. During the validation period, R-2 and NSE values were greater than 0.50 for runoff and streamflow, and 0.30 for baseflow in the two watersheds. The various application levels of barrel/cistern and porous pavement resulted in 2-12% reduction in runoff and pollutant loads for the two watersheds. Baseflow loads slightly increased with increase in baseflow by more than 1%. However, reduction in runoff led to reduction in total streamflow and associated pollutant loads by 1-9% in the watersheds. The results also indicate that the application of 50% rain barrel/cistern, 50% porous pavement and 25% rain barrel/cistern combined with 25% porous pavement are good retrofitting options in these watersheds. The L-THIA-LID model can be used to inform management and decision-making for implementation of LID practices at the watershed scale. (C) 2013 Published by Elsevier Ltd.

Archer, D. and M. Newson (2002). "The use of indices of flow variability in assessing the hydrological and instream habitat impacts of upland afforestation and drainage." Journal of Hydrology **268**(1-4): 244–258.

> Although the impact of plantation forestry and ground-preparation drainage on headwater runoff response has been widely studied, there are remaining uncertainties concerning the time scale of changes. scale effects of catchment size and impacts on flow variability. Flow variability, along with changes in sediment loads and water quality. is likely to be a defining element of the overall instream habitat quality of headwater catchments. In this paper a method is described for the characterisation of flow variability using 15-min data on the 1.5 km(2) Coalburn catchment, from 1967 to 1998. over a period of change from natural moorland to closed canopy coniferous forest. The method is based on annual number. and average and total duration of pulses above selected threshold flows but decouples the effects of variable annual rainfall. The number of pulses increased from pre- to post-drainage but pulse number

has declined steadily and pulse duration increased with forest growth-the catchment has become more, then less 'flashy'. The method provides a comprehensive. continuous and quantitative picture of changes in hydrological regime that is relevant to current assessments of instream physical habitat and 'environmentally acceptable flows'. It is possible that low invertebrate numbers and low levels of fish recruitment in the Coalburn channel may be in part attributable to changes in flow regime. (C) 2002 Elsevier Science B.V. All rights reserved.

Bain, D.J., et al. (2014). "Characterizing A Major Urban Stream Restoration Project: Nine Mile Run (Pittsburgh, Pennsylvania, USA)." Journal of the American Water Resources Association **50**(6):1608–1621.

Urban stream restoration continues to be used as an ecological management tool, despite uncertainty about the long-term sustainability and resilience of restored systems. Evaluations of restoration success often focus on specific instream indicators, with limited attention to the wider basin or parallel hydrologic and geomorphic process. A comprehensive understanding of urban stream restoration progress is particularly important for comparisons with nonurban sites as urban streams can provide substantial secondary benefits to urban residents. Here, we utilize a wide range of indicators to retrospectively examine the restoration of Nine Mile Run, a multi-million dollar stream restoration project in eastern Pittsburgh (Pennsylvania, USA). Examination of available continuous hydrological data illustrates the high cost of failures to incorporate the data into planning and adaptive management. For example, persistent extreme flows drive geomorphic degradation threatening to reverse hydrologic connections created by the restoration and impact the improved instream biotic communities. In addition, human activities associated with restoration efforts suggest a positive feedback as the stream restoration has focused effort on the basin beyond the reach. Ultimately, urban stream restoration remains a potentially useful management tool, but continued improvements in post-project assessment should include examination of a wider range of indicators.

Bedan, E.S. and J.C. Clausen (2009). "Stormwater Runoff Quality and Quantity From Traditional and Low Impact Development Watersheds(1)." Journal of the American Water Resources Association **45**(4):998–1008.

The quality and quantity of residential stormwater runoff from a control, traditional, and low impact development (LID) watershed were compared in a paired watershed study. A traditional neighborhood was built using typical subdivision standards while a LID design was constructed with best management practices including grass swales, cluster housing, shared driveways, rain gardens, and a narrower pervious concrete-paver road. Weekly, flow-weighted, composite samples of stormwater were analyzed for nitrate + nitrite-nitrogen (NO3 + NO2-N), ammonia-nitrogen (NH3-N), total Kjeldahl nitrogen (TKN), total phosphorus (TP), and total suspended solids (TSS). Monthly composite samples were analyzed for total copper (Cu), lead (Pb), and zinc (Zn). Mean weekly storm flow increased (600x) from the traditional watershed in the postconstruction period. Increased exports of TKN, NO3 + NO2-N, NH3-N, TP, Cu, Zn, and TSS in runoff were associated with the increased storm flow. **Postconstruction storm flow in the LID watershed was reduced by 42% while peak discharge did not change from preconstruction conditions**. Exports were reduced from the LID watershed for NH3-N, TKN, Pb, and Zn, while TSS and TP exports increased.

Beechie, T., et al. (2008). "Setting River Restoration Priorities: A Review of Approaches and a General Protocol for Identifying and Prioritizing Actions." North American Journal of Fisheries Management **28**(3):891–900.

Boavida, I., et al. (2012). "Benchmarking River Habitat Improvement." River Research and Applications **28**(10):1768–1779.

River ecosystems have witnessed a long history of human pressure, particularly the disruption of freshwater fish populations. The awareness of this situation has led to many habitat improvement projects, with a variable degree of success. In natural situations, fish populations co-inhabit throughout the hydrological cycle with different degrees of adequacy, and the sequence of favourable and unfavourable conditions dictates abiotic constraints and biotic interactions that shape the final biological assemblages. We postulate that a part of unsuccessful restoration results is related to insufficient closeness to the natural habitat conditions of the river type that is to be restored, including the naturally adverse periods. We used the river2d model to predict habitat availability as weighted usable area (WUA) at a degraded site that is to be restored, for two native Mediterranean species and their life stagesthe Southwestern nase Iberochondrostoma almacai and the Arade chub Squalius aradensis. We then analysed the yearly evolution of the natural WUA at a nearby reference site. Overall, the reference site exhibited the longest periods during which the WUA was continuously lower than the chosen WUA thresholds for each of the four bioperiods. Considerable divergences from natural habitat availability values can be seen for the spawning, rearing and growth bioperiods. Restoration outcomes can result in appreciable deviationsfavourable or unfavourable to fish populationsfrom the WUA occurring under natural conditions over the course of the year. Restoration should therefore take account of local hydraulic and habitat patterns that govern population dynamics and result in the final fish assemblage. Copyright (c) 2011 John Wiley & Sons, Ltd.

Booth, D.B. (2005). "Challenges and prospects for restoring urban streams: a perspective from the Pacific Northwest of North America." Journal of the North American Benthological Society **24**(3):724–737.

Abstract. Undoing harm caused by catchment urbanization on stream channels and their resident biota is challenging because of the range of stressors in this environment. One primary way in which urbanization degrades biological conditions is by changing flow patterns; thus, reestablishing natural flow regimes in urban streams demands particular attention if restoration is to have a chance for success.

Enhancement efforts in urban streams typically are limited to rehabilitating channel morphology and riparian habitat, but such physical improvements alone do not address all factors affecting biotic health. Some habitat-forming processes such as the delivery of woody debris or sediment may be amenable to partial restoration, even in highly disturbed streams, and they constitute obvious high-priority actions. There is no evidence to suggest, however, that improving nonhydrologic factors can fully mitigate hydrologic consequences of urban development. In the absence of effective hydrologic mitigation, appropriate short-term rehabilitation objectives for urban channels should be to 1) eliminate point sources of pollution, 2) reconstruct physical channel elements to resemble equivalent undisturbed channels, and 3) provide habitat for self-sustaining biotic communities, even if those communities depart significantly from predisturbance conditions. Long-term improvement of stream conditions is not feasible under typical urban constraints, so large sums of money should not be spent on unrealistic or unreachable targets for stream rehabilitation. However, such a strategy should not be an excuse to preclude potential future gains by taking irreversible present-day development or rehabilitative actions.

Booth, D.B., et al. (2002). "Forest cover, impervious-surface area, and the mitigation of stormwater impacts." Journal of the American Water Resources Association **38**(3):835–845.

For 20 years, King County, Washington, has implemented progressively more demanding structural and nonstructural strategies in an attempt to protect aquatic resources and declining salmon populations from the cumulative effects of urbanization. This history holds lessons for planners, engineers, and resource managers throughout other urbanizing regions. Detention ponds, even with increasingly restrictive designs, have still proven inadequate to prevent channel erosion, Costly structural retrofits of urbanized watersheds can mitigate certain problems, such as flooding or erosion, but cannot restore the predevelopment flow regime or habitat conditions. Widespread conversion of forest to pasture or grass in rural areas, generally unregulated by most jurisdictions, degrades aquatic systems even when watershed imperviousness remains low. Preservation of aquatic resources in developing areas will require integrated mitigation, which must including impervious-surface limits, forest-retention policies, stormwater detention, riparian-buffer maintenance, and protection of wetlands and unstable slopes. New management goals are needed for those watersheds whose existing development precludes significant ecosystem recovery; the same goals cannot be achieved in both developed and undeveloped watersheds.

Brasher, A.M.D., Konrad, C.P., May, J.T., Edmiston, C.S., and Close, R.N. (2010). Streamflow Characteristics and Benthic Invertebrate Assemblages in Streams Across the Western United States. Salt Lake City, Utah, U.S. Geological Survey.

Brederveld, R.J., et al. (2011). "Dispersal as a limiting factor in the colonization of restored mountain streams by plants and macroinvertebrates." Journal of Applied Ecology **48**(5):1241–1250.

> 1. Over the past centuries, European streams have been heavily influenced by humans through pollution and regulation. As a result, the quality and diversity of freshwater riparian habitats have declined strongly, and the diversity of riparian flora and fauna has decreased. Recent restoration measures have resulted in stream habitat improvements, but biodiversity improvements have failed to follow in fragmented streams. It has been suggested that dispersal limitation could play an important role in the lack of biodiversity improvement in restored streams, but to date, there is no conclusive evidence for this assumption. 2. In this study, we investigated whether colonization of restored streams by plants and macroinvertebrates is limited by dispersal. We hypothesized that colonization success increases with increasing availability of (nearby) source populations and with increasing ability of species to disperse over long distances. We related species composition in seven restored stream sections to species' abundances in the surroundings and to species' dispersal abilities. 3. For both plants and macroinvertebrates, colonization success is strongly related to the abundance of species in the local and regional species pools. 4. For plants, dispersal strategy has an additional influence on colonization success: short-lived plants with high production of small, well-dispersed seeds colonized best within the 3- to 5-year period after restoration. 5. The existence of dispersal strategy constraints could not be confirmed in macroinvertebrates, possibly because these are limited by a lack of connectivity on larger spatial scales. On the landscape scale, beneficial effects of increased plant diversity might further improve habitat suitability for macroinvertebrates. 6. Synthesis and applications. Dispersal appears to be a limiting factor for successful (re)colonization of restored streams in fragmented landscapes. In plants, this is attributed to limitations in seed dispersal abilities and likely to a lack of nearby source populations as well. In macroinvertebrates, lack of nearby source populations may also be a limiting factor. Hence, we suggest restoring landscape connectivity at larger spatial scales and optimizing the availability of near-natural 'source' areas in the vicinity of restoration projects, at least for plants, to improve the success of biodiversity restoration in fragmented habitats.

Bryant, M.D. (1995). "PULSED MONITORING FOR WATERSHED AND STREAM RESTORATION." Fisheries **20**(11): 6–13.

> Long-term habitat degradation has increased public recognition of the need for watershed and stream habitat restoration. With such recognition is the demand for accountability, but the effects of restoration and recovery of watersheds are complex and long-term. A monitoring program that provides sufficient information to evaluate the effectiveness of these efforts will be expensive. A pulsed monitoring strategy that consists of a series of short-term (3-5 years), high-intensity studies separated by longer periods (10-15 years) of low-density data collection can provide an effective means of implementing a long-term monitoring program with a reasonable degree of success and cost.

Buchanan, B.P., et al. (2012). "Monitoring and assessment of a river restoration project in central New York." River Research and Applications **28**(2):216–233.

> A widespread lack of post-project appraisals (PPAs) not only hinders progress in the field of river restoration but also limits the application of adaptive management a powerful heuristic tool particularly well suited to dynamic fluvial environments. In an effort to contribute to the limited body of scientific literature pertaining to PPAs, we evaluated a stream restoration project completed in the fall of 2005 in central New York. Using a variety of evaluation approaches, we documented both successes (e.g. enhanced in-stream habitat) and short-comings (e.g. channel avulsions). Overall, we concluded that the project was marginally successful in achieving its stated goals and that future prospects remain uncertain based on current trajectory. Lessons learned from this monitoring study include: (i) protect vulnerable banks and floodplains until vegetation is established, e.g. via integrated bio- and geo-technical methods, (ii) perform scour depth analyses and excavate scour pools associated with hydraulic structures to design depth to prevent clogging of the channel during post-construction floods, (iii) orient bank vanes such that cross-stream flows are not deflected towards the bank, (iv) cross-validate restoration designs via multiple methods, including process-based sediment transport relations, especially in unstable gravel-bed rivers, (v) anticipate and fund for fixing natural channel design (NCD) projects for 35 years after completion to account for uncertainties and (vi) identify measurable, goal-specific success criteria that account for watershed scale stressors and site constraints prior to construction to facilitate successful project design and ensure effective outcomes appraisal. Copyright (C) 2010 John Wiley & Sons, Ltd.

Bukaveckas, P. (2007). "Effects of channel restoration on water velocity, transient storage, and nutrient uptake in a channelized stream." Environmental Science & Technology **41**(5):1570–1576.

> Channel design is an important component of stream restoration, but little is known of the interplay between hydrogeomorphic features and ecosystem processes within designed channels. Water velocity, transient storage, and nutrient uptake were measured in channelized (prerestoration) and naturalized (postrestoration) reaches of a 1 km segment of Wilson Creek (KY) to assess the effects of restoration on mechanisms of nutrient retention. **Stream restoration decreased flow velocity and reduced the downstream transport of nutrients. Median travel time was 50% greater in the restored channel due to lower reach scale water velocity and the longer length of the meandering channel.** Transient storage and the influence of transient storage on travel time were largely unaffected except in segments where backwater areas were created. First order uptake rate coefficients for N and P were 30- and 3-fold higher (respectively) within the restored channel relative to its channelized state. Changes in uptake velocities were comparatively small, suggesting that restoration had little effect on biochemical demand. **Results from this study suggest that channel naturalization enhances nutrient uptake by slowing water velocity.** Solute injection experiments revealed differences in the functional

properties of channelized, restored, and reference streams and provided a means for quantifying benefits associated with restoration of ecosystem services.

Burns, M.J., et al. (2012). "Hydrologic shortcomings of conventional urban stormwater management and opportunities for reform." Landscape and Urban Planning **105**(3):230–240.

Conventional approaches to stormwater management for environmental protection fail because they do not address all of the changes to the flow regime caused by conventional stormwater drainage. In this paper, we contrasted the hydrologic effects of two conventional approaches to urban stormwater management - (a) drainage-efficiency focused and (b) pollutant-load-reduction focused - identifying their shortcomings and contrasting their hydrologic outcomes with those of a proposed alternative approach focused on restoring important elements of the natural flow regime. Under conventional approaches, both high-flow and low-flow hydrology remain perturbed. We suggest that urban stormwater management should emphasize the restoration or protection of natural hydrologic processes at small scales, with the aim of restoring natural flow regimes at larger scales downstream. We therefore suggest that, despite recent advances in managing stormwater to reduce pollutant loads and peak flow rates, a more complete approach is needed, one which includes as a goal the restoration or protection of ecologically important elements of the pre-development hydrograph. We propose an approach, flow-regime management, which aims as much as possible to restore and protect ecological structure and function of urban streams by retaining the pre-urban frequency of untreated storm flows, reducing the total stormwater runoff volume through evapotranspiration or harvesting, and delivering filtered flow rates to match pre-urban baseflow rates. We note, however, that the cumulative effects of urban stormwater management at smaller scales on catchment-scale hydrology are not yet fully understood. Crown Copyright (C) 2011 Published by Elsevier B.V. All rights reserved.

Canobbio, S., et al. (2013). "A multivariate approach to assess habitat integrity in urban streams using benthic macroinvertebrate metrics." Water Science and Technology **67**(12):2832–2837.

Benthic macroinvertebrates are widely used as indicators of the health of freshwater ecosystems, responding both to water quality and to the hydromorphological integrity. In urban streams, evaluations can be tricky for the synergistic effects of multiple stressors and confounding factors. In these situations, the most broadly used multimetric indices can be used to assess the overall damage to the invertebrate community and, thus, the overall anthropogenic pressure, but they do not allow to understand the specific causal effects. Particularly, habitat loss due to morphological alterations can be difficult to evaluate, especially due to the often concurrent disturbance caused by water pollution. We used a multivariate approach to focus on the characteristics of the streams and rivers in an urban district and to define which macroinvertebrate metrics should be used to assess the influence of the different kinds of alteration in a severely damaged environment. Some metrics enabling the assessment of habitat loss (ratio of oligochaeta, ratio of filterers) were identified.

These metrics may help to raise a better awareness in the evaluation of river restoration success and, thus, in the support of decision-making processes.

Chang, H., et al. (2014). "Relationships between environmental governance and water quality in a growing metropolitan area of the Pacific Northwest, USA." Hydrology and Earth System Sciences **18**(4):1383–1395.

We investigate relationships between environmental governance and water quality in two adjacent growing metropolitan areas in the western US. While the Portland, Oregon and Vancouver, Washington metro areas share many common biophysical characteristics, they have different land development histories and water governance structures, providing a unique opportunity for examining how differences in governance might affect environmental quality. We conceptualize possible linkages in which water quality influences governance directly, using monitoring efforts as a metric, and indirectly by using the change in the sale price of single-family residential properties. Governance may then influence water quality directly through riparian restoration resulting from monitoring results and indirectly through land use policy. We investigate evidence to substantiate these linkages. Our results showed that changes in monitoring regimes and land development patterns differed in response to differences in growth management policy and environmental governance systems. Our results also showed similarities in environmental quality responses to varying governance systems. For example, we found that sales prices responded positively to improved water quality (e.g., increases in DO and reductions in bacteria counts) in both cities. Furthermore, riparian restoration efforts improved over time for both cities, indicating the positive effect of governance on this land-based resource that may result in improved water quality. However, as of yet, there were no substantial differences across study areas in water temperature over time, despite an expansion of these urban areas of more than 20% over 24 years. The mechanisms by which water quality was maintained was similar in the sense that both cities benefited from riparian restoration, but different in the sense that Portland benefited indirectly from land use policy. A combination of long-term legacy effects of land development, and a relatively short history of riparian restoration in both the Portland and Vancouver regions, may have masked any subtle differences between study areas. An alternative explanation is that both cities exhibited combinations of positive indirect and direct water quality governance that resulted in maintenance of water quality in the face of increased urban growth. These findings suggest that a much longer-term water quality monitoring effort is needed to identify the effectiveness of alternative land development and water governance policies.

Clausen, J.C. (2007). Jordan Cove Watershed Project: Final Report. Storrs, Connecticut, Department of Natural Resources Management and Engineering, University of Connecticut**:** 113.

BMP Watershed
The volume of stormwater runoff from the BMP Watershed decreased (-97%) during the construction period and remained lower than expected (-74%) during the post-

construction period. During construction, the concentrations of TSS, NO3-N, NH3-N, TKN, and TP increased. Following construction, TSS, NO3-N, TP, and TKN concentrations remained higher than expected but metals decreased. NH3-N concentrations were also lower but near detection limits. Concentration peaks during construction were associated with turfgrass development. Exports from the BMP watershed generally did not change during the construction period, except for TSS and TP which increased and Zn which decreased. **Following construction, exports generally decreased except TSS and TP, which increased.**

Traditional Watershed

During construction and following construction, stormwater runoff from the traditional watershed increased. During construction, concentrations either did not change, or for TKN and TP, declined. Following construction, TSS, TKN, and TP concentrations declined. However, exports increased for all variables during both construction and post-construction periods, except for Pb following construction. The increase in flow controlled these export increases. The erosion and sediment controls used during construction appeared to work at this site.

Driveway Runoff Study

Stormwater runoff and mass export of solids, nutrients, and metals was greater from the asphalt than the pavers than the crushed stone driveways. Concentrations of solids, nutrients and metals were lower in runoff from the paver driveways than the asphalt driveways. Concentrations of TP and Pb were lower in runoff from the crushed stone driveways than from the asphalt driveways.

Lawn Nutrient Study

NO3-N desorbed from AEM strips, soil water NO3-N concentrations and plant reflectance all indicate that the BMP lawns being monitored have lower values than the non-BMP lawns. Soil P concentrations in the BMP watershed were ranked medium during the study.

Household Survey

The survey of residents in the three watersheds revealed little differences among their behaviors. BMP residents mulch their leaves and mow their own lawns compared to the control watershed. No differences in fertilizer habits were observed. There were also no differences in behaviors across years within each watershed.

Conclusions and Recommendations

The BMPs used were able to keep runoff volume and peak at predevelopment levels, which was a project goal. Reduced N and P export goals were also met but TSS export goals were not met. For future projects, cluster designs, LID-based regulations and stormwater disconnects are recommended. Future construction projects should control compaction, maximize undisturbed soils, and use on-site supervision. **Earthen berms were an effective BMP**. Sediment control for swales and following soil test recommendations are important. Following construction, maintenance of bioretention areas, infiltrating pavers, turf dams, and appropriate

grass mixes is needed. Further study is needed of groundwater effects, behavioral social indicators, the economics of LID, and soil testing.

Clements, W.H., et al. (2010). "Use of ecological thresholds to assess recovery in lotic ecosystems." Journal of the North American Benthological Society **29**(3):1017–1023.

Ecological thresholds have been applied conventionally to characterize relationships between stressors and biological responses. We demonstrated how ecological thresholds can be used to assess recovery in a system where stressors have been removed. We applied a relatively new statistical approach, the significant zero crossings (SiZer) model, which approximates a response function and its derivatives and then shows how these functions vary across the range of an explanatory variable. We applied the model to a long-term macroinvertebrate data set collected from the Arkansas River, a Colorado stream undergoing restoration from historical mining pollution. SiZer analysis identified distinct threshold responses of benthic communities through time and related these shifts to improvements in water quality. With respect to restoration success, a recovery threshold was observed similar to 10 y after clean up was initiated. Recovery trajectories in the Arkansas River were relatively complex, with multiple thresholds, and these responses were strongly influenced by temporal variation in heavy metal concentrations and stream discharge. A unique aspect of SiZer is that it easily handles multiple thresholds and displays significant change points along a predictor variable graphically. In addition, SiZer allows investigators to examine potential thresholds at different levels of resolution and provides a transparent representation of the threshold and how it responds to variability of the data.

Cockerill, K. and W.P. Anderson (2014). "Creating False Images: Stream Restoration In An Urban Setting." Journal of the American Water Resources Association **50**(2):468–482.

Stream restoration has become a multibillion dollar business with mixed results as to its efficacy. This case study utilizes pre- and post-monitoring data from restoration projects on an urban stream to assess how well stream conditions, publicly stated project goals, and project implementation align. Our research confirms previous studies showing little communication among academic researchers and restoration practitioners as well as provides further evidence that restoration efforts tend to focus on small-scale, specific sites without considering broader land use patterns. This study advances our understanding of restoration by documenting that although improving ecological conditions is a stated goal for restoration projects, the implemented measures are not always focused on those issues that are the most ecologically salient. What these projects have accomplished is to protect the built environment and promote positive public perception. We argue that these disconnects among publicized goals for restoration, the implemented features, and actual stream conditions may create a false image of what an ecologically stable stream looks like and therefore perpetuate a false sense of optimism about the feasibility of restoring urban streams.

Cuffney, T.F., et al. (2010). "Responses of benthic macroinvertebrates to environmental changes associated with urbanization in nine metropolitan areas." Ecological Applications **20**(5):1384–1401.

> Responses of benthic macroinvertebrates along gradients of urban intensity were investigated in nine metropolitan areas across the United States. Invertebrate assemblages in metropolitan areas where forests or shrublands were being converted to urban land were strongly related to urban intensity. In metropolitan areas where agriculture and grazing lands were being converted to urban land, invertebrate assemblages showed much weaker or nonsignificant relations with urban intensity because sites with low urban intensity were already degraded by agriculture. Ordination scores, the number of EPT taxa, and the mean pollution-tolerance value of organisms at a site were the best indicators of changes in assemblage condition. Diversity indices, functional groups, behavior, and dominance metrics were not good indicators of urbanization. Richness metrics were better indicators of urban effects than were abundance metrics, and qualitative samples collected from multiple habitats gave similar results to those of single habitat quantitative samples (riffles or woody snags) in all metropolitan areas. Changes in urban intensity were strongly correlated with a set of landscape variables that was consistent across all metropolitan areas. In contrast, the instream environmental variables that were strongly correlated with urbanization and invertebrate responses varied among metropolitan areas. The natural environmental setting determined the biological, chemical, and physical instream conditions upon which urbanization acts and dictated the differences in responses to urbanization among metropolitan areas. Threshold analysis showed little evidence for an initial period of resistance to urbanization. Instead, assemblages were degraded at very low levels of urbanization, and response rates were either similar across the gradient or higher at low levels of urbanization. Levels of impervious cover that have been suggested as protective of streams (5–10%) were associated with significant assemblage degradation and were not protective.

DeGasperi, C.L., et al. "Linking Hydrologic Alteration to Biological Impairment in Urbanizing Streams of the Puget Lowland, Washington, USA." Journal of the American Water Resources Association **45** (2) (2009): 512–533.

> We used a retrospective approach to identify hydrologic metrics with the greatest potential for ecological relevance for use as resource management tools (i.e., hydrologic indicators) in rapidly urbanizing basins of the Puget Lowland. We proposed four criteria for identifying useful hydrologic indicators: (1) sensitive to urbanization consistent with expected hydrologic response, (2) demonstrate statistically significant trends in urbanizing basins (and not in undeveloped basins), (3) be correlated with measures of biological response to urbanization, and (4) be relatively insensitive to potentially confounding variables like basin area. Data utilized in the analysis included gauged flow and benthic macroinvertebrate data collected at 16 locations in 11 King County stream basins. Fifteen hydrologic metrics were calculated from daily average flow data and the Pacific Northwest Benthic Index of Biological Integrity (B-IBI) was used to represent the gradient of response of stream macroinvertebrates to

urbanization. Urbanization was represented by percent Total Impervious Area (%TIA) and percent urban land cover (%Urban). We found eight hydrologic metrics that were significantly correlated with B-IBI scores (Low Pulse Count and Duration; High Pulse Count, Duration, and Range; Flow Reversals, TQmean, and R-B Index). Although there appeared to be a great deal of redundancy among these metrics with respect to their response to urbanization, only two of the metrics tested – High Pulse Count and High Pulse Range – best met all four criteria we established for selecting hydrologic indicators. The increase in these high pulse metrics with respect to urbanization is the result of an increase in winter high pulses and the occurrence of high pulse events during summer (increasing the frequency and range of high pulses), when practically none would have occurred prior to development. We performed an initial evaluation of the usefulness of our hydrologic indicators by calculating and comparing hydrologic metrics derived from continuous hydrologic simulations of selected basin management alternatives for Miller Creek, one of the most highly urbanized basins used in our study. We found that the preferred basin management alternative appeared to be effective in restoring some flow metrics close to simulated fully forested conditions (e.g., TQmean), but less effective in restoring other metrics such as High Pulse Count and Range. If future research continues to support our hypothesis that the flow regime, particularly High Pulse Count and Range, is an important control of biotic integrity in Puget Lowland streams, it would have significant implications for stormwater management.

Deletic, A., et al. (2012). "Assessing uncertainties in urban drainage models." Physics and Chemistry of the Earth **42-44**:3–10.

The current state of knowledge regarding uncertainties in urban drainage models is poor. This is in part due to the lack of clarity in the way model uncertainty analyses are conducted and how the results are presented and used. There is a need for a common terminology and a conceptual framework for describing and estimating uncertainties in urban drainage models. Practical tools for the assessment of model uncertainties for a range of urban drainage models are also required to be developed. This paper, produced by the International Working Group on Data and Models, which works under the IWA/IAHR Joint Committee on Urban Drainage, is a contribution to the development of a harmonised framework for defining and assessing uncertainties in the field of urban drainage modelling. The sources of uncertainties in urban drainage models and their links are initially mapped out. This is followed by an evaluation of each source, including a discussion of its definition and an evaluation of methods that could be used to assess its overall importance. Finally, an approach for a Global Assessment of Modelling Uncertainties (GAMU) is proposed, which presents a new framework for mapping and quantifying sources of uncertainty in urban drainage models. Crown Copyright (C) 2011 Published by Elsevier Ltd. All rights reserved.

Dietz, M.E. and J.C. Clausen (2008). "Stormwater runoff and export changes with development in a traditional and low impact subdivision." Journal of Environmental Management **87**(4):560–566.

Development continues at a rapid pace throughout the country. Runoff from the impervious surfaces in these watersheds continues to be a major cause of degradation to freshwater bodies and estuaries. Low impact development techniques have been recommended to reduce these impacts. **In this study, stormwater runoff and pollutant concentrations were measured as development progressed in both a traditional development, and a development that used low impact development techniques.** Increases in total impervious area in each watershed were also measured. Regression relationships were developed between total impervious area and stormwater runoff/pollutant export. Significant, logarithmic increases in stormwater runoff and nitrogen and phosphorus export were found as development occurred in the traditional subdivision. The increases in stormwater runoff and pollutant export were more than two orders of magnitude. TN and TP export after development was 10 and 1 kg ha(-1) yr(-1), respectively, which was consistent with export from other urban/developed areas. In contrast, stormwater runoff and pollutant export from the low impact subdivision remained unchanged from pre-development levels. TN and TP export from the low impact subdivision were consistent with export values from forested watersheds. The results of this study indicate that the use of low impact development techniques on a watershed scale can greatly reduce the impacts of development on local waterways.

Dietz, M.E., et al. (2004). "Education and changes in residential nonpoint source pollution." Environmental Management **34**(5): 684–690.

Urban areas contribute pollutants such as excess nitrogen and bacteria to receiving water bodies. The objective of this project was to determine if stormwater quality could be improved by **educating homeowners** and implementing best management practices (BMPs) in a suburban neighborhood. **The paired watershed design was used, where a control and treatment watershed are monitored during a calibration and treatment period.** Treatment consisted of the education of homeowners and structural changes designed to minimize nonpoint pollution. Some changes in measured behavior were reported. According to the treatment period survey, 11% of respondents in the treatment watershed began fertilizing their lawn based on the results of a soil test, whereas none had done so previously. In addition, 82% of respondents in the treatment watershed stated that they left clippings on the lawn compared to 62% from the initial survey. Twelve of 34 lots (35%) adopted some BMPs following education efforts, indicating a significant (P = 0.001) increase in BMP use overall. However, a chi(2) analysis of survey data indicated no significant changes in measured behavior with regard to specific questions. Analysis of covariance (ANCOVA) results indicated that a 75% reduction in nitrite + nitrate - N (change in intercept, P = 0.001) and a 127% reduction in fecal coliform bacteria (change in slope, P = 0.05) concentrations occurred. However, the treatment period regression was nonsignificant for bacteria. Total nitrogen, total phosphorus, and ammonia-N concentrations did not change significantly. Intensive education efforts produced BMP implementation and measurable water quality improvements.

Doll, B.A., et al. (2014). "Evaluating the Eco-Geomorphological Condition of Restored Streams Using Visual Assessment and Macroinvertebrate Metrics." JAWRA Journal of the American Water Resources Association: 1–16.

The Stream Performance Assessment (SPA), a new rapid assessment method, was applied to 93 restored, 21 impaired, 29 reference, and 13 reference streams with some incision throughout North Carolina. Principal component analysis (PCA) indicated restored streams align more closely with reference streams rather than impaired streams. Further, PCA-based factor analysis revealed restored streams were similar to reference streams in terms of morphologic condition, but exhibited a greater range of scores relative to aquatic habitat and bedform. Macroinvertebrate sampling and GIS watershed analyses were conducted on 84 restored streams. SPA and watershed data were compared to Ephemeroptera, Plecoptera, and Trichoptera (EPT) taxa to determine which factors indicate stream health. SPA and watershed factors were used in least squares, ridge, and principal component regression (PCR) to develop a prediction model for EPT taxa. All three methods produced reasonable predictions for EPT taxa. Cross-validation indicated ridge regression resulted in the lowest prediction error. The ridge model was then used to predict EPT taxa numbers for 21 impaired and 25 reference streams in addition to the 84 restored streams. Statistical comparisons of the predicted scores indicated urban streams (>10% impervious watershed cover) have lower expected numbers of EPT taxa. Rural restored streams have macroinvertebrate metric scores similar to those predicted for rural reference streams.

Fausch, K.D., et al. (1995). "The role of dispersal in trout population response to habitat formed by large woody debris in Colorado mountain streams." Bulletin Francais De La Peche Et De La Pisciculture **337-339**:179–190.

Fishery managers commonly use logs to create pool habitat for salmonids in mountain streams throughout the world, often to compensate for a lack of natural large woody debris (LWD) due to deforestation or other disturbances in riparian forests. Measurements of LWD in 11 Colorado mountain streams that drain patches of old-growth spruce-fir (Picea-Abies) forest indicated that most pools were formed by LWD. These pool-forming pieces were, on average, larger than pieces that did not form pools. The majority spanned the channel perpendicular to flow and formed plunge and dammed pools. Fishery managers that use perpendicular logs to form pools generally assume that the added habitat will increase survival of resident salmonids during critical periods such as winter. Results of a long-term experiment to test this hypothesis in six Colorado mountain streams showed that resident trout populations increased rapidly and significantly in 250-m treatment sections versus adjacent controls. **However, recaptures of marked trout and direct trapping to measure dispersal indicated that the pool-forming logs increased adult trout populations primarily by inducing fish that were moving to remain in the treatment sections, rather than by increasing in situ overwinter survival as reported by others.**

Research and management of resident stream salmonids has been guided by the restricted movement paradigm, which states that most adult fish are relatively sedentary. However, analysis of previous movement studies revealed that most investigators focused only on fish recaptured in the reaches where they were released, a critical design flaw that causes a bias against detecting movement. Substantial fish movement has important implications for habitat enhancement and restoration, and calls for a watershed management approach.

Filoso, S. and M.A. Palmer (2011). "Assessing stream restoration effectiveness at reducing nitrogen export to downstream waters." Ecological Applications **21**(6):1989–2006.

The degradation of headwater streams is common in urbanized coastal areas, and the role these streams play in contributing to downstream pollution is a concern among natural resource managers and policy makers. Thus, many urban stream restoration efforts are increasingly focused on reducing the downstream flux of pollutants. In regions that suffer from coastal eutrophication, it is unclear whether stream restoration does in fact reduce nitrogen (N) flux to downstream waters and, if so, by how much and at what cost. In this paper, we evaluate whether stream restoration implemented to improve water quality of urban and suburban streams in the Chesapeake Bay region, USA, is effective at reducing the export of N in stream flow to downstream waters. We assessed the effectiveness of restored streams positioned in the upland vs. lowland regions of Coastal Plain watershed during both average and stormflow conditions. We found that, during periods of low discharge, lowland streams that receive minor N inputs from groundwater or bank seepage reduced in-stream N fluxes. Furthermore, lowland streams with the highest N concentrations and lowest discharge were the most effective. During periods of high flow, only those restoration projects that converted lowland streams to stream-wetland complexes seemed to be effective at reducing N fluxes, presumably because the design promoted the spillover of stream flow onto adjacent floodplains and wetlands. The observed N-removal rates were relatively high for stream ecosystems, and on the order of 5% of the inputs to the watershed. The dominant forms of N entering restored reaches varied during low and high flows, indicating that N uptake and retention were controlled by distinctive processes during different hydrological conditions. Therefore, in order for stream restoration to effectively reduce N fluxes exported to downstream waters, restoration design should include features that enhance the processing and retention of different forms of N, and for a wide range of flow conditions. The use of strategic designs that match the dominant attributes of a stream such as position in the watershed, influence of groundwater, dominant flow conditions, and N concentrations is crucial to assure the success of restoration.

Fletcher, T.D., et al. (2014). "Protection of stream ecosystems from urban stormwater runoff: The multiple benefits of an ecohydrological approach." Progress in Physical Geography **38**(5):543–555.

There is now widespread recognition of the degrading influence of urban stormwater runoff on stream ecosystems and of the need to mitigate these impacts using

stormwater control measures. Unfortunately, however, understanding of the flow regime requirements to protect urban stream ecosystems remains poor, with a focus typically on only limited aspects of the flow regime. We review recent literature discussing ecohydrological approaches to managing urban stormwater and, building on the natural flow paradigm, identify ecologically relevant flow metrics that can be used to design stormwater control measures to restore more natural magnitude, duration, timing, frequency and variability of both high and low flows. Such an approach requires a consideration of the appropriate flow and water quality required by the receiving water, and the application of techniques at or near source to meet appropriate flow regime and water quality targets. The ecohydrological approach provides multiple benefits beyond the health of urban streams, including flood mitigation, water supply augmentation, human thermal comfort, and social amenity. There are, however, uncertainties that need to be addressed. Foremost is the need to define ecologically and geomorphically appropriate flow regimes for channels which have already been modified by existing land use. Given the excess of water generated by impervious surfaces, there is also an urgent need to test the feasibility of the natural flow paradigm in urban streams, for example using catchment-scale trials.

Fletcher, T.D., et al. (2011). "Restoration of stormwater retention capacity at the allotment-scale through a novel economic instrument." Water Science and Technology **64**(2):494–502.

Urbanisation results in changes to runoff behaviour which, if not addressed, inevitably degrade receiving waters. To date, most stormwater management has focussed on the streetscape and public open space. Given that much of the catchment imperviousness is located on private land, we developed and tested a novel economic instrument (a uniform price auction) for encouraging allotment-scale stormwater retention. We evaluated bids using an integrated environmental benefit index (EBI), based on the ability of the proposed works to reduce runoff frequency, pollutant loads and to reduce potable water demand. The uniform price auction resulted in 1.4 ha of impervious areas being effectively 'disconnected' from the stormwater system. The EBI provided an objective and transparent method of comparing bids, which varied in the type of works proposed (e.g. rainwater tank, rain-garden), the cost and the resulting environmental benefit. Whilst the pilot auction was a success, the public subsidy of works undertaken was around 85%, meaning that property owners a relatively small private benefit in the works. Future auction rounds will be revised to (i) test an EBI which is more focussed on the protection of streams (assessing changes to runoff frequency, baseflow volumes and water quality) and (ii) provide an auction process which is simpler to understand, and provides greater practical support for landholders who wish to undertake works.

Frissell, C. and R. Nawa (1992). "Incidence and Causes of Physical Failure of Artificial Habitat Structures in Streams of Western Oregon and Washington." North American Journal of Fisheries Management **12**(1):182–197.

In recent years an increasing share of fishery management resources has been committed to alteration offish habitat with artificial stream structures. **We evaluated**

rates and causes of physical impairment or failure for 161 fish habitat structures in 15 streams in southwest Oregon and southwest Washington, following a flood of a magnitude that recurs every 2-10 years. The incidence of functional impairment and outright failure varied widely among streams; the **median failure rate was 18.5% and the median damage rate (impairment plus failure) was 60%**. Modes of failure were diverse and bore no simple relationship to structure design. Damage was frequent in low-gradient stream segments and widespread in streams with signs of recent watershed disturbance, high sediment loads, and unstable channels. Comparison of estimated 5–10-year damage rates from 46 projects throughout western Oregon and southwest Washington showed high but variable rates (median, 14%; range, 0–100%) in regions where peak discharge at 10-year recurrence intervals has exceeded 1.0 m3s–1km–2. **Results suggest that commonly prescribed structural modifications often are inappropriate and counterproductive in streams with high or elevated sediment loads, high peak flows, or highly erodible bank materials.** Restoration of fourth-order and larger alluvial valley streams, which have the greatest potential for fish production in the Pacific Northwest, will require reestablishment of natural watershed and riparian processes over the long term.

Grimm, N.B., et al. (2000). "Integrated approaches to long-term studies of urban ecological systems." BioScience **50**(7):571–584.

We cannot confine ourselves to the so-called "natural" entities and ignore the processes and expressions of vegetation now so abundantly provided by man. Such a course is not scientifically sound because scientific analysis must penetrate beneath the forms of the "natural" entities, and it is not practically useful because ecology must be applied to conditions brought about by human activity. The "natural" entities and the anthropogenic derivates alike must be analyzed in terms of the most appropriate concepts we can find.

Haase, P., et al. (2013). "The impact of hydromorphological restoration on river ecological status: a comparison of fish, benthic invertebrates, and macrophytes." Hydrobiologia **704**(1):475–488.

The European Water Framework Directive (WFD) has led to an increase in hydromorphological restoration attempts in European rivers, but data on the ecological responses of rivers to these restoration attempts are scarce. We investigated the effects of 24 hydromorphological river restoration projects in Germany. We compared hydromorphological parameters and biological diversity of macroinvertebrates, fish, and macrophytes in restored reaches to nearby unrestored sections. We applied, for the first time, the WFD to assess the results of these restoration projects. While hydromorphology changed significantly in the restored sections, differences between restored and unrestored sections in terms of biological parameters were lower. Positive restoration effects were observed for fish (11 of 24 cases) only. Based on the synthesis of results from the different organism groups, only one of the 24 restored sections reached a "good" Ecological Quality Class as demanded by the WFD. Our results indicate that stressors other than hydromorphological degradation still affect the biota in restored sections. We emphasize the need for advanced restoration strategies based on catchment analyses considering water pollution, source populations, and dispersal capacities of sensitive species, and recommend the inclusion of additional parameters, including societal and stakeholder perspectives, in assessing the initial success of restoration projects.

Hammersmark, C.T., et al. (2008). "Quantifying the hydrological effects of stream restoration in a montane meadow, northern California, USA." River Research and Applications **24**(6):735–753.

Stream restoration efforts, particularly within meadow systems, increasingly rely on 'pond and plug' type methods in which (a) alluvial materials are excavated from the floodplain, forming ponds; (b) excavated alluvial materials are used to plug incised channels and (c) smaller dimension channels are restored to the floodplain surface. A commonly stated objective of these efforts is to restore ecologically significant hydrological processes to degraded riparian systems. However, little research has been conducted to evaluate and quantify the restoration of these hydrological processes. Direct comparisons of pre- and post-restoration hydrological observations are often misleading due to an inter-annual climatic variability. To overcome this issue and accurately quantify the hydrological effects of restoration, we developed, calibrated and validated a hydrological model of a 230 ha mountain meadow along a 3.6 km restored reach of Bear Creek in the northeastern California. We then applied the model to simulate the pre- and post-restoration scenarios by altering the floodplain topography and stream channel networks. Our results document three general hydrological responses to the meadow restoration effort: (1) increased groundwater levels and volume of subsurface storage; (2) increased frequency/duration of floodplain inundation and decreased magnitude of flood peaks and (3) decreased annual runoff and duration of baseflow. This study supports and quantifies the hypothesis that 'pond and plug' type stream restoration projects have the capacity to re-establish hydrological processes necessary to sustain riparian systems. In addition, the results of this study can be used to improve quantitative objectives for 'pond and plug' type stream restoration activities in similar settings. Copyright (C) 2008 John Wiley & Sons, Ltd.

Heinrich, K.K., et al. (2014). "Cascading Ecological Responses to an In-Stream Restoration Project in a Midwestern River." Restoration Ecology **22**(1):72–80.

River restoration projects are increasingly common, but assessments of ecological responses and overall success of the vast majority of efforts are lacking. Information on potential positive ecological effects of restoration efforts can be used to justify further projects and refine methods. We examined responses of multiple trophic levels, aquatic insects and riparian birds, to a series of rock weirs installed in an Illinois river to stabilize the channel. We quantified adult insect emergence and performed weekly point counts of birds in spring at four weir and four non-weir (control) sites. Emerging insect abundance was higher at control sites, but species richness and diversity were higher at weir sites. Total insect emergence production did not differ between site types, but emergence production of larger-bodied taxa was higher at weir sites. Ordinations and analysis of similarity indicated differences in insect and bird assemblages between site types. Birds showed a positive numerical response to large-bodied emerging insects, and total bird abundance was higher at weir sites. Clutch size and feeding rates of a focal bird species, Prothonotaria citrea (Prothonotary Warbler), did not differ between sites, but the number of hatchlings and fledglings was higher at control sites. Molothrus ater (cowbird) parasitism was higher at weir sites, likely because of increased edge habitat associated with weir construction activities. Results show positive ecological impacts of in-stream restoration and provide justification for further efforts. However, forest disturbance associated with construction could offset some benefits to some species, and thus refinements to procedures may be necessary.

Henshaw, P.C. and D.B. Booth (2000). "Natural restabilization of stream channels in urban watersheds." Journal of the American Water Resources Association **36**(6):1219–1236.

Stream channels are known tb change their form as a result of watershed urbanization, but do they restabilize under subsequent conditions of constant urban land use? Streams in seven developed and developing watersheds (drainage areas 5–35 km(2)) in the Puget Sound lowlands were evaluated for their channel stability and degree of urbanization, using geld and historical data. Protocols for determining channel stability by visual assessment, calculated bed mobility at bankfull flows, and resurveyed cross-sections were compared and yielded nearly identical results. We found that channel restabilization generally does occur within one or two decades of constant watershed land use, but it is not universal. When (or if) an individual stream will restabilize depends on specific hydrologic and geomorphic characteristics of the channel and its watershed; observed stability is not well predicted by simply the magnitude of urban development or the rate of ongoing land-use change. The tendency for channel restabilization suggests that management efforts focused primarily on maintaining stability, particularly in a still-urbanizing watershed, may not always be necessary. Yet physical stability alone is not a sufficient condition for a biologically healthy stream, and additional rehabilitation measures will almost certainly be required to restore biological conditions in urban systems.

Hilderbrand, R.H., et al. (1997). "Effects of large woody debris placement on stream channels and benthic macroinvertebrates." Canadian Journal of Fisheries and Aquatic Sciences **54**(4):931–939.

Large woody debris (LWD) was added as an experimental stream restoration technique in two streams in southwest Virginia. Additions were designed to compare human judgement in log placements against a randomized design and an unmanipulated reach, and also to compare effectiveness in a low- and a high-gradient stream. **Pool area increased 146% in the systematic placement and 32% in the random placement sections of the low-gradient stream, lending support to the notion that human judgement can be more effective than placing logs at random in low-gradient streams. Conversely, the high-gradient stream changed very little**

after LWD additions, suggesting that other hydraulic controls such as boulders and bedrock override LWD influences in high-gradient streams. Logs oriented as dams were responsible for all pools created by additions regardless of stream or method of placement. Multiple log combinations created only two pools, while the other seven pools were created by single LWD pieces. **Total benthic macroinvertebrate abundance did not change as a result of LWD additions in either stream**, but net abundances of Plecoptera, Coleoptera, Trichoptera, and Oligochaeta decreased, while Ephemeroptera increased significantly with the proportional increase in pool area in the low-gradient stream.

Hines, S.L. and A.E. Hershey (2011). "Do channel restoration structures promote ammonium uptake and improve macroinvertebrate-based water quality classification in urban streams?" Inland Waters **1**(2):133–145.

Comparisons of ammonium uptake parameters in restored and unrestored urban streams suggest that sufficient light penetration to areas where hard substrates have been installed should be an important management consideration to enhance biofilm accumulation and subsequent ammonium removal to the streambed. We studied ammonium uptake parameters and macroinvertebrate communities in 3 types of restoration structures (riffle, cross vane, and step pool) in restored streams and in unrestored urban streams in Greensboro, North Carolina, USA, where urbanization has led to high nutrient concentrations, degraded channel conditions, and low biotic diversity in streams. Restored streams had a significantly higher percentage of large substrates (boulder, cobble, and gravel) and less canopy cover compared to unrestored streams ($P = 0.029$; t-test), providing substrates and sufficient light penetration for biofilm growth. Benthic chlorophyll a was higher in restored compared to unrestored streams. Significantly shorter ammonium uptake length ($P = 0.02$) was observed in restored compared to unrestored sites. This effect was probably related to greater biofilm development and therefore more assimilation sites for removal of ammonium from the stream water. Differences in uptake velocity ($P < 0.07$) and areal uptake ($P < 0.06$) were not significant. Despite the shorter ammonium uptake length in restored streams, there was little improvement in measures of macroinvertebrate-based water quality classifications between restored and unrestored streams ($P = 0.545$). Because this study was completed 2 years postrestoration, continued, longer-term monitoring of restored streams is needed for full evaluation of the effects of the restoration approaches used in these streams.

Hood, M.J., et al. (2007). "Comparison of stormwater lag times for low impact and traditional residential development." Journal of the American Water Resources Association **43**(4):1036–1046.

This study compared lag time characteristics of low impact residential development with traditional residential development. Also compared were runoff volume, peak discharge, hydrograph kurtosis, runoff coefficient, and runoff threshold. Low impact development (LID) had a significantly greater centroid lag-to-peak, centroid lag, lag-to-peak, and peak lag-to-peak times than traditional development.

Traditional development had a significantly greater depth of discharge and runoff coefficient than LID. The peak discharge in runoff from the traditional development was 1,100% greater than from the LID. The runoff threshold of the LID (6.0 mm) was 100% greater than the traditional development (3.0 mm). The hydrograph shape for the LID watershed had a negative value of kurtosis indicating a leptokurtic distribution, while traditional development had a positive value of kurtosis indicating a platykurtic distribution. The lag times of the LID were significantly greater than the traditional watershed for small (< 25.4 mm) but not large (>= 25.4 mm) storms; short duration (< 4 h) but not long duration (>= 4 h) storms; and low antecedent moisture condition (AMC; < 25.4 mm) storms but not high AMC (>= 25.4 mm) storms. **This study indicates that LID resulted in lowered peak discharge depth, runoff coefficient, and discharge volume and increased lag times and runoff threshold compared with traditional residential development.**

Jahnig, S.C., et al. (2010). "A comparative analysis of restoration measures and their effects on hydromorphology and benthic invertebrates in 26 central and southern European rivers." Journal of Applied Ecology **47**(3):671–680.

Hydromorphological river restoration usually leads to habitat diversification, but the effects on benthic invertebrates, which are frequently used to assess river ecological status, are minor. We compared the effects of river restoration on morphology and benthic invertebrates by investigating 26 pairs of non-restored and restored sections of rivers in Austria, Czech Republic, Germany, Italy and the Netherlands.

2. Sites were grouped according to (1) region: central Europe vs. southern Europe; (2) river type: mountain vs. lowland rivers; (3) restoration approach: active vs. passive restoration and (4) a combination of these parameters. All sites were sampled according to the same field protocol comprising hydromorphological surveys of river and floodplain mesohabitats, microhabitats at the river bottom and habitat-specific sampling of benthic invertebrates. Restoration effects were compared using Shannon-Wiener Indices (SWIs) of mesohabitats, microhabitats and invertebrate communities. Differences in metric values between non-restored and restored sites were compared for 16 metrics that evaluated hydromorphology and the benthic invertebrate community.

3. Mean SWIs differed for both mesohabitats (1 center dot 1 non-restored, 1 center dot 7 restored) and microhabitats (1 center dot 0 non-restored, 1 center dot 3 restored), while SWIs for invertebrate communities were not significantly different (2 center dot 4 non-restored, 2 center dot 3 restored). Meso- and microhabitat metrics in the restored sections were usually higher compared with the non-restored sections, but the effects on invertebrate metrics were negligible.

4. Measures in southern Europe and mountainous regions yielded larger differences between non-restored and restored sections of rivers. Differences in the meso- and microhabitat metrics were largest for actively restored sections of central European mountain rivers and rivers from southern Europe, followed by passively restored mountain rivers in central Europe. The smallest differences were observed for lowland

sites. **There was no significant restoration effect on invertebrate metrics in any categories.**

5. Synthesis and applications. Restoration measures addressing relatively short river sections (several hundred metres) are successful in terms of improving habitat diversity of the river and its floodplain. Active restoration measures are suitable if short-term changes in hydromorphology are desired. To realize changes in benthic invertebrate community composition, habitat restoration within a small stretch is generally not sufficient. We conclude that restoring habitat on a larger scale, using more comprehensive measures and tackling catchment-wide problems (e.g. water quality, source populations) are required for a recovery of the invertebrate community.

Jahnig, S.C., et al. (2011). "River restoration success: a question of perception." Ecological Applications **21**(6):2007–2015.

What defines success and failure of river restoration measures is a strongly debated topic in restoration science, but standardized approaches to evaluate either are still not available. The debate is usually centered on measurable parameters, which adhere to scientific objectivity. More subjective aspects, such as landscape aesthetics or recreational value, are usually left out, although they play an important role in the perception and communication of restoration success. In this paper, we show that different perceptions of restoration success exist by analyzing data from 26 river restoration measures in Germany. We addressed both objective parameters, such as hydromorphological changes and changes in fish and benthic invertebrate assemblages, from field investigations, and subjective parameters, such as opinions and perceptions, from water managers via an online survey. With regard to the objective hydromorphological and biotic parameters, our results agree with many studies that have reported improvements in the hydromorphology following restoration; however, there is no similar agreement between results concerning changes in the benthic invertebrate and fish assemblages. **The objective results do not correspond to the subjective parameters because self-evaluation of the restoration projects by water managers was overly positive. Indeed, 40% of the respondents admitted that their evaluation was based on gut feeling, and only 45% of the restoration measures were monitored or occasionally checked. This lack of objectively recorded data meant that the water managers were not able to reasonably evaluate restoration success.** In contrast, some self-evaluation responses reflected a different perception of the restoration success that was based on landscape aesthetic values or on benefit for the public; others adopted a general "condemned to success" attitude. Based on our data, we argue (1) that goals should be thoughtfully formulated prior to restoration implementation and (2) that it is necessary to monitor river restoration success from different perspectives.

Jansson, R., et al. (2005). "Stating mechanisms and refining criteria for ecologically successful river restoration: a comment on Palmer et al. (2005)." Journal of Applied Ecology **42**(2):218–222.

> 1. To encourage more project assessment and reporting of restoration outcomes, Palmer et al. (2005) propose five criteria for assessing the ecological success of river restoration. They also suggest that these criteria should help to clarify which activities should qualify for ecological restoration funding and facilitate consistency about what constitutes an ecologically successful restoration project. 2. We critique the five criteria and agree they all merit inclusion in an assessment of successful river restoration. However, the practical application of measuring self-sustainability (resilience) following restoration is potentially problematic and an explicit timeframe is needed to evaluate the results of the restoration. 3. A sixth criterion is proposed that encourages specific hypotheses and/or a conceptual model of the ecological mechanisms by which the proposed activities will achieve their target. This would enhance our understanding of the mechanisms at play for successful river restoration, and provide a more powerful deductive framework likely to lead to appropriate practices that can be applied across rivers. To explore the potential practical applicability of these six criteria, we applied them to a recently published example of river restoration to ascertain its ecological success. 4. Synthesis and applications. We agree with the criteria proposed by Palmer et al. (2005), although the problems of measuring resilience and defining a timeline for recovery should be addressed. We suggest strengthening the deductive framework of restoration projects by formulating some sort of conceptual model. This step could involve scientists, and be a useful way of involving science more explicitly in restoration activities. Agreed-upon criteria for successful restoration will greatly facilitate evaluation of river ecosystem recovery at the critical broader scales where our knowledge is still limited.

Johnson, T.A.N., et al. (2014). "Effects of stormwater management and stream restoration on watershed nitrogen retention." Biogeochemistry **121**(1):81–106.

> Restoring urban infrastructure and managing the nitrogen cycle represent emerging challenges for urban water quality. We investigated whether stormwater control measures (SCMs), a form of green infrastructure, integrated into restored and degraded urban stream networks can influence watershed nitrogen loads. We hypothesized that hydrologically connected floodplains and SCMs are "hot spots" for nitrogen removal through denitrification because they have ample organic carbon, low dissolved oxygen levels, and extended hydrologic residence times. We tested this hypothesis by comparing nitrogen retention metrics in two urban stream networks (one restored and one urban degraded) that each contain SCMs, and a forested reference watershed at the Baltimore Long-Term Ecological Research site. We used an urban watershed continuum approach which included sampling over both space and time with a combination of: (1) longitudinal reach-scale mass balances of nitrogen and carbon conducted over 2 years during baseflow and storms (n = 24 sampling dates x 15 stream reaches = 360) and (2) N-15 push-pull tracer experiments to measure in situ denitrification in SCMs and floodplain features (n = 72). The SCMs consisted of inline

wetlands installed below a storm drain outfall at one urban site (restored Spring Branch) and a wetland/wet pond configured in an oxbow design to receive water during high flow events at another highly urbanized site (Gwynns Run). The SCMs significantly decreased total dissolved nitrogen (TDN) concentrations at both sites and significantly increased dissolved organic carbon concentrations at one site. At Spring Branch, TDN retention estimated by mass balance (g/day) was similar to 150 times higher within the stream network than the SCMs. There were no significant differences between mean in situ denitrification rates between SCMs and hydrologically connected floodplains. Longitudinal N budgets along the stream network showed that hydrologically connected floodplains were important sites for watershed nitrogen retention due to groundwater-surface water interactions. Overall, our results indicate that hydrologic variability can influence nitrogen source/sink dynamics along engineered stream networks. Our analysis also suggests that some major predictors for watershed N retention were: (1) streamwater and groundwater flux through stream restoration or stormwater management controls, (2) hydrologic residence times, and (3) surface area of hydrologically connected features.

Jordan, F. and D.A. Arrington (2014). "Piscivore Responses to Enhancement of the Channelized Kissimmee River, Florida, USA." Restoration Ecology **22**(3):418–425.

Evaluation of the success of ecosystem restoration projects requires identification of appropriate ecological metrics. Comparison of reconstructed food webs (or subsets thereof) from restored and non-restored habitats may be a valuable tool to evaluate restoration success because food webs help identify critical predator-prey relationships, keystone species, relative importance of direct and indirect trophic interactions, and other aspects of ecological function. We compared the diets of apex predatory fishes collected from enhanced and non-enhanced portions of the channelized Kissimmee River, Florida, USA to determine whether food web structure responded to experimental hydrologic manipulations. Diets were reconstructed for black crappie (Pomoxis nigromaculatus), bowfin (Amia calva), chain pickerel (Esox niger), Florida gar (Lepisosteus platyrhincus), largemouth bass (Micropterus salmoides), and warmouth (Lepomis gulosus) collected from enhanced and non-enhanced portions of the Kissimmee River. Prey eaten by apex predatory fishes in the enhanced portion of the Kissimmee River were quantitatively and qualitatively different from prey eaten in non-enhanced portions of the river. Predators in the enhanced portion of the river had fewer empty stomachs, more prey items per individual, more prey types per individual, more fish prey per individual, greater overall richness of prey, and a multivariate suite of prey distinct from predators in non-enhanced portions of the river. Results from hydrologic manipulations suggest that large-scale restoration of hydrologic linkages between the main channel and floodplain habitats will positively affect food web structure and ecosystem function in the Kissimmee River.

Kail, J., et al. (2012). "Limiting factors and thresholds for macroinvertebrate assemblages in European rivers: Empirical evidence from three datasets on water quality, catchment urbanization, and river restoration." Ecological Indicators **18**:63–72.

It has been widely stated that pressures acting at large spatial scales influence local habitat conditions and might limit the effects of local restoration measures. However, only a few empirical studies have used statistical methods that have explicitly been developed to investigate such wedge-shaped relationships. The objectives of the present study were (i) to identify pressures acting as limiting factors and to investigate the mitigating effects of local restoration measures in three datasets from European rivers, (ii) to derive thresholds for the ecological status of invertebrates, and (iii) to compare results derived from two statistical approaches, one using aggregated response variables like biological metrics (quantile regression trees), another using taxon-specific responses to derive separate community thresholds for the negative response of sensitive and the positive response of tolerant taxa (Threshold Indicator Taxa Analysis, TITAN). The results indicated that wedge-shaped relationships, typically resulting from limiting factors, are common in datasets from Central European rivers. There was empirical evidence for limiting effects of water pollution and catchment land use and an indication of a mitigating effect of hydromorphological restoration measures. The results emphasize the need to consider such large-scale pressures in river management and restoration because they potentially constrain the effects of local restoration measures. The thresholds derived for the aggregated response variables (metrics) and the community thresholds for sensitive taxa were in good agreement with values reported in the literature but differed markedly depending on the statistical method used. A possible reason is the different focuses of the methods on (i) the threshold for an aggregated response variable (metric), which includes the negative and positive response, and hence, reflects ecosystem functioning, and (ii) the community threshold of sensitive taxa based on taxon-specific negative responses, which is possibly best suited for species conservation issues. However, this interpretation requires further analysis since the results of the two methods showed no consistent differences.

Kaushal, S.S. and K.T. Belt (2012). "The urban watershed continuum: evolving spatial and temporal dimensions." Urban Ecosystems **15**(2):409–435.

Urban ecosystems are constantly evolving, and they are expected to change in both space and time with active management or degradation. An urban watershed continuum framework recognizes a continuum of engineered and natural hydrologic flowpaths that expands hydrologic networks in ways that are seldom considered. It recognizes that the nature of hydrologic connectivity influences downstream fluxes and transformations of carbon, contaminants, energy, and nutrients across 4 space and time dimensions. Specifically, it proposes that (1) first order streams are largely replaced by urban infrastructure (e.g. storm drains, ditches, gutters, pipes) longitudinally and laterally within watersheds, (2) there is extensive longitudinal and lateral modification of organic carbon and nutrient retention in engineered headwaters (3) there are longitudinal downstream pulses in material and energy

exports that are amplified by interactive land-use and hydrologic variability, (4) there are vertical interactions between leaky pipes and ground water that influence stream solute transport, (5) the urban watershed continuum is a transformer and transporter of materials and energy based on hydrologic residence times, and (6) temporally, there is an evolution of biogeochemical cycles and ecosystem functions as land use and urban infrastructure change over time. We provide examples from the Baltimore Ecosystem Study Long-Term Ecological (LTER) site along 4 spatiotemporal dimensions. Long-term monitoring indicates that engineered headwaters increase downstream subsidies of nitrate, phosphate, sulfate, carbon, and metals compared with undeveloped headwaters. There are increased longitudinal transformations of carbon and nitrogen from suburban headwaters to more urbanized receiving waters. Hydrologic connectivity along the vertical dimension between ground water and leaky pipes from Baltimore's aging infrastructure elevates stream solute concentrations. Across time, there has been increased headwater stream burial, evolving stormwater management, and long-term salinization of Baltimore's drinking water supply. Overall, an urban watershed continuum framework proposes testable hypotheses of how transport/transformation of materials and energy vary along a continuum of engineered and natural hydrologic flowpaths in space and time. Given interest in transitioning from sanitary to sustainable cities, it is necessary to recognize the evolving relationship between infrastructure and ecosystem function along the urban watershed continuum.

Kaushal, S.S., et al. (2008). "Effects of stream restoration on denitrification in an urbanizing watershed." <u>Ecological Applications</u> **18**(3):789–804.

Increased delivery of nitrogen due to urbanization and stream ecosystem degradation is contributing to eutrophication in coastal regions of the eastern United States. We tested whether geomorphic restoration involving hydrologic "reconnection" of a stream to its floodplain could increase rates of denitrification at the riparian-zone-stream interface of an urban stream in Baltimore, Maryland. Rates of denitrification measured using in situ N-15 tracer additions were spatially variable across sites and years and ranged from undetectable to > 200 mu g N center dot(kg sediment)(-1) center dot d(-1). Mean rates of denitrification were significantly greater in the restored reach of the stream at 77.4 +/- 12.6 mu g N center dot kg(-1) center dot d(-1) (mean 6 SE) as compared to the unrestored reach at 34.8 +/- 8.0 mu g N center dot kg(-1) center dot d(-1). Concentrations of nitrate-N in groundwater and stream water in the restored reach were also significantly lower than in the unrestored reach, but this may have also been associated with differences in sources and hydrologic flow paths. Riparian areas with low, hydrologically "connected" streambanks designed to promote flooding and dissipation of erosive force for storm water management had substantially higher rates of denitrification than restored high "nonconnected" banks and both unrestored low and high banks. Coupled measurements of hyporheic groundwater flow and in situ denitrification rates indicated that up to 1.16 mg NO3--N could be removed per liter of groundwater flow through one cubic meter of sediment at the riparian-zone-stream interface over a mean residence time of 4.97 d in the

unrestored reach, and estimates of mass removal of nitrate-N in the restored reach were also considerable. Mass removal of nitrate-N appeared to be strongly influenced by hydrologic residence time in unrestored and restored reaches. Our results suggest that stream restoration designed to "reconnect" stream channels with floodplains can increase denitrification rates, that there can be substantial variability in the efficacy of stream restoration designs, and that more work is necessary to elucidate which designs can be effective in conjunction with watershed strategies to reduce nitrate-N sources to streams.

Kemp, S. (2014). "The potential and limitations of linking biological monitoring data and restoration needs of urbanized waterways: a case study." Environmental Monitoring and Assessment **186**(6):3859–3873.

The implementation of effective strategies to mitigate the impacts of urbanization on waterways represents a major global challenge. Monitoring data plays an important role in the formulation of these strategies. Using monitoring and historical data compiled from around an urban area (Baltimore, USA), this paper is an assessment of the potential and limitations of the use of fish assemblage monitoring data in watershed restoration. A discriminant analysis between assemblages from urban and reference sites was used to determine faunal components which have been reduced or eliminated from Baltimore area waterways. This analysis produced a strong discrimination between fish assemblages from urban and reference sites. **Species primarily associated with reference sites varied taxonomically and ecologically, were generally classified as pollution intolerant, and were native. Species associated with urbanized sites were also native, varied taxonomically and ecologically, and were mixed in pollution tolerance**. One factor linking most species associated with reference sites was spawning mode (lithophilic). Spawning habitat limitations may be the mechanism through which these species have been reduced in the urbanized faunas. While this presents a strong general hypothesis, information regarding the specific habitat requirements and responses to urbanization of these species is limited. This represents a limitation to producing effective restoration strategies based on exact goals and targets. Without these, determining the type and number of restoration activities required to restore ecological communities remains problematic.

King County (2014). Assessing Land Use Effects and Regulatory Effectiveness on Streams in Rural Watersheds of King County, Washington. J. B. G. Lucchetti, C. Gregersen, L. Fore, C. Knutson, J. Latterell, P. McCombs, R. Timm, J. Vanderhoof, J. Wilhelm. Seattle, Washington, King County Water and Land Resource Division.

King, K.W. and R.D. Harmel (2003). "Considerations in selecting a water quality sampling strategy." Transactions of the Asae **46**(1): 63–73.

Water quality monitoring programs have expanded in an effort to quantify loadings to streams and lakes from various watershed activities and managements. At the core of

monitoring programs are strategies or schemes that determine when and how samples are taken for estimating stream loadings. Quantification of the differences between these schemes has not been adequately documented. An analytic approach was used to evaluate 45 commonly used sampling strategies that included time-based (5,10, 15, 30, 60, 120, 180, 300, and 360 min) and flow stratified (2.5, 5.0, 7.5,10.0, 12.5, and 15.0 mm) schemes using discrete and composite sampling procedures. A total of 300 storm hydrographs from 87 different watersheds in the U.S: were coupled with two concentration graphs (a 100% positive correlation of concentration to flow, and a 100% negative correlation to flow) to estimate average bias values for each sampling strategy. The mean bias and absolute error. for time-based sampling, as determined by the standardized root mean square error (SRMSE), always increased with a greater sampling time interval. For time-based sampling, a positive correlated concentration graph generally resulted in under-prediction (positive,bias) from the true load, while a negative correlated concentration always resulted in over prediction (negative bias). For flow-stratified sampling, the direction of bias was generally reversed from the time-based case, but the SRMSE increased with a greater flow interval. Even at the lowest flow interval used in this study (2.5 mm), the median residual values were significantly different from zero (a = 0.05). Time discrete sampling schemes less than or equal to15-min provided the only bias and mean residual values not significantly different from zero (a = 0:05). When an equal number of samples was obtained, the flow-stratified approach had less absolute error than did the time-based approach. The results indicate that, prior to water quality monitoring, careful consideration should be given to. the sampling strategy and its overall impact on load estimates.

King, K.W., et al. (2008). "Validation of paired watersheds for assessing conservation practices in the Upper Big Walnut Creek watershed, Ohio." Journal of Soil and Water Conservation **63**(6):380–395.

Impacts of,watershed scale conservation practice adoption oil sediment, nutrient, and pesticide losses and adjacent stream biota are not v,,ell understood. The objective of this study was to examine the suitability of selected paired watersheds to quantify hydrology, chemical, and ecology effects of conservation practice implementation for channelized Mid unchannelized watersheds in Upper Big Walnut Creek watershed, Ohio. Channelized watersheds were more similar in watershed characteristics than the unchannelized watersheds. One hydrology, eight water chemistry, and five fish community response variables were measured. Most response variables in both watershed pairs were moderately correlated (r > 0.6) but the minimum percent change required to detect a response difference was greater for the unchannelized watersheds. Detectable temporal trends in the difference between like response variables For the channelized and unchannelized watershed pairs were minimal. These results validate the paired watershed design and suggest that conservation practice induced changes in hydrologic water quality, and fish communities can be quantified.

Klein, L.R., et al. (2007). "Long-term monitoring and evaluation of the Lower Red River Meadow Restoration Project, Idaho, USA." Restoration Ecology **15**(2):223–239.

Although public and financial support for stream restoration projects is increasing, long-term monitoring and reporting of project successes and failures are limited. We present the initial results of a long-term monitoring program for the Lower Red River Meadow Restoration Project in north-central Idaho, U.S.A. We evaluate a natural channel design's effectiveness in shifting a degraded stream ecosystem onto a path of ecological recovery. Field monitoring and hydrodynamic modeling are used to quantify post-restoration changes in 17 physical and biological performance indicators. Statistical and ecological significance are evaluated within a framework of clear objectives, expected responses (ecological hypotheses), and performance criteria (reference conditions) to assess post-restoration changes away from pre-restoration conditions. Compared to pre-restoration conditions, we observed ecosystem improvements in channel sinuosity, slope, depth, and water surface elevation; quantity, quality, and diversity of in-stream habitat and spawning substrate; and bird population numbers and diversity. Modeling documented the potential for enhanced river-floodplain connectivity. Failure to detect either statistically or ecologically significant change in groundwater depth, stream temperature, native riparian cover, and salmonid density is due to a combination of small sample sizes, high interannual variability, external influences, and the early stages of recovery. Unexpected decreases in native riparian cover led to implementation of adaptive management strategies. Challenges included those common to most project-level monitoring-isolating restoration effects in complex ecosystems, securing long-term funding, and implementing scientifically rigorous experimental designs. Continued monitoring and adaptive management that support the establishment of mature and dense riparian shrub communities are crucial to overall success of the project.

Kondolf, G.M., et al. (2011). "Post-Project Appraisals of River Restoration in Advanced University Instruction." Restoration Ecology **19**(6):696–700.

Post-project appraisals (PPAs) are systematic assessments of built restoration projects, which provide feedback on performance of restoration approaches to improve future restoration efforts. Unfortunately, most restoration projects are not subject to systematic assessment because of lack of institutional arrangements to sustain long-term evaluation and the orientation of most funding agencies towards project implementation rather than "studies." As semester-long courses on river restoration increasingly appear in university curricula at the graduate and advanced undergraduate level, independent student research projects for such courses can provide a mechanism for building a database of PPAs (and components thereof) and providing the students with a powerful learning experience. In two UC Berkeley courses, we require independent student projects involving original field research, peer review of first drafts, instructor (and often outside) review of second drafts, and presentation of results to a public symposium. Since 1995, the revised, final papers have been added to the University of California library, where they constitute one of the largest collections of restoration-related studies currently available for any region:

over 300 restoration-related studies, of which 80 are PPAs or components thereof. Since 2003, the papers have been posted on-line, with 40,000 full text downloads through 2010. Some term projects have directly influenced river restoration programs, inducing changes in salmon habitat enhancement project design, documenting failure of projects based on inappropriate restoration approaches, and contributing to systematic assessments of step-pool and compound channel designs in urban areas. Student evaluations cite the term projects as valuable learning experiences.

Kondolf, G.M. and E.R. Micheli (1995). "Evaluating Stream Restoration Projects." Environmental Management **19**(1):1–15.

River and stream restoration projects are increasingly numerous but rarely subjected to systematic postproject evaluation. Without conducting such evaluation and widely disseminating the results, lessons will not be learned from successes and failures, and the field of river restoration cannot advance. Postproject evaluation must be incorporated into the initial design of each project, with the choice of evaluation technique based directly upon the specific project goals against which performance will be evaluated. We emphasize measurement of geomorphic characteristics, as these constitute the physical framework supporting riparian and aquatic ecosystems. Techniques for evaluating other components are briefly discussed, especially as they relate to geomorphic variables. Where possible, geomorphic, hydrologic, and ecological variables should be measured along the same transects. In general, postproject monitoring should continue for at least a decade, with surveys conducted after each flood above a predetermined threshold. Project design should be preceded by a historical study documenting former channel conditions to provide insights into the processes responsible for the present channel condition and to suggest earlier, potentially stable channel configurations as possible design models.

Konrad, C.P. and D. Booth (2002). Hydrologic Trends Associated with Urban Development for Selected Streams in the Puget Sound Basin, Western Washington. Tacoma, Washington, U.S. Geological Survey.

Kristensen, E.A., et al. (2011). "An evaluation of restoration practises in lowland streams: Has the physical integrity been re-created?" Ecological Engineering **37**(11):1654–1660.

Intensive land use by humans has led to severe degradation of streams and rivers, especially in highly industrialised countries and in lowland agricultural areas. Restorations have been conducted with the aim to improve hydromorphological conditions in modified streams. However, success has often been limited, partly because the restorations have been conducted without due regard to river-type-specific characteristics. The aim of this study was to evaluate restorations of Danish lowland streams by applying a type-specific approach. We compared the physical condition of restored streams with that of near-natural streams (least disturbed condition) and channelized streams. We stratified the data according to different stream types and included also reference sites from a less impacted country

(Lithuania) in the evaluation. Our results revealed that restorations have created physical conditions that do not resemble river-type-specific LDCs, primarily due to the addition of large amounts of coarse substrate. This may have implications for the ecological communities and for biodiversity and consequently for the implementation of the Water Framework Directive in restored lowland streams. We also found that observations of physical condition in nearby reference streams may be used to advantage in future restoration planning, thereby assuring a higher degree of physical integrity in restored streams. (C) 2011 Elsevier B.V. All rights reserved.

Kristensen, E.A., et al. (2013). "Comparison of active and passive stream restoration: effects on the physical habitats." Geografisk Tidsskrift-Danish Journal of Geography **113**(2):109–120.

Modification and channelization of streams and rivers have been conducted extensively throughout the world during the past century. Subsequently, much effort has been directed at re-creating the lost habitats and thereby improving living conditions for aquatic organisms. However, as restoration methods are plentiful, it is difficult to determine which one to use to get the anticipated result. The aim of this study was to compare two commonly used methods in small Danish streams to improve the physical condition: re-meandering and passive restoration through cease of maintenance. Our investigation included measurement of the physical conditions in 29 stream reaches covering four different groups: (1) re-meandered streams, (2) LDC streams (the least disturbed streams available), (3) passively restored streams (>10 years stop of maintenance) and (4) channelized and non-restored streams. The in-stream habitats were compared through analysis of the measured physical parameters and by applying a habitat model. We found that re-meandering is a more effective way of re-creating near-natural physical conditions in small streams compared to passive restoration. This is probably due to the limited energy in small streams which restricts re-shaping of the stream channel. However, based on habitat suitability modelling, the change to the physical condition did not translate into improved habitat suitability for young of the year brown trout highlighting the value of using several methods when evaluating restoration success.

Kurth, A.M. and M. Schirmer (2014). "Thirty years of river restoration in Switzerland: implemented measures and lessons learned." Environmental Earth Sciences **72**(6):2065–2079.

In the age of climate change and ecosystem degradation, governments realise more and more that it is crucial to protect ecosystem health, to preserve water resources and to maintain flood protection. Therefore, several countries, among those Switzerland, have implemented laws to make the restoration of riverine ecosystems a legal obligation. In Switzerland, restoration projects were implemented as early as 1979, prior to these laws coming into force. **For this article, 848 Swiss restoration projects, implemented between 1979 and 2012, were investigated, spanning a total of 307 river kilometres**. No correlation was found between the geographical distribution of total restored lengths in a way that larger cantons performed more restorations. Neither was there a correlation between the total restored length and the canton's population density or financial status. Restoration activities increased

steadily after 1992, with most restorations being reported for the years 2004, 2005 and 2009. The average restoration rate was 9.8 km per year, ranging between 0.5 km in 1979 and 23.9 km in 2004. Restoration measures were very diverse, ranging from measures that directly affected the wildlife, e.g. by providing habitats, to measures which indirectly enhanced conditions for the ecosystem, such as water quality ameliorations. **Data regarding success evaluation was only available for 232 of the 848 projects, making it difficult to state whether the implemented restoration projects reached the intended objectives**. Over the next 80 years, a further 4,000 km of Swiss rivers will be restored, requiring a restoration rate of 50 km per year, which, according to the data, is an achievable goal.

Laasonen, P., et al. (1998). "Recovery of macroinvertebrate communities from stream habitat restoration." Aquatic Conservation: Marine and Freshwater Ecosystems **8**(1):101–113.

1. **Many streams channelized for timber floating in Finland are now being restored to their original condition. The most frequently used restoration structures are boulder dams, flow deflectors, excavations and channel enlargements. By increasing substrate heterogeneity and leaf litter retention, restoration may enhance the formation of detritivore-dominated macroinvertebrate assemblages. In this study, macroinvertebrate communities in streams with differing recovery periods (from 0 to 16 years) from restoration, were compared with those in channelized and near-pristine streams.**

2. Water depth and current velocity were lower, and relative bed roughness higher in restored than in dredged channels. Moss cover was negligibly low in recently restored streams, but mosses had recovered well within three years from restoration. The standing stock of leaf litter was lower than in natural streams, but in most cases higher than in channelized streams.

3. **Abundances of all invertebrates were highest in natural streams and lowest in streams restored 1 month before sampling. All other restored streams had abundances comparable to, or slightly lower than, those in channelized streams**. There was a tendency toward higher abundances of shredders with a long recovery period, but streams restored 8 or 16 years ago still contained relatively sparse shredder populations.

4. Canonical Correspondence Analysis of the October data could be attributed to among-site variation in habitat hydraulics, moss cover and leaf litter. Dredged channels with high velocities and low bed profiles, and natural streams with high retention efficiency were the end points of this gradient. There was little indication of macroinvertebrate assemblages approaching pristine conditions with a longer recovery period.

5. Enhanced litter retention increases the capacity of restored streams to support high abundances of detritivorous invertebrates. Indirectly, restoration may also benefit animals that are not dependent on detrital food. Clearly, macroinvertebrates and other non-vertebrate components of the stream biota should be given a higher priority

in the design and execution of stream restoration programmes. (C) 1998 John Wiley & Sons, Ltd.

Larson, M.G., et al. (2001). "Effectiveness of large woody debris in stream rehabilitation projects in urban basins." Ecological Engineering **18**(2):211–226.

Urban stream rehabilitation projects commonly include log placement to establish the types of habitat features associated with large woody debris (LWD) in undisturbed streams. Six urban in-stream rehabilitation projects were examined in the Puget Sound Lowland of western Washington. Each project used in-stream log placement as the primary strategy for achieving project goals; none included systematic watershed-scale rehabilitation measures. **The effectiveness of LWD in these projects was evaluated by characterizing physical stream conditions using common metrics, including LWD frequency and pool spacing, and by sampling benthic macroinvertebrates.** In all project reaches where pre-project data existed, pool spacing narrowed after LWD installation. All project sites exhibited fewer pools for a given LWD loading, however, than has been reported for forested streams. **In project reaches where the objective was to control downstream sedimentation, only limited success was observed. At none of the sites was there any detectable improvement in biological conditions due to the addition of LWD. Our results indicate that, although LWD projects can modestly improve physical habitat in, a stream reach over a time scale of 2-10 years, they apparently do not achieve commensurate improvement in biological conditions.**

Lave, R. (2014). "Freedom and constraint: Generative expectations in the US stream restoration field." Geoforum **52**:236–244.

The modern holistic wave of stream restoration was born in the 1970s from the combined support of a strong grassroots movement and new federal environmental legislation, most notably the Clean Water Act. Before holistic stream restoration could properly start, however, it was stopped in its tracks by two big issues: were the far more intensive interventions necessary to holistic restoration actually doable; and was it possible to reconcile the ecological goals of setting streams and rivers free with the powerful economic demands to minimize impacts from flooding and erosion? Taken together, these two issue called the whole project of stream restoration into doubt. But then a consultant, Dave Rosgen, stepped up with a restoration approach that promised both freedom and constraint: picturesque rivers teaming with game fish in a channel that stayed where it was put. Drawing on the sociology of expectations literature within STS, I argue that it was the expectations raised by this apparent resolution of the contradiction at the heart of stream restoration that transformed both Rosgen and the restoration field from shaky prospects into contenders, setting the stage for the exponential growth of stream restoration, and Rosgen's success within in it. (C) 2013 Elsevier Ltd. All rights reserved.

Lawrence, J.E., et al. (2013). "Hyporheic Zone in Urban Streams: A Review and Opportunities for Enhancing Water Quality and Improving Aquatic Habitat by Active Management." Environmental Engineering Science **30**(8):480–501.

> Tremendous opportunities exist for enhancing water quality and improving aquatic habitat by actively managing urban water infrastructure to operate in conjunction with natural systems. The hyporheic zone (HZ) of streams, which is the area of active mixing between surface water and groundwater, is one such system that is overlooked by many water professionals, because the state of the science on this topic has not been transferred into practice. As a biogeochemically active zone, the HZ offers great potential to provide natural treatment of organic compounds, nutrients, and pathogens in urban streams, which are often strongly impacted by flow modifications and water pollution. Reliable treatment is most likely in streams in which the majority of flow occurs through the HZ, the flow is aerated, and sufficient residence times occur, which may be limited to specific channel morphologies and seasons. Integration of the HZ into stream management plans could also provide quality habitat in a landscape with increasingly depauperate biodiversity. Here, we review current knowledge on hydrological, chemical, and biological aspects of the HZ, with a focus on urban settings, and include a set of examples drawn from the literature of low-flow, effluent-dominated streams in which there is significant hyporheic flow and potential for contaminant attenuation. The HZ can be incorporated much more effectively into urban water management, including stream restoration efforts, by understanding the surface and subsurface features conducive to HZ flow and the water-quality and biodiversity improvements that can be gained in the HZ without posing unreasonable risk. The main barriers to implementation of HZ considerations include lack of information, absence of established metrics for evaluating success, small number of controlled HZ experiments in urban settings, and concern over risks to both public health and aquatic organisms. A combination of field studies, laboratory experiments, and model development that consider hydrological, chemical, and biological interactions in the HZ can overcome these barriers.

Lepori, F., et al. (2005). "Does restoration of structural heterogeneity in streams enhance fish and macroinvertebrate diversity?" Ecological Applications **15**(6):2060–2071.

> Restoration schemes often rely on the assumption that enhancing habitat complexity through addition of in-stream structures such as boulders and woody debris leads to increased biodiversity, but evidence for this assumption is. scarce. **We compared structural heterogeneity and fish and invertebrate diversity at restored, unrestored, and reference sites on tributaries of the Ume River, northern Sweden, where several kilometers of streams have been restored from channelization through placement of boulders into the channel.** Structural heterogeneity at the study sites was assessed using a contour tracer at two spatial resolutions likely to be affected by restoration. These are the patch scale (0.7 in), reflecting substratum characteristics, and the reach scale (50 in), reflecting general channel topography. Fish and invertebrate samples collected via electroshocking were used to assess taxonomic richness, taxonomic density, evenness, and assemblage composition at the

study sites. **Measures of structural heterogeneity were substantially higher at restored relative to channelized sites; however, components of fish and invertebrate diversity were similar between these treatments.** At restored sites, measures of structural heterogeneity and fish and invertebrate diversity Were consistent with, or slightly exceeded reference levels. This implies that local (patch to reach) heterogeneity did not structure fish and invertebrate assemblages in the study streams. Our results suggest that restoration might have little beneficial effect on biodiversity if the restoration schemes (and the original impact under amelioration) do not affect structural heterogeneity relevant to the target organisms.

Levell, A.P. and H. Chang (2008). "Monitoring the channel process of a stream restoration project in an urbanizing watershed: A case study of Kelley Creek, Oregon, USA." River Research and Applications **24**(2):169–182.

Pacific Northwest (PNW) streams in the United States were impacted by the 20th century development, when removal of instream structure and channelization degraded an aquatic habitat. The lower Kelley Creek in southeast Portland, USA was channelized during the 1930's Works Progress Administration (WPA) projects. Stream restoration reintroduced pool-riffle sequences and heterogeneous substrates to protect salmonids while mitigating impacts from flooding. We investigated whether the restored pool-riffle morphology changed substantially following effective discharge events. We examined channel forms for four reaches representing three time periods-pre-development (two reference reaches), development and restoration. We conducted thalweg profiles, cross-sections and pebble counts along the reaches to examine how channel geometry, residual pool dimensions and particle size distribution changed following effective discharge events. The effective discharge flows altered the restoration reach more substantially than the reference reaches. The restoration reach decreased in median particle size, and its cross-sectional geometry aggraded near its margins. However, the residual pool morphology remained in equilibrium. Richardson Creek's reference reach degraded at the substrate level, while Kelley Creek's reference reach remained in equilibrium. The restoration reach's aggradation may have resulted from sedimentation along the nearby Johnson Creek. In contrast, Richardson Creek's degradation occurred as upstream land use may have augmented flows. Stream channels with low gradient pool-riffle morphologies are ideal for salmonid spawning and rearing and should be protected and restored within urban corridors. The findings of our study suggest that the connectivity of streams and the dynamic fluvial geomorphology of stream channels should be considered for stream restoration projects in humid temperate climates. Copyright (C) 2008 John Wiley & Sons, Ltd.

Line, D.E., et al. (2012). "Effectiveness of LID for Commercial Development in North Carolina." Journal of Environmental Engineering-Asce **138**(6):680–688.

The purpose of this project was to characterize runoff and pollutant export from three commercial sites: one with no storm water control measures (NoTreat), one with a wet detention basin (WetBasin), and one with low impact development (LID)

measures. The sites were located in the Piedmont and Coastal Plain physiographic regions of central North Carolina. Rainfall, runoff, and pollutant concentrations were monitored at each site for more than one year by using automated rain gauges and samplers. The storm event mean concentrations (EMCs) of total kjeldahl nitrogen (TKN), nitrate+nitrite nitrogen (NOx-N), and total phosphorus (TP) in runoff were generally less than corresponding EMCs for many other urban areas in the United States. Also, EMCs were similar to those found for eight parking lots in North Carolina. **Storm runoff to rainfall ratio was greatest for the NoTreat site and least for the WetBasin site, which was anticipated because the NoTreat site had no detention/storage and the WetBasin site had the greatest detention/storage. Export of TKN, ammonia nitrogen (NH3-N), TP, and total suspended solids (TSS) was lowest for the LID site, whereas export of NOx-N and TN was lowest for the WetBasin site.** Although by no means definitive, the monitoring data indicated that the LID site with its multiple LID measures was more effective at reducing export for most pollutants than the WetBasin site with its wet detention basin. DOI: 10.1061/(ASCE)EE.1943-7870.0000515.

Lorenz, A.W. and C.K. Feld (2013). "Upstream river morphology and riparian land use overrule local restoration effects on ecological status assessment." Hydrobiologia **704**(1):489–501.

River restoration is a central issue of present-day River Basin Management. Unfortunately, many studies have shown limited ecological improvements, hypothesizing catchment influences and missing donor populations as main impeding factors. This study evaluates the ecological status after restoration at 46 river reaches in light of catchment influences upstream. Three groups of environmental parameters were investigated: (i) riparian land use and (ii) physical habitat quality in different lengths upstream of the restorations and (iii) land use in the whole catchment upstream. Ecological quality ratios of standardized fish, invertebrate and macrophyte samples were used as response variables. The results imply that sub-catchment variables influence the ecological status more than local habitat improvements. In particular, fish and invertebrate ecological status was positively linked to percent deciduous forest upstream of restored sites, while macrophytes revealed an opposite trend. Furthermore, we found a strong linkage of site-scale ecological status and physical habitat quality up to 5 km upstream of the restorations; the more natural were riparian land use and river habitat quality upstream, the higher was the chance of a good ecological quality in restored reaches. We conclude that site-scale restoration measures are likely to be unsuccessful, if the sub-catchment physical habitat upstream is degraded.

Lorenz, A.W., et al. (2012). "Macrophytes respond to reach-scale river restorations." Journal of Applied Ecology **49**(1):202–212.

1. In recent years, river restoration science has been searching for biological indicators of improvement in the physical habitats of streams. To date, research has mainly focused on the use of fish and macroinvertebrates as indicators. Despite their

importance in aquatic ecosystems, the response of macrophytes to habitat restoration has been rarely studied.

2. We investigated the macrophyte communities of 40 restored river reaches in the lowland and lower mountainous areas of Germany. Each restored reach was compared to an upstream, unrestored reach using a space-for-time-substitution approach. At each reach, a 100 m stretch was surveyed for submerged and emergent macrophytes, recording the quantity, abundance and growth form of each species. Additionally, microhabitat patterns (substrate, depth, current velocity) and channel parameters (mean and bankfull width, number of channel elements) were recorded.

3. Restored reaches had a significantly higher macrophyte cover, richness, diversity and number of growth forms. Macrophyte diversity and richness were both positively correlated with depth, current and substrate.

4. The analysis of growth forms showed that Lemnids, Helodids, Parvopotamids, Elodids, Peplids and Juncids are all significant indicators of restoration. These species all responded directly to the restoration measures either by highly increasing in abundance or by being present in the restored reaches and absent in the unrestored reaches. While the restored reaches of the lowland rivers were characterized by a high abundance of Peplids and Parvopotamids, the restored reaches of the mountain rivers showed a significantly higher presence and abundance of Lemnids and Helodids.

5. Three macrophyte species (Lemna minor, Persicaria hydropiper, Potamogeton crispus) were regarded as significant indicators of restoration. No species were found to be indicators of unrestored reaches.

6. Synthesis and applications. Macrophyte communities benefit from river restoration by showing increased cover, abundance and diversity. The main drivers of this enhancement are more natural and diverse substrates and an increased floodplain area in the restored reaches, as well as a greater variability of current and depth patterns. Monitoring of macrophytes could thus be an easy and cost-effective means to gauge the success of river restoration measures.

Luderitz, V., et al. (2011). "Restoration of the Upper Main and Rodach rivers - The success and its measurement." Ecological Engineering **37**(12):2044–2055.

Large-scale restoration of streams and rivers is a mandatory prerequisite for the implementation of the European Water Framework Directive (WFD) to reach good ecological status of water bodies. This contribution analyzes the success of the largest river restoration in Germany at the Upper Main. Sections with a length of more than 18 km were restored between 1990 and 2008, including re-connection of former oxbow-lakes, multiple-channelling, and establishment of wide riparian buffer zones. Measuring the success of restoration by means of a multimetric assessment system, we found a clear success of restoration indicated by the status of hydromorphology and by the biological parameters. including macroinvertebrates, fishes, and macrophytes. Unlike non-restored reaches, the restored reaches attained a good ecological status.

As such, the restoration of the Upper Main is shown to be a pilot project for the implementation of the WFD on a large scale.

Matthews, J., et al. (2010). "Lessons from practice: assessing early progress and success in river rehabilitation." Hydrobiologia **655**(1):1–14.

This article comprises a literature analysis of 41 river rehabilitation projects to assess the short-term (5 years) ability of indicator groups to demonstrate progress towards river rehabilitation goals. Positive indications were compared to land-use, river size, rehabilitation intervention and time. A questionnaire was developed to investigate river manager's interpretation of rehabilitation success and to assess their level of adherence to recommendations in the literature with regard to rehabilitation assessment on a conceptual level. A total of 54 responses were received from respondents based in Germany, The Netherlands and the United Kingdom. The results indicate that macroinvertebrate indicators, while widely used in assessing river rehabilitation efforts, exhibited a lower frequency of positive responses than most other indicator types in the short term. Conversely, terrestrial floodplain indicators exhibited the most frequent level of positive response for all ecological type indicators leading to recommendations for further investigations into their use for short-term monitoring. Assessment procedures recommended in literature are largely followed, illustrating the advances that have been made with regard to assessment planning. Indicator responses are influenced by scale factors, for example, land-use and river size, that are often not considered by rehabilitation managers. While an emphasis is placed on ecological, hydrological and morphological indicators in monitoring schemes, the socioeconomic perspective (emphasized in the literature as forming an integral part of the river system) is neglected.

Miller, S.W., et al. (2010). "Quantifying Macroinvertebrate Responses to In-Stream Habitat Restoration: Applications of Meta-Analysis to River Restoration." Restoration Ecology **18**(1):8–19.

The assumption that restoring physical habitat heterogeneity will increase biodiversity underlies many river restoration projects, despite few tests of the hypothesis. With over 6,000 in-stream habitat enhancement projects implemented in the last decade at a cost exceeding $1 billion, there is a clear need to assess the consistency of responses, as well as factors explaining project performance. We adopted an alternative approach to individual case-studies by applying meta-analysis to quantify macroinvertebrate responses to in-stream habitat restoration. Meta-analysis of 24 separate studies showed that increasing habitat heterogeneity had significant, positive effects on macroinvertebrate richness, although density increases were negligible. Large woody debris additions produced the largest and most consistent responses, whereas responses to boulder additions and channel reconfigurations were positive, yet highly variable. Among all strategies, the strength and consistency of macroinvertebrate responses were related to land use or watershed-scale conditions, but appeared independent of project size, stream size, or recovery time. Overall, the low quality and quantity of pre- and post-project monitoring data reduced the

robustness of our meta-analysis. Specifically, the scope and strength of conclusions regarding the ubiquity of macroinvertebrate responses to restoration, as well as the identification of variables controlling project performance was limited. More robust applications of meta-analysis to advance the science and practice of river restoration will require implementing rigorous study designs, including pre- and post-project monitoring replicated at both restored and control sites, collection of abiotic and biotic variables at relevant spatiotemporal scales, and increased reporting of monitoring results in peer-reviewed journals and/or regional databases.

Moerke, A.H., et al. (2004). "Restoration of an Indiana, USA, stream: bridging the gap between basic and applied lotic ecology." Journal of the North American Benthological Society **23**(3):647–660.

Stream restoration attempts to reverse the global degradation of rivers and streams, but rigorous evaluations are needed to advance the science. We evaluated a 3(rd)-order channelized Indiana (USA) stream that was restored in 1997 by constructing two meanders, each similar to400 m long. Pool and riffle sequences were constructed, coarse substrate and wood were added to the channel, banks were stabilized and revegetated, and sedimentation was reduced by creating a sediment retention basin upstream. Habitat, periphyton, macroinvertebrates, and fishes were measured before restoration and for 5 y after restoration in the restored reaches and in an upstream, unrestored reach. Restoration improved habitat conditions (e.g., more pools, fewer fine sediments) in both restored reaches compared to the unrestored reach. Within 1 y after restoration, major trophic groups (i.e., periphyton, macroinvertebrates, and fishes) recovered to or exceeded levels in the degraded, unrestored reach. However, biotic responses varied with time, trophic level, and community parameter measured. Five years after the restoration, habitat quality, algal abundance, and macroinvertebrate density remained higher in the restored reaches, whereas macroinvertebrate diversity and fish abundance in the restored reaches were similar to or below levels in the unrestored, channelized reach. Although biotic recovery was relatively rapid, long-term persistence is uncertain because of continued sedimentation at a watershed scale. In many instances, reach-scale restorations may be ineffective in the face of basin-wide degradation. This study illustrates the importance of conducting long-term assessments of stream restorations, which can improve both knowledge and management of stream ecosystems.

Moerke, A.H. and G.A. Lamberti (2004). "Restoring stream ecosystems: Lessons from a midwestern state." Restoration Ecology **12**(3):327–334.

Reach-scale stream restorations are becoming a common approach to repair degraded streams, but the effectiveness of these projects is rarely evaluated or reported. We surveyed governmental, private, and nonprofit organizations in the state of Indiana to determine the frequency and nature of reach-scale stream restorations in this midwestern U.S. state. For **10 attempted restorations in Indiana,** questionnaires and on-site assessments were used to better evaluate current designs for restoring stream ecosystems. At each restoration site, habitat and water quality were evaluated in restored and unrestored reaches. Our surveys identified commonalities across all restorations, including the type of restoration, project goals, structures installed, and level of monitoring conducted. **In general, most restorations were described as stream-relocation projects that combined riparian and in-stream enhancements.** Fewer than half of the restorations conducted pre- or post-restoration monitoring, and most monitoring involved evaluations of riparian vegetation rather than aquatic variables. **On-site assessments revealed that restored reaches had significantly lower stream widths and greater depths than did upstream unrestored reaches, but riparian canopy cover often was lower in restored than in unrestored reaches.** This study provides basic information on midwestern restoration strategies, which is needed to identify strengths and weaknesses in current practices and to better inform future stream restorations.

Montalto, F., et al. (2007). "Rapid assessment of the cost-effectiveness of low impact development for CSO control." Landscape and Urban Planning **82**(3):117–131.

This paper presents a simple model for assessing the cost-effectiveness of investments in low impact development (LID) for reducing combined sewer overflows (CSOs) in urban watersheds. LID systems, including green roofs, porous pavement, and stormwater treatment wetlands, are site-specific controls for stormwater runoff. If applied throughout a watershed, LID systems like these can reduce the amount of runoff entering the sewer system and reduce CSOs. To be conservative, we focus solely on the function of LID systems as stormwater management techniques, neglecting the other environmental benefits commonly associated with these technologies. **A model is presented that can be used to simulate the cost-effectiveness of reducing CSOs through incremental installation of LID technologies across urban watersheds, when they are introduced alone, or in combination with conventional CSO abatement technologies.** The potential reduction in CSOs resulting from various levels of LID adoption is simulated using a modified Rational Method. A life-cycle cost analysis is used to compare LID with other alternatives. Given that LID implementation on private property leads to reduced CSOs, a cost sharing scheme is presented that divides the total LID cost into a private cost fraction (born by the property owner) and a public cost fraction (provided by a public agency). The implications of such a policy are discussed with reference to a CSO-shed that drains to the Gowanus Canal (Brooklyn, NY). **The results indicate that individual LID systems have differing levels of cost-effectiveness in terms of CSO reduction, but that under a variety of performance and cost scenarios a public subsidy to encourage LID installation represents a cost-effective alternative for public agencies to consider in their efforts to reduce CSOs**. Future areas of research in this field are outlined. (c) 2007 Elsevier B.V. All rights reserved.

Montgomery, D.R., et al. (2003). Restoration of Puget Sound Rivers. Seattle, Washington, Center for Water and Watershed Studies in association with University of Washington Press.

Moore, J. N. and H. W. Langner (2012). "Can a River Heal Itself? Natural Attenuation of Metal Contamination in River Sediment." Environmental Science & Technology **46**(5):2616–2623.

> Sediment sampling of bed sediment from a large river contaminated by mining and smelting was used to determine rates of natural attenuation of metal concentrations. A "natural decay model" was developed from high-resolution temporal data and used to predict when restoration guidelines would be met without restoration and with various degrees of restoration success. The natural decay model estimates that in the most contaminated reaches it will take about 90 years for average concentrations of As, Cd, Cu, Pb, and Zn to fall below "probable effects concentrations" (PEC), i.e. levels above which we expect to see adverse environmental effects. At sites farther downstream, all metals will fall below PEC in <35 +/- 8 years. It will take longer to reach "threshold effects concentrations" (TEC), i.e. concentrations at which no effects are expected. But, even in the most contaminated reaches, Cd, Pb, and Zn will reach TEC in <80 +/- 57 years, while Cu and As will take 200 years. Model simulations with different levels of remediation success show that recovery is highly dependent on source reduction and how far the goal is from the basin background concentration. Furthermore, beneficial effects of restoration may be unexpectedly small: for example a likely decrease of similar to 20% in the source concentration would shorten the time to reach the Cu PEC by only 13 years. We argue that conducting analyses like these can provide insight into remediation approaches and ultimately decrease the cost of restoration by identifying the role of natural attenuation in restoration design and implementation.

Morandi, B., et al. (2014). "How is success or failure in river restoration projects evaluated? Feedback from French restoration projects." Journal of Environmental Management **137**:178–188.

> Since the 1990s, French operational managers and scientists have been involved in the environmental restoration of rivers. The European Water Framework Directive (2000) highlights the need for feedback from restoration projects and for evidence-based evaluation of success. Based on 44 French pilot projects that included such an evaluation, the present study includes: 1) an introduction to restoration projects based on their general characteristics 2) a description of evaluation strategies and authorities in charge of their implementation, and 3) a focus on the evaluation of results and the links between these results and evaluation strategies. **The results show that: 1) the quality of an evaluation strategy often remains too poor to understand well the link between a restoration project and ecological changes; 2) in many cases, the conclusions drawn are contradictory, making it difficult to determine the success or failure of a restoration project; and 3) the projects with the poorest evaluation strategies generally have the most positive conclusions about the effects of restoration. Recommendations are that evaluation strategies should be designed early in the project planning process and be based on clearly-defined objectives.**

Morley, S.A. and J.R. Karr (2002). "Assessing and restoring the health of urban streams in the Puget Sound basin." Conservation Biology **16**(6):1498–1509.

Rapid urbanization threatens the biota of streams and rivers around the globe. Efforts to manage urban streams traditionally take an engineering approach focused on stormwater runoff, physical channel condition, and chemical water quality. Our objective was to use the biology of streams - measured with the multimetric benthic index of biological integrity (B-IBI) based on benthic macroinvertebrates - to assess stream health. From 1997 to 1999, we sampled invertebrates at 45 sites in second- and third-order streams in the Puget Sound lowlands of Washington State. Land cover upstream of each site was characterized by analysis of a 1998 satellite image. We evaluated associations between five land cover categories and biological condition across three spatial scales. The relationships between B-IBI (and its component metrics) and stream substrate and hydrologic features were also analyzed at a subset of sites. Across all study sites, B-IBI declined as the percentage of urban land cover increased ($r < -0.71$, $p < 0.001$, $n > 31$). Most metrics were better predicted by sub-basin rather than local-scale urbanization. Within individual basins, however, local land-cover urbanization and B-IBI were strongly correlated ($r = -0.91$, $p < 0.001$, $n = 9$). The biological condition of a site was also related to measures of hydrologic alteration and stream substrate. The aquatic biota is sensitive to a variety of urban effects, expressed at both large and small spatial scales. Biological assessment tools such as B-IBI can identify areas of excellent biological condition for conservation and guide the design and evaluation of efforts to restore the biota of degraded streams.

Mueller, M., et al. (2014). "The ecological value of stream restoration measures: An evaluation on ecosystem and target species scales." Ecological Engineering **62**:129–139.

Stream restoration is widely applied for conservation of freshwater ecosystems, but systematic comparisons on the effects of different techniques are rare. In this study, we systematically evaluated two types of gravel introduction, substratum raking and the placement of boulders in six streams. We compared indicator-based and multi-scale approaches that simultaneously assess effects on target species, different taxonomic groups and on ecosystem scale. Gravel introduction had by far the strongest effects on macroinvertebrates (increase of species density and numbers of individuals), periphyton (increase of cell numbers) and macrophytes (decrease of coverage, species numbers and biomass), followed by substratum raking. The placement of boulders had no significant long-term effects on aquatic communities. Over all investigated restoration treatments, fish community composition only changed significantly in 50% of the study rivers depending on the occurrence of species sensitive to the structures introduced by the restoration treatments. These were lithophilic, rheophilic and invertivorous fishes, comprising several species listed in the Red List of endangered species, which used the added 16-32 mm gravel as juvenile habitat. Areas with introduced gravel were also most frequently used by spawning Salmo trutta, Thymallus thymallus and Phoxinus phoxinus. In contrast, active bioindication using Salmo trutta eggs indicated that none of the restoration treatments was sufficient to enhance habitat conditions in deeper substratum layers throughout the egg incubation period. Our results suggest that instream restoration measures can contribute to freshwater biodiversity conservation, but reproductive success of species depending on long-term improvement of interstitial water quality cannot be achieved without considering catchment effects and natural substratum dynamics.

Murdock, J., et al. (2004). "Interactions between flow, periphyton, and nutrients in a heavily impacted urban stream: implications for stream restoration effectiveness." Ecological Engineering **22**(3):197–207.

Urban stream restoration is a very complex task due largely to the interactions between the physical, chemical, and biological stream components. Because of these interactions, restoring only a single component to a more natural state could have a negative affect on stream health. We studied pre-restoration interactions between hydrology, nutrients, and periphyton in a stream where wastewater effluent and a highly developed urban watershed dominated stream flow. Floods capable of scouring all visible periphyton from the stream were produced from rainfall events as small as 1.3 cm and created 47 periphyton biomass reset events during our 22-month study period. Despite these disturbances, periphyton biomass rapidly accumulated throughout the stream and reached nuisance levels after 5 days of growth during every season. Floods did, however, severely limit the occurrence of steady-state assemblages, which attained biomass levels 30 times the nuisance level. Although the high frequency of floods did not prevent nuisance levels of periphyton, it did allow more edible early stage periphyton assemblages to become far more common than late-stag, less edible assemblages. In the case of the stream studied, a successful restoration strategy must consider coupled processes relating to hydrology, chemistry, and biota.

Nakano, D. and F. Nakamura (2006). "Responses of macroinvertebrate communities to river restoration in a channelized segment of the Shibetsu River, Northern Japan." River Research and Applications **22**(6):681–689.

The effects of restoration of channel meandering and of groyne structures on physical variables and river-dwelling macroinvertebrates were examined in a lowland river, the Shibetsu River in Northern Japan. The lowland segment of the Shibetsu River, which previously meandered, was straightened by channelization and groynes installed on some portions of the channelized reach. In 2002, the channelization works were partly reversed to improve the degraded river ecosystem.

Physical environment variables and macroinvertebrate community structure and composition were compared among reconstructed meanders and channelized reaches with and without groynes. The shear stress of the river edge in reconstructed meanders and groyne reaches was lower than that in a channelized reach. **In addition, the edge habitat near the stream bank created by the reconstructed meander and groyne reaches had higher total density and taxon richness of macroinvertebrates than those of the channelized reach**. Restoration provided a relatively stable edge habitat, contributing to the recovery of macroinvertebrate communities in such channelized lowland rivers. The placement of groynes can be an effective method of in-stream habitat restoration for macroinvertebrates. Copyright (c) 2006 John Wiley & Sons, Ltd.

Niezgoda, S.L. and P.A. Johnson (2005). "Improving the Urban Stream Restoration Effort: Identifying Critical Form and Processes Relationships." *Environmental Management* **35**(5):579–592.

> Stream restoration projects are often based on morphological form or stream type and, as a result, there needs to be a clear tie established between form and function of the stream. An examination of the literature identifies numerous relationships in naturally forming streams that link morphologic form and stream processes. Urban stream restoration designs often work around infrastructure and incorporate bank stabilization and grade control structures. Because of these imposed constraints and highly altered hydrologic and sediment discharge regimens, the design of urban channel projects is rather unclear. In this paper, we examine the state of the art in relationships between form and processes, the strengths and weaknesses of these existing relationships, and the current lack of understanding in applying these relationships in the urban environment. In particular, we identify relationships that are critical to urban stream restoration projects and provide recommendations for future research into how this information can be used to improve urban stream restoration design. It is also suggested that improving the success of urban restoration projects requires further investigation into incorporating process-based methodologies, which can potentially reduce ambiguity in the design and the necessity of using an abundant amount of in-stream structures.

Palmer, M., et al. (2007). "River restoration in the twenty-first century: Data and experiential future efforts." *Restoration Ecology* **15**(3):472–481.

> Despite some highly visible projects that have resulted in environmental benefits, recent efforts to quantify the number and distribution of river restoration projects revealed a paucity of written records documenting restoration outcomes. Improving restoration designs and setting watershed priorities rely on collecting and making accessible this critical information. Information within the unpublished notes of restoration project managers is useful but rarely documents ecological improvements. This special section of Restoration Ecology is devoted to the current state of knowledge on river restoration. We provide an overview of the section's articles, reflecting on lessons learned, which have implications for the implementation, legal, and financing frameworks for restoration. Our reflections are informed by two databases developed under the auspices of the National River Restoration Science Synthesis project and by extensive interactions with those who fund, implement, and permit restoration. Requiring measurable ecological success criteria, comprehensive watershed plans, and tracking of when and where restoration projects are implemented are critical to improving the health of U.S. waters. Documenting that a project was put in the ground and stayed intact cannot be equated with ecological improvements. However, because significant ecological improvements can come with

well-designed and -implemented stream and river restorations, a small investment in documenting the factors contributing to success will lead to very large returns in the health of our nation's waterways. Even projects that may appear to be failures initially can be turned into success stories by applying the knowledge gained from monitoring the project in an adaptive restoration approach.

Palmer, M.A., et al. (2005). "Standards for ecologically successful river restoration." Journal of Applied Ecology **42**(2):208–217.

1. Increasingly, river managers are turning from hard engineering solutions to ecologically based restoration activities in order to improve degraded waterways. River restoration projects aim to maintain or increase ecosystem goods and services while protecting downstream and coastal ecosystems. There is growing interest in applying river restoration techniques to solve environmental problems, yet little agreement exists on what constitutes a successful river restoration effort.

2. We propose five criteria for measuring success, with emphasis on an ecological perspective. First, the design of an ecological river restoration project should be based on a specified guiding image of a more dynamic, healthy river that could exist at the site. Secondly, the river's ecological condition must be measurably improved. Thirdly, the river system must be more self-sustaining and resilient to external perturbations so that only minimal follow-up maintenance is needed. Fourthly, during the construction phase, no lasting harm should be inflicted on the ecosystem. Fifthly, both pre- and post-assessment must be completed and data made publicly available.

3. Determining if these five criteria have been met for a particular project requires development of an assessment protocol. We suggest standards of evaluation for each of the five criteria and provide examples of suitable indicators.

4. Synthesis and applications. Billions of dollars are currently spent restoring streams and rivers, yet to date there are no agreed upon standards for what constitutes ecologically beneficial stream and river restoration. We propose five criteria that must be met for a river restoration project to be considered ecologically successful. It is critical that the broad restoration community, including funding agencies, practitioners and citizen restoration groups, adopt criteria for defining and assessing ecological success in restoration. Standards are needed because progress in the science and practice of river restoration has been hampered by the lack of agreed upon criteria for judging ecological success. Without well-accepted criteria that are ultimately supported by funding and implementing agencies, there is little incentive for practitioners to assess and report restoration outcomes. Improving methods and weighing the ecological benefits of various restoration approaches require organized national-level reporting systems.

Pander, J. and J. Geist (2013). "Ecological indicators for stream restoration success." Ecological Indicators **30**:106–118.

Exploitation of freshwater resources is essential for sustenance of human existence and alteration of rivers, lakes and wetlands has facilitated economic development for

centuries. Consequently, freshwater biodiversity is critically threatened, with stream ecosystems being the most heavily affected. To improve the status of freshwater habitats, e.g. in the context of the European Water Framework Directive and the US Clean Water Act, it is essential to implement the most effective restoration measures and identify the most suitable indicators for restoration success. Herein, several active and passive bioindication approaches are reviewed in light of existing legal frameworks, current targets and applicable implementation of river restoration. Such approaches should move from the use of single biological indicators to more holistic ecological indicators simultaneously addressing communities, multiple life stages and habitat properties such as water quality, substrate composition and stream channel morphology. The proposed Proceeding Chain of Restoration (PCoR) can enable the integration of natural scientific, political and socioeconomic dimensions for restoration of aquatic ecosystems and associated services. Generally, an analysis that combines target species-based active bioindication with community-based passive bioindication and multivariate statistics seems to be most suitable for a holistic evaluation of restoration success, as well as for the monitoring of stream ecosystem health. Since the response of biological communities to changing environmental conditions can differ between taxonomic groups and rivers, assessments at the ecosystem scale should include several levels of biological organisation. A stepwise evaluation of the primary factors inducing disturbance or degradation is needed to integrate increasing levels of complexity from water quality assessments to the evaluation of ecological function. The proposed PCoR can provide a step-by-step guide for restoration ecologists, comprising all planning steps from the determination of the conservation objectives to the use of ecological indicators in post-restoration monitoring. (C) 2013 Elsevier Ltd. All rights reserved.

Parasiewicz, P., et al. (2013). "Use of quantitative habitat models for establishing performance metrics in river restoration planning." Ecohydrology **6**(4):668–678.

The ecological effectiveness and success of river restoration strongly depend on the resources invested in planning. Unfortunately, this trend of restoration engineering is frequently compromised by the application of qualitative assessment and resource intensive adaptive management processes. Habitat simulation models are effective tools for selecting ecologically effective restoration measures as part of the Environmental Benefits Analysis. Through the support from a mesohabitat simulation model, we identified three habitat metrics: (1) Habitat Quantity Deficiency; (2) Alteration of Habitat Structure; and (3) Habitat Stress Days Alteration to quantify and visualize differences between restoration options in Restoration Alternatives Assessment diagram. This concept of quantifying habitat models is supported by an example of application in the Wekepeke Brook in Massachusetts, in which the habitat metrics were used to define quantitative benchmarks, goals and targets to guide the restoration process from the design to the evaluation phase. The three habitat metrics are a cost effective alternative for evaluating the ecological benefits of a planned action. The methodology contributes to a high potential for designing and monitoring restoration projects. Copyright (C) 2012 John Wiley & Sons, Ltd.

Pess, G.R., et al. (2014). "Re-colonization of Atlantic and Pacific rivers by anadromous fishes: linkages between life history and the benefits of barrier removal." Reviews in Fish Biology and Fisheries **24**(3):881–900.

The last two decades have seen a rapid increase in barrier removals on rivers of the Northern Hemisphere, often for the explicit purpose of expanding the abundance, spatial distribution, and life history diversity of migratory fishes. However, differences in life history such as seasonal timing of migration and reproduction, iteroparity versus semelparity, and the extent of natal homing are likely to affect the capacity for expansion and re-colonization by taxa such as alosines, lamprey, and salmonids. We first review some basic life history traits that may affect re-colonization by migratory fishes, and then present selected examples from Atlantic and Pacific basins to illustrate these patterns and their implications for the success of barrier removal as a measure to advance the goal of fish conservation. We conclude that diadromous fishes have the capacity to rapidly re-colonize newly available habitats, though the life history patterns of each species, the proximity to source populations in the same or nearby river systems, and the diversity of habitats available may control the patterns and rates of re-colonization.

Phillips, B.M., B.S. Anderson, K. Siegler, J. Voorhees, D. Tadesse, L. Webber, R. Breuer. (2014). Trends in Chemical Contamination, Toxicity and Land Use in California Watersheds: Stream Pollution Trends (SPoT) Monitoring Program. Third Report - Five-Year Trends 2008–2012. Sacramento, California, California State Water Resources Control Board.

Pitt, R., et al. (2013). Performance Results from Small- and Large-Scale System Monitoring and Modeling of Intensive Applications of Green Infrastructure In Kansas City. 2013 International Low Impact Development Symposium, Saint Paul, Minnesota.

The US EPA's Green Infrastructure Demonstration project in Kansas City, MO, incorporates both small-scale individual biofiltration device monitoring, along with large-scale watershed monitoring. The test watershed (40 ha, 100 acres) has as many green infrastructure components (including curb-cut biofilters with extra subsurface storage, rain gardens, cascading biofilters, and porous concrete sidewalks). An adjacent 35 ha (87 acre) control watershed is also being monitored for comparison and to track effects of different rains affecting the watershed responses. A locally calibrated version of the WinSLAMM stormwater model was used to evaluation specific design options of these stormwater controls and for analyses of green infrastructure alternatives at other areas of the city. SWMM and SUSTAIN are also being used in this demonstration project to obtain insights in applying the lessons learned to larger city-wide applications.

Performance plots were prepared using the calibrated WinSLAMM model relating the size of green infrastructure components with expected flow reductions considering local design approaches and site conditions. As an example, the curb-cut biofilters being used are about 1.5 to 2% of their drainage areas (containing substantial surface

and subsurface storage) and are expected to provide about 90% long-term reductions in stormwater runoff to the combined sewer. During the monitoring period, none of the rain gardens on private property had any surface overflows, and the monitored biofilters contained well over 90% of their flows.

More than half of the 100-acre pilot area is directly treated by about 135 individual green infrastructure control installations. The remaining areas were not treated as they drained to private property yard drains or had no suitable locations due to interferences (large trees, driveways, etc.). The area treated was associated with the largest flow portion of the whole site (mostly being along the roads). The large system flow monitoring at the test and control locations in the combined sewer indicated significant and large flow reductions. The period of construction was associated with continuously decreasing runoff yields, stabilizing to about 50 to 70% runoff volume reductions after all the controls were completed. The EPA-sponsored monitoring program will continue through the summer of 2013.

Pizzuto, J.E., et al. (2000). "Comparing gravel-bed rivers in paired urban and rural catchments of southeastern Pennsylvania." Geology **28**(1):79–82.

Surveys in eight paired urban and rural watersheds illustrate how urbanization changes fluvial morphology and processes. Our data also provide quantitative criteria for evaluating stream-restoration projects in urban areas. Bankfull depth, reach-averaged bed slope, and median grain size are similar in urban and rural watersheds. The median width of urban channels is 26% larger than the median width of rural channels. The median sinuosity is 8% lower in urban channels and pools are 31% shallower, The median composite Manning's n based on median grain diameter, pool depth, and channel sinuosity is 10% lower in urban streams, while the median bankfull discharge per unit drainage basin area is 131% higher in urban channels. Histograms of bed sediment-size distributions in urban channels lack a secondary mode in the size range 2–64 mm characteristic of rural channels, indicating that these sizes tend to be selectively removed from urban channels. However, bankfull Shields stresses in urban and rural channels exceed typical threshold values at most sites, indicating significant bedload transport at bankfull stage. Apparently, increased peak discharges caused by decades of urbanization have not removed all the transportable sediment from these urban stream channels. We speculate that the supply of sediment to urban channels from hillslope processes and channel erosion remains significant, even though much of the upland surfaces of these urban catchments are covered with nonerodible impervious surfaces.

Potter, K.W. (1991). "HYDROLOGICAL IMPACTS OF CHANGING LAND MANAGEMENT-PRACTICES IN A MODERATE-SIZED AGRICULTURAL CATCHMENT." Water Resources Research **27**(5):845–855.

Since the mid-1930s a variety of soil conservation practices have been applied to agricultural lands throughout the United States. While intended to reduce soil erosion, if effective, these practices should alter the hydrology of streams which drain the treated lands. This hypothesis was explored for the East Branch of the Pecatonica River, a gaged 221 square mile agricultural catchment in southwestern Wisconsin. On the basis of the analysis of peak and daily flow data there has been a decrease in flood peaks and in winter/spring flood volumes and an increase in hydrologic rise times and in the contribution of winter/spring snowmelt events to base flow. These changes do not appear to be due to climatic variations, reservoir construction, or major land use changes. Instead, they appear to have resulted from the adoption of various soil conservation practices, particularly those involving the treatment of gullies and the adoption of conservation tillage.

Pretty, J.L., et al. (2003). "River rehabilitation and fish populations: assessing the benefit of instream structures." Journal of Applied Ecology **40**(2):251–265.

1. River rehabilitation schemes are now widespread in the UK and elsewhere, but there have been few systematic assessments of their ecological effect, particularly on target organisms such as fish. Fish populations were therefore assessed in 13 lowland rivers using point abundance measures and depletion electrofishing. Each river was sampled in two reaches, respectively containing a small-scale rehabilitation scheme (artificial riffles or flow deflectors) and an unrehabilitated control reach. Detailed geomorphological surveys were undertaken for the two study reaches in each river to assess the physical and hydraulic effect of rehabilitation.

2. There were large qualitative and quantitative differences among rivers and some had relatively impoverished fish faunas. **Overall, total fish abundance, species richness, diversity and equitability were not significantly different between rehabilitated and control reaches.** This was true for both the sampling methods used. Bullhead Cottus gobio and stone loach Barbatula barbatula tended to be more abundant in rehabilitated reaches, but this was significant only for artificial riffles. There was a significant between-year difference in fish abundance.

3. **In general, rehabilitation schemes increased depth and flow heterogeneity, and fish species richness and diversity appeared to respond positively to increased flow velocity in restored reaches. However, there were few significant relationships between the fish fauna and physical variables, indicating that increasing physical (habitat) heterogeneity does not necessarily lead to higher biological diversity. We therefore caution against the use of physical responses to rehabilitation as a surrogate or reliable predictor of ecological response.**

4. **The weak response of fishes to rehabilitation may have been because the schemes were inappropriate in design and scale for low-gradient rivers. Furthermore, fish assemblages may have lacked the potential for recovery because of poor water quality and/or because the schemes were isolated within longer sections of degraded river.** More extensive and directed biological monitoring is essential to improve understanding and enable future improvements in the design of schemes and the selection of sites with greater potential for successful rehabilitation.

5. Synthesis and applications. From this substantial sample of lowland rivers, there is little evidence of any general benefit to fish of small-scale instream structures in river rehabilitation. From present ecological knowledge it may be that resources would be better devoted to promoting the development of lateral and off-channel habitats

within the river corridor. Physical restoration will be most effective when used alongside other strategies to augment fish populations such as water quality management.

Purcell, A.H., et al. (2009). "Assessment Tools For Urban Catchments: Developing Biological Indicators Based On Benthic Macroinvertebrates." Journal of the American Water Resources Association **45**(2):306–319.

Biological indicators, particularly benthic macroinvertebrates, are widely used and effective measures of the impact of urbanization on stream ecosystems. A multimetric biological index of urbanization was developed using a large benthic macroinvertebrate dataset (n = 1,835) from the Baltimore, Maryland, metropolitan area and then validated with datasets from Cleveland, Ohio (n = 79); San Jose, California (n = 85); and a different subset of the Baltimore data (n = 85). The biological metrics used to develop the multimetric index were selected using several criteria and were required to represent ecological attributes of macroinvertebrate assemblages including taxonomic composition and richness (number of taxa in the insect orders of Ephemeroptera, Plecoptera, and Trichoptera), functional feeding group (number of taxa designated as filterers), and habit (percent of individuals which cling to the substrate). Quantile regression was used to select metrics and characterize the relationship between the final biological index and an urban gradient (composed of population density, road density, and urban land use). Although more complex biological indices exist, this simplified multimetric index showed a consistent relationship between biological indicators and urban conditions (as measured by quantile regression) in three climatic regions of the United States and can serve as an assessment tool for environmental managers to prioritize urban stream sites for restoration and protection.

Roberts, B., et al. (2007). "Effects of upland disturbance and instream restoration on hydrodynamics and ammonium uptake in headwater streams." Journal of the North American Benthological Society **26**(1):38–53.

Delivery of water, sediments, nutrients, and organic matter to stream ecosystems is strongly influenced by the catchment of the stream and can be altered greatly by upland soil and vegetation disturbance. At the Fort Benning Military Installation (near Columbus, Georgia), spatial variability in intensity of military training results in a wide range of intensities of upland disturbance in stream catchments. A set of 8 streams in catchments spanning this upland disturbance gradient was selected for investigation of the impact of disturbance intensity on hydrodynamics and nutrient uptake. The size of transient storage zones and rates of NH4þ uptake in all study streams were among the lowest reported in the literature. **Upland disturbance did not appear to influence stream hydrodynamics strongly, but it caused significant decreases in instream nutrient uptake.** In October 2003, **coarse woody debris (CWD) was added to ½ of the study streams (spanning the disturbance gradient) in an attempt to increase hydrodynamic and structural complexity, with the goals of enhancing biotic habitat and increasing nutrient uptake rates**. CWD **additions had positive short-term**

(within 1 mo) effects on hydrodynamic complexity (water velocity decreased and transient storage zone cross-sectional area, relative size of the transient storage zone, fraction of the median travel time attributable to transient storage over a standardized length of 200 m, and the hydraulic retention factor increased) and nutrient uptake (NH4þ uptake rates increased). Our results suggest that water quality in streams with intense upland disturbances can be improved by enhancing instream biotic nutrient uptake capacity through measures such as restoring stream CWD.

Roni, P., et al. (2002). "A review of stream restoration techniques and a hierarchical strategy for prioritizing restoration in Pacific northwest watersheds." North American Journal of Fisheries Management **22**(1):1–20.

Millions of dollars are spent annually on watershed restoration and stream habitat improvement in the U.S. Pacific Northwest in an effort to increase fish populations. It is generally accepted that watershed restoration should focus on restoring natural processes that create and maintain habitat rather than manipulating instream habitats. However, most process-based restoration is site-specific, that is, conducted on a short stream reach. To synthesize site-specific techniques into a process-based watershed restoration strategy, **we reviewed the, effectiveness of various restoration techniques at improving fish habitat** arid developed a hierarchical strategy for prioritizing them. The hierarchical strategy we present is based on three elements: (I) principles of watershed processes, (2) protecting existing high-quality habitats, and (3) current knowledge of the effectiveness of specific techniques. **Initially, efforts should focus on protecting areas with intact processes and high-quality habitat.** Following a watershed assessment, we recommend that r**estoration focus on reconnecting isolated high-quality fish habitats, such as instream or off-channel habitats made inaccessible by culverts or other artificial obstructions.** Once the connectivity of habitats within a basin has been restored, efforts should focus on restoring hydrologic, geologic (sediment delivery and routing), and riparian processes through road decommissioning and maintenance, exclusion of livestock, and restoration of riparian areas. Instream habitat enhancement (e.g., additions of wood, boulders, or nutrients) should be employed. after restoring natural processes or where short-term improvements in habitat are needed (e.g., habitat for endangered species). Finally, existing research and monitoring is inadequate for all the techniques we reviewed, and additional, comprehensive physical and biological evaluations of most watershed restoration methods are needed.

Roper, B.B., et al. (1998). "Durability of Pacific Northwest Instream Structures Following Floods." North American Journal of Fisheries Management **18**(3):686–693.

The durability of 3,946 instream structures in 94 streams that had floods with return intervals exceeding 5 years were assessed. **Overall structure durability (defined as the degree to which a structure remained at its original location) was high; less than 20% of the sampled structures had been removed from the site of original placement.** The **magnitude of flood events had a significant effect on structure**

durability with higher magnitude floods reducing durability. Stream order also affected structure durability; **structures in large streams were 20 times more likely to have been removed from the site of original placement than structures in small streams**. Other conditions that affected structure durability included location of the structure within the stream channel, whether the structure was anchored or not, structure material, and upslope landslide frequency. **Instream structures are most appropriate when used as short-term tools to improve degraded stream conditions** while activities that caused the habitat degradation are simultaneously modified. When instream structures are part of a properly sequenced watershed restoration strategy, they can improve habitat conditions through a range of flow conditions including large floods.

Roy, A., et al. (2008). "Impediments and Solutions to Sustainable, Watershed-Scale Urban Stormwater Management: Lessons from Australia and the United States." Environmental Management **42**(2):344–359.

In urban and suburban areas, stormwater runoff is a primary stressor on surface waters. Conventional urban stormwater drainage systems often route runoff directly to streams and rivers, thus exacerbating pollutant inputs and hydrologic disturbance, and resulting in the degradation of ecosystem structure and function. Decentralized stormwater management tools, such as low impact development (LID) or water sensitive urban design (WSUD), may offer a more sustainable solution to stormwater management if implemented at a watershed scale. These tools are designed to pond, infiltrate, and harvest water at the source, encouraging evaporation, evapotranspiration, groundwater recharge, and re-use of stormwater. While there are numerous demonstrations of WSUD practices, there are few examples of widespread implementation at a watershed scale with the explicit objective of protecting or restoring a receiving stream. **This article identifies seven major impediments to sustainable urban stormwater management: (1) uncertainties in performance and cost, (2) insufficient engineering standards and guidelines, (3) fragmented responsibilities, (4) lack of institutional capacity, (5) lack of legislative mandate, (6) lack of funding and effective market incentives, and (7) resistance to change**. By comparing experiences from Australia and the United States, two developed countries with existing conventional stormwater infrastructure and escalating stream ecosystem degradation, we highlight challenges facing sustainable urban stormwater management and offer several examples of successful, regional WSUD implementation. We conclude by identifying solutions to each of the seven impediments that, when employed separately or in combination, should encourage widespread implementation of WSUD with watershed-based goals to protect human health and safety, and stream ecosystems.

Roy, A.H., et al. (2014). "How Much Is Enough? Minimal Responses of Water Quality and Stream Biota to Partial Retrofit Stormwater Management in a Suburban Neighborhood." Plos One **9**(1).

Decentralized stormwater management approaches (e. g., biofiltration swales, pervious pavement, green roofs, rain gardens) that capture, detain, infiltrate, and filter runoff are now commonly used to minimize the impacts of stormwater runoff from impervious surfaces on aquatic ecosystems. However, there is little research on the effectiveness of retrofit, parcel-scale stormwater management practices for improving downstream aquatic ecosystem health. A reverse auction was used to encourage homeowners to mitigate stormwater on their property within the suburban, 1.8 km(2) Shepherd Creek catchment in Cincinnati, Ohio (USA). **In 2007-2008, 165 rain barrels and 81 rain gardens were installed on 30% of the properties in four experimental (treatment) subcatchments, and two additional subcatchments were maintained as controls.** At the base of the subcatchments, we sampled monthly baseflow water quality, and seasonal (5x/year) physical habitat, periphyton assemblages, and macroinvertebrate assemblages in the streams for the three years before and after treatment implementation. Given the minor reductions in directly connected impervious area from the rain barrel installations (11.6% to 10.4% in the most impaired subcatchment) and high total impervious levels (13.1% to 19.9% in experimental subcatchments), we expected minor or no responses of water quality and biota to stormwater management. There were trends of increased conductivity, iron, and sulfate for control sites, but no such contemporaneous trends for experimental sites. **The minor effects of treatment on streamflow volume and water quality did not translate into changes in biotic health, and the few periphyton and macroinvertebrate responses could be explained by factors not associated with the treatment (e.g., vegetation clearing, drought conditions). Improvement of overall stream health is unlikely without additional treatment of major impervious surfaces (including roads, apartment buildings, and parking lots).** Further research is needed to define the minimum effect threshold and restoration trajectories for retrofitting catchments to improve the health of stream ecosystems.

Sansalone, J., et al. (2013). "Retrofitting impervious urban infrastructure with green technology for rainfall-runoff restoration, indirect reuse and pollution load reduction." Environmental Pollution **183**:204–212.

The built environs alter hydrology and water resource chemistry. Florida is subject to nutrient criteria and is promulgating "no-net-load-increase" criteria for runoff and constituents (nutrients and particulate matter, PM). With such criteria, green infrastructure, hydrologic restoration, indirect reuse and source control are potential design solutions. The study simulates runoff and constituent load control through urban source area re-design to provide long-term "no-net-load-increases". A long-term continuous simulation of pre- and post-development response for an existing surface parking facility is quantified. Retrofits include a biofiltration area reactor (BAR) for hydrologic and denitrification control. A linear infiltration reactor (LIR) of cementitious permeable pavement (CPP) provides infiltration, adsorption and

filtration. Pavement cleaning provided source control. Simulation of climate and source area data indicates re-design achieves "no-net-load-increases" at lower costs compared to standard construction. The retrofit system yields lower cost per nutrient load treated compared to Best Management Practices (BMPs). (C) 2013 Elsevier Ltd. All rights reserved.

Schiff, R., et al. (2011). "Evaluating Stream Restoration: A Case Study From Two Partially Developed 4th Order Connecticut, USA Streams And Evaluation Monitoring Strategies." River Research and Applications **27**(4):431–460.

Stream rehabilitation and enhancement projects in the Norwalk River (urban-forest watershed) and Merrick Brook (agriculture-forest watershed) were evaluated. Instream structure installation, streambank stabilization and meander re-creation were performed 2-5 years before monitoring. Physical, chemical and biological variables were monitored at control, enhanced (treatment sites originally controls), impaired and rehabilitated (treatment sites originally impaired) sites for three field seasons to evaluate the projects and formulate monitoring strategies. Small improvements in local habitat and macroinvertebrate assemblages were observed at rehabilitated sites on the Norwalk River however control conditions were not attained. Changes to stream health were less evident at the reach scale suggesting that watershed processes that form and maintain habitat were too altered for more widespread recovery. A localized sediment source from a failing streambank was eliminated from Merrick Brook protecting the abundant nearby quality habitat, yet fining occurred at the rehabilitation site due to hydraulic changes leading to localized shifts in macroinvertebrate assemblages. Single-season sampling created a useful snapshot to compare enhanced and rehabilitated sites to control and impaired sites. We recommend a tiered sampling strategy where effectiveness monitoring may include a detailed effort at many sites over a short time (as performed here), a relatively low level of detail (e. g. a rapid assessment) at an intermediate number of sites over a short time, and a detailed long-term monitoring at few sites (e. g. before-after-control-impact, BACI). More research is needed to continue the trend of increased project evaluation to advance the science and application of stream restoration. Copyright (C) 2010 John Wiley & Sons, Ltd.

Schilling, K.E. (2002). "Chemical transport from paired agricultural and restored prairie watersheds." Journal of Environmental Quality **31**(4):1184–1193.

A five-year record of streamflow and chemical sampling data was evaluated to assess the effects of large-scale prairie restoration on transport of NO3-N, Cl, and SO4 loads from paired 5000-ha watersheds located in Jasper County, Iowa. **Water quality conditions monitored during land use conversion from row crop agriculture to native prairie in the Walnut Creek watershed were compared with a highly agricultural control watershed (Squaw Creek)**. Combining hydrograph separation with a load estimation program, baseflow and stormflow loads of NO3-N, Cl, and SO4 were estimated at upstream and downstream sites on Walnut Creek and a downstream site on Squaw Creek. Chemical export in both watersheds was found to occur primarily

with baseflow, with baseflow transport greatest during the late summer and fall. **Lower Walnut Creek watershed, which contained the restored prairie areas, exported less NO3-N and Cl compared with upper Walnut Creek and Squaw Creek watersheds**. Average How-weighted concentrations of NO3-N exceeded 10 mg/L in upper Walnut Creek and Squaw Creek, but were estimated to be 6.6 mg/L in lower Walnut Creek. Study results demonstrate the utility of partitioning loads into baseflow and stormflow components to identify sources of pollutant loading to streams.

Selbig, W.R., et al. (2008). A comparison of runoff quantity and quality from two small basins undergoing implementation of conventional and low-impact-development (LID) strategies : Cross Plains, Wisconsin, water years 1999–2005. Reston, Virginia, U.S. Geological Survey.

Environmental managers are often faced with the task of designing strategies to accommodate development while minimizing adverse environmental impacts. Low-impact development (LID) is one such strategy that attempts to mitigate environmental degradation commonly associated with impervious surfaces. The U.S. Geological Survey, in cooperation with the Wisconsin Department of Natural Resources, studied two residential basins in Cross Plains, Wis., during water years 1999–2005. **A paired-basin study design was used to compare runoff quantity and quality from the two basins, one of which was developed in a conventional way and the other was developed with LID.** The conventional-developed basin (herein called "conventional basin") consisted of curb and gutter, 40-foot street widths, and a fully connected stormwater-conveyance system. The LID basin consisted of grassed swales, reduced impervious area (32-foot street widths), street inlets draining to grass swales, a detention pond, and an infiltration basin. Data collected in the LID basin represented predevelopment through near-complete build-out conditions.

Smaller, more frequent precipitation events that produced stormwater discharge from the conventional basin were retained in the LID basin. **Only six events with precipitation depths less than or equal to 0.4 inch produced measurable discharge from the LID basin.** Of these six events, five occurred during winter months when underlying soils are commonly frozen, and one was likely a result of saturated soil from a preceding storm. In the conventional basin, the number of discharge events, using the same threshold of precipitation depth, was 180, with nearly one-half of those resulting from precipitation depths less than 0.2 inch. Precipitation events capable of producing appreciable discharge in the LID basin were typically those of high intensity or precipitation depth or those that occurred after soils were already saturated. Total annual discharge volume measured from the conventional basin ranged from 1.3 to 9.2 times that from the LID basin.

Development of the LID basin did not appreciably alter the hydrologic response to precipitation characterized during predevelopment conditions. **Ninety-five percent or more of precipitation in the LID basin was retained during each year of construction from predevelopment through near-complete build-out,** surpassing the 90-percent benchmark established for new development by the Wisconsin Department of Natural Resources. The amount of precipitation retained in the conventional basin did not exceed 94 percent and fell below the 90-percent standard 2 of the 6 years monitored.

Much of the runoff in the LID basin was retained by an infiltration basin, the largest control structure used to mitigate storm-runoff quantity and quality. The infiltration basin also was the last best-management practice (BMP) used to treat runoff before it left the LID basin as discharge. From May 25, 2002, to September 30, 2005, only 24 of 155 precipitation events exceeded the retention/ infiltrative capacity of the infiltration basin. The overall reduction in runoff volume from these few events was 51 percent. The effectiveness of the infiltration basin decreased as precipitation intensities exceeded 0.5 inch per hour.

Annual loads were estimated to characterize the overall effectiveness of low-impact design practices for mitigating delivery of total solids, total suspended solids, and total phosphorus. **Annual loads of these three constituents were greater in the LID basin than in the conventional basin in 2000 and 2004.** Seventy percent or more of all constituent annual loads were associated with two discharge events in 2000, and a single discharge event produced 50 percent or more of constituent annual loads in 2004. Each of these discharge events was associated with considerable precipitation depths and (or) intensities, ranging from 4.89 to 6.21 inches and from 1.13 to 1.2 inches per hour, respectively. These same storms did not contribute as much of the annual load in the conventional basin. **With large storms and saturated soils, the ability of low-impact design techniques to reduce runoff, and thus constituent loads, can be greatly diminished.**

For both the LID and conventional basins, the temperature of runoff was largely affected by ambient air temperatures. However, the temperature of discharge from the LID basin increased upon runoff cessation. This increase is likely due to solar heating of water that is temporarily stored in the detention pond and infiltration basin.

Selvakumar, A., et al. (2010). "Role of Stream Restoration on Improving Benthic Macroinvertebrates and In-Stream Water Quality in an Urban Watershed: Case Study." Journal of Environmental Engineering-Asce **136**(1):127–139.

Many stream restoration projects do not include a requirement for long-term monitoring after the project has been completed, resulting in a lack of information about the success or failure of certain restoration techniques. The National Risk Management Research Laboratory, part of the U.S. EPA Office of Research and Development, evaluated the effectiveness of stream bank and channel restoration as a means of improving in-stream water quality and biological habitat in Accotink Creek, Fairfax City, Va., using discrete sampling and continuous monitoring techniques before and after restoration. This project monitored the effects of a 549 m (1,800 linear-ft) restoration of degraded stream channel in the North Fork of Accotink Creek. Restoration, which was intended to restore the stream channel to a stable condition, thereby reducing stream bank erosion and sediment loads in the stream, included installation of native plant materials along the stream and bioengineering structures to

stabilize the stream channel and bank. Results of sampling and monitoring for 2 years after restoration indicated a slight improvement in biological quality for macroinvertebrate indices such as Virginia Stream Condition Index, Hilsenhoff Biotic Index, and Ephemeroptera, Plecoptera, Trichoptera taxa; the differences were statistically significant at 90% level of confidence with the power of greater than 0.8. However, indices were all below the impairment level, indicating poor water quality conditions. No statistically significant differences in chemical constituents and bacteriological indicator organisms were found before and after restoration as well as upstream and downstream of the restoration. The results indicated that stream restoration alone had little effect in improving the conditions of in-stream water quality and biological habitat, though it has lessened further degradation of stream banks in critical areas where the properties were at risk. Control of storm-water flows by placing best management practices in the watershed might reduce and delay discharge to the stream and may ultimately improve habitat and water quality conditions.

Shilla, D.J. and D.A. Shilla (2011). "The effects of catchment land use on water quality and macroinvertebrate assemblages in Otara Creek, New Zealand." Chemistry and Ecology **27**(5):445–460.

The effect of catchment land use on water quality and macroinvertebrate communities was examined by using data gathered during a 2004 reconnaissance of nine sites in the Otara Creek, New Zealand. Data collected included macroinvertebrate, water chemistry and sediments characteristics. Macroinvertebrate data were used in metric and index calculations. A total of 61 macroinvertebrate taxa, with 3032 total individuals, were identified from the macroinvertebrates samples collected from nine sites in Otara Creek. The greatest number of macroinvertebrate taxa was recorded within bush sites (mean > 25), while the urban sites had the least number of taxa (mean = 10). Pasture sites were intermediate with the mean > 17. Taxa number differed significantly across land use. Mean macroinvertebrates abundance varied across the sites and land uses. The highest macroinvertebrates mean abundance was recorded in urban and pasture sites, while bush sites had significantly lower mean abundance. Physico-chemical parameters decreased from bush toward urban streams. Biotic indices were sensitive to changes in macroinvertebrates community structure across land uses with mean scores decreasing from bush to urban and pasture streams. Ordination of biological data showed a clear separation of bush from urban and pastures streams. Analysis of similarities revealed significant differences in macroinvertebrates between both stream groups and land-use groups. The observed macroinvertebrate assemblage pattern was best correlated with a single variable, conductivity, temperature, turbidity, nitrate and dissolved oxygen. The combination of these environmental variables best explained the changes in the macroinvertebrate assemblages between sites. This study demonstrates that catchment land use may significantly affect the water quality and macroinvertebrate communities in an ecosystem.

Shuster, W. and L. Rhea (2013). "Catchment-scale hydrologic implications of parcel-level stormwater management (Ohio USA)." Journal of Hydrology **485**:177–187.

> The effectiveness of stormwater management strategies is a key issue affecting decision making on urban water resources management, and so proper monitoring and analysis of pilot studies must be addressed before drawing conclusions. We performed a pilot study in the suburban Shepherd Creek watershed located in Cincinnati, Ohio to evaluate the practicality of voluntary incentives for stormwater quantity reduction on privately owned suburban properties. **Stream discharge and precipitation were monitored 3 years before and after implementation of the stormwater management treatments**. To implement stormwater control measures, we elicited the participation of citizen landowners with two successive reverse-auctions. Auctions were held in spring 2007, and 2008, resulting in the **installation of 85 rain gardens and 174 rain barrels**. We demonstrated an analytic process of increasing model flexibility to determine hydrologic effectiveness of stormwater management at the sub-catchment level. A significant albeit small proportion of total variance was explained by both the effects of study period (similar to 69%) and treatment-vs.-control (similar to 7%). Precipitation-discharge relationships were synthesized in estimated unit hydrographs, which were decomposed and components tested for influence of treatments. Analysis of unit hydrograph parameters showed a weakened correlation between precipitation and discharge, and support the output from the initial model that parcel-level green infrastructure added detention capacity to treatment basins. **We conclude that retrofit management of stormwater runoff quantity with green infrastructure in a small suburban catchment can be successfully initiated with novel economic incentive programs, and that these measures can impart a small, but statistically significant decrease in otherwise uncontrolled runoff volume**. Given consistent monitoring data and analysis, water resource managers can use our approach as a way to estimate actual effectiveness of stormwater runoff volume management, with potential benefits for management of both separated and combined sewer systems. We also discuss lessons-learned with regard to monitoring design for catchment-scale hydrologic studies.

Simenstad, C., et al. (2006). "When is restoration not? Incorporating landscape-scale processes to restore self-sustaining ecosystems in coastal wetland restoration." Ecological Engineering **26**(1):27–39.

Sivirichi, G.M., et al. (2011). "Longitudinal variability in streamwater chemistry and carbon and nitrogen fluxes in restored and degraded urban stream networks." Journal of Environmental Monitoring **13**(2):288–303.

> Stream restoration has increasingly been used as a best management practice for improving water quality in urbanizing watersheds, yet few data exist to assess restoration effectiveness. This study examined the longitudinal patterns in carbon and nitrogen concentrations and mass balance in two restored (Minebank Run and Spring Branch) and two unrestored (Powder Mill Run and Dead Run) stream networks in

Baltimore, Maryland, USA. Longitudinal synoptic sampling showed that there was considerable reach-scale variability in biogeochemistry (e. g., total dissolved nitrogen (TDN), dissolved organic carbon (DOC), cations, pH, oxidation/reduction potential, dissolved oxygen, and temperature). TDN concentrations were typically higher than DOC in restored streams, but the opposite pattern was observed in unrestored streams. Mass balances in restored stream networks showed net uptake of TDN across subreaches (mean +/- standard error net uptake rate of TDN across sampling dates for Minebank Run and Spring Branch was 420.3 +/- 312.2 and 821.8 +/- 570.3 mg m(-2) d(-1), respectively). There was net release of DOC in the restored streams (1344 +/- 1063 and 1017 +/- 944.5 mg m(-2) d(-1) for Minebank Run and Spring Branch, respectively). Conversely, degraded streams, Powder Mill Run and Dead Run showed mean net release of TDN across sampling dates (629.2 +/- 167.5 and 327.1 +/- 134.5 mg m(-2) d(-1), respectively) and net uptake of DOC (1642 +/- 505.0 and 233.7 +/- 125.1 mg m(-2) d(-1), respectively). There can be substantial C and N transformations in stream networks with hydrologically connected floodplain and pond features. Assessment of restoration effectiveness depends strongly on where monitoring is conducted along the stream network. Monitoring beyond the stream-reach scale is recommended for a complete perspective of evaluation of biogeochemical function in restored and degraded urban streams.

Smith, J.G., et al. (2011). "Long-Term Benthic Macroinvertebrate Community Monitoring to Assess Pollution Abatement Effectiveness." Environmental Management **47**(6):1077–1095.

The benthic macroinvertebrate community of East Fork Poplar Creek (EFPC) in East Tennessee was monitored for 18 years to evaluate the effectiveness of a water pollution control program implemented at a major United States (U.S.) Department of Energy facility. Several actions were implemented to reduce and control releases of pollutants into the headwaters of the stream. Four of the most significant actions were implemented during different time periods, which allowed assessment of each action. Macroinvertebrate samples were collected annually in April from three locations in EFPC (EFK24, EFK23, and EFK14) and two nearby reference streams from 1986 through 2003. Significant improvements occurred in the macroinvertebrate community at the headwater sites (EFK24 and EFK23) after implementation of each action, while changes detected 9 km further downstream (EFK14) could not be clearly attributed to any of the actions. Because the stream was impacted at its origin, invertebrate recolonization was primarily limited to aerial immigration, thus, recovery has been slow. As recovery progressed, abundances of small pollution-tolerant taxa (e.g., Orthocladiinae chironomids) decreased and longer lived taxa colonized (e. g., hydropsychid caddisflies, riffle beetles, Baetis). While assessments lasting three to four years may be long enough to detect a response to new pollution controls at highly impacted locations, more time may be needed to understand the full effects. Studies on the effectiveness of pollution controls can be improved if impacted and reference sites are selected to maximize spatial and temporal trending, and if a multidisciplinary approach is used to broadly assess environmental responses (e.g., water quality trends, invertebrate and fish community assessments, toxicity testing, etc.).

Smucker, N.J. and N.E. Detenbeck (2014). "Meta-Analysis of Lost Ecosystem Attributes in Urban Streams and the Effectiveness of Out-of-Channel Management Practices." Restoration Ecology **22**(6):741–748.

> Urban development is a leading cause of stream impairment that reduces biodiversity and negatively affects ecosystem processes and habitat. Out-of-stream restoration practices, such as stormwater ponds, created wetlands, and restored riparian vegetation, are increasingly implemented as management strategies to mitigate impacts. However, uncertainty exists regarding how effectively they improve downstream ecosystems because monitoring is uncommon and results are typically reported on a case-by-case basis. We conducted a meta-analysis of literature and used response ratios to quantify how downstream ecosystems change in response to watershed development and to out-of-stream restoration. Biodiversity in unrestored urban streams was 47% less than that in reference streams, and ecological communities, habitat, and rates of nutrient cycling were negatively affected as well. Mean measures of ecosystem attributes in restored streams were significantly greater than, and 156% of, those in unrestored urban streams. Measures of biodiversity in restored streams were 132% of those in unrestored urban streams, and indices of biotic condition, community structure, and nutrient cycling significantly improved. However, ecosystem attributes and biodiversity at restored sites were significantly less than, and only 60% and 45% of, those in reference streams, respectively. Out-of-stream management practices improved ecological conditions in urban streams but still failed to restore reference stream conditions. Despite statistically significant improvements, assessing restoration success remains difficult due to few comparisons to reference sites or to clearly defined targets. These findings can inform future monitoring, management, and development strategies and highlight the need for preventative actions in a watershed context.

Stewart, G.B., et al. (2009). "Effectiveness of engineered in-stream structure mitigation measures to increase salmonid abundance: a systematic review." Ecological Applications **19**(4):931–941.

> Engineered in-stream structures are often installed to increase salmonid abundance, either for commercial gain in fisheries or for conservation purposes in degraded habitats. Having been in widespread use for the last 80 years, at an estimated cost of hundreds of millions of U.S. dollars each year, the effectiveness of these structures is still widely debated in the literature. Many studies of varying quality have been undertaken that attempt to address this issue, but it has proved difficult for practitioners to develop a consensus regarding the utility of these structures, despite their continued use. Systematic review methodology was used to formally synthesize empirical evidence regarding the effectiveness of engineered instream structures as a management tool to increase salmonid abundance. Meta-analysis shows that evidence regarding the effectiveness of in-stream devices is equivocal. Heterogeneity is significant both for population size and local habitat preference. This heterogeneity is related to stream width, with in-stream devices being less effective in larger streams.

Consequently, widespread use of in-stream structures for restoration, particularly in larger streams, is not supported by the current scientific evidence base.

Stillwater Sciences (2015). Integrated Design for Habitat and Water Quality Status and Trends Monitoring in the Lower Columbia ESU. Portland, Oregon.

Most of the monitoring objectives will be addressed using a probabilistic design, wherein sites are randomly selected across the entire area of interest. This approach stands in contrast to the more commonly implemented opportunistic design, with sites selected for ease of access, expert opinion, or other subjective criteria. However, several of the monitoring objectives can only be addressed with a more directed, pseudo-randomized approach, which will be developed and evaluated as part of the forthcoming Implementation Plan.

Qa/Qx sampling will take advantage of the “continuity” of flowing water, under the assumption that most water-quality parameters vary spatially only gradually, if at all, along a given channel reach in the absence of tributary inputs. Thus, the population of Qa/Qx sites from which sampling locations will be drawn will be reaches (not individual points) having a specified range of drainage areas. Within each selected reach, the location chosen for sampling should have little to no influence on the collected data, and thus ancillary considerations (such as site access or the reoccupation of legacy sampling sites that are located within the selected reaches) can be incorporated without undermining the random spatial design.

Strange, E.M., et al. (1999). "Sustaining ecosystem services in human-dominated watersheds: Biohydrology and ecosystem processes in the South Platte River Basin." Environmental Management **24**(1):39–54.

Sustaining ecosystem services important to humans while providing a dependable water supply for agriculture and urban needs is a major challenge raced by managers of human-dominated watersheds. Modification of natural flow regimes alters the abundance and composition of native plant and animal communities, affecting ecosystem services such as water storage and nutrient cycling that depend on particular species or functional groups. Because complete restoration of natural hydrology is generally not an option in human-dominated watersheds, there is a need to determine which specific flow manipulations are necessary to restore species-dependent ecosystem services in particular systems. Mere we propose a framework for predicting ecological consequences of flow manipulations that is based on the role of hydrology in linking population, community, and ecosystem processes. We use a case-study approach to examine how interactions among the flow regime and species' functional traits help organize local biotic communities and generate alternate states of ecosystem functioning. Results indicate the importance of integrating hydrology and biology to predict ecological consequences of flow regime manipulations and the need to apply general flow-restoration principles on a case-by-case basis.

Stranko, S.A., et al. (2012). "Comparing the Fish and Benthic Macroinvertebrate Diversity of Restored Urban Streams to Reference Streams." Restoration Ecology **20**(6):747–755.

> Urbanization is associated with substantial losses to stream biological diversity throughout the United States' mid-Atlantic. Stream restoration has been used to improve stream conditions and, in part, to ameliorate these losses. However, the relationship between restoration and recovery of biological diversity is unclear. **Our objective was to critically examine the efficacy of urban stream restorations with regard to biological diversity. We compared restored urban streams to urban nonrestored, nonurban, and reference (minimally degraded) streams using five measures each of fish and benthic macroinvertebrate diversity. Both multivariate and univariate statistical analyses show biological diversity of restored urban streams to be similar to nonrestored urban streams and lower than nonurban and reference streams. Restored urban sites showed no apparent increase in biological diversity through time, while diversity decreased at two of the reference streams coincident with increased urban development within their catchments.** Our results indicate that restoration approaches commonly used regionally as in these urban streams are not leading to recovery of native stream biodiversity. Evidence from several sources indicates a need for dramatic changes in restoration approach, and we argue for a watershed-scale focus including protection of the least impacted streams and adopting other land-based actions within the watershed where possible.

Sundermann, A., et al. (2011). "River restoration success depends on the species pool of the immediate surroundings." Ecological Applications **21**(6):1962–1971.

> Previous studies evaluating the success of river restorations have rarely found any consistent effects on benthic invertebrate assemblages. In this study, we analyzed data from 24 river restoration projects in Germany dating back 1 to 12 years and 1231 data sets from adjacent river reaches that lie within 0-5, 5-10, and 10–15 km rings centered on the restored sites. We calculated restoration success and recolonization potential of adjacent river reaches based on stream-type-specific subsets of taxa indicative for good or bad habitat quality. On average, the restorations did not improve the benthic invertebrate community quality. However, we show that restoration success depends on the presence of source populations of desired taxa in the surrounding of restored sites. Only where source populations of additional desired taxa existed within a 0-5 km ring around the restored sites were benthic invertebrate assemblages improved by the restoration. Beyond the 5-km rings, this recolonization effect was no longer detected. We present here the first field results to support the debated argument that a lack of source populations in the areas surrounding restored sites may play an important role in the failure to establish desired invertebrate communities by the means of river restorations. In contrast, long-range dispersal of invertebrates seems to play a subordinate role in the recolonization of restored sites. However, because the surroundings of the restored sites were far from good ecological quality, the potential for improvement of restored sites was limited.

Suren, A.M. and S. McMurtrie (2005). "Assessing the effectiveness of enhancement activities in urban streams: II. Responses of invertebrate communities." River Research and Applications **21**(4):439–453.

The effects of habitat enhancement on the invertebrate communities in five urban streams in Christchurch, Nev, Zealand, were investigated. All streams underwent riparian planting, while extensive channel modifications were made at two streams, where a concrete dish channel and a wooden timber-lined stream were removed and natural banks reinstated. **Benthic invertebrates were collected before enhancement and 5 years after from the same locations.** Invertebrates were also collected from control sites in each stream in 2001. Desired goals of enhancement activities included increasing the densities of mayflies and caddisflies, and decreasing densities of oligochaetes, snails and midges. Enhancement activities changed riparian vegetation and bank conditions, as well as substrate composition, instream organic matter and variability of instream velocities. Invertebrate communities prior to enhancement were typical of those in urban environments, and dominated by snails (Potamopyrgus, Physa), the amphipod Paracalliope, the hydroptilid caddisfly Oxyethira, oligochaetes and chironomids. **Stream enhancement caused only small changes to the invertebrate community, with subtle shifts in overall abundance, species evenness, diversity, and ordination scores. Lack of a consistent strong response by invertebrates to enhancement activities, and continued absence of caddisflies and mayflies from enhanced sites may reflect lack of sufficient change to instream conditions as a result of stream enhancement, colonization bottlenecks for aerial stages of these animals, and the inability of individuals outside the urban watershed to perceive these enhanced 'islands' of good habitat.** Alternatively, contamination of streambed sediments, excess sedimentation and reduced base flows may be limiting factors precluding successful invertebrate colonization in enhanced sited. These results highlight the importance of setting clear goals and objectives necessary to meet these goals. Enhancement of riparian zones in urban streams may not be adequate to improve benthic invertebrate communities. Identifying over-arching factors that potentially limit invertebrate communities will enable the enhancement potential of streams to be better assessed, and allow managers to identify sites where recovery of biological communities is possible, and where such recovery is not.

Talebi, L., et al. (2014). Evaluation of Retrofitted Green Infrastructure Stormwater Controls in Urban Areas Served by Combined and Separate Sewer Systems in Cincinnati, OH. World Environmental and Water Resources Congress 2014: Water without Borders**:** 95–104.

Thompson, D.M. (2002). "Long-term effect of instream habitat-improvement structures on channel morphology along the Blackledge and Salmon rivers, Connecticut, USA." Environmental Management **29**(2):250–265.

Habitat-improvement structures on the Black-ledge and Salmon rivers date back to the 1930s and 1950s, Forty of these structures were investigated to determine their long-

term impact on channel morphology. These structures include designs that continue to be used in modern restoration efforts. During the intervening period since these structures were introduced, several major floods have affected the two channels. The floods include three flows in excess of the 50-year event, including the flood of record, which has an estimated recurrence interval of almost 300 years. Despite the extreme flooding, many structures were discovered in varying conditions of operation. Grade-control structures and low-flow deflectors generally create some low-flow habitat ($P = 0.815$) but do not produce the depth of water predicted by design manuals ($P < 0.0001$). **Unintended erosion has developed in response to many of the channel modifications especially along the outside of meanders. In addition, the mode of failure of grade-control structures has created localized channel widening with associated bank erosion.** Meanwhile, cover structures have produced a 30% reduction in streamside vegetation with over 75% less overhead cover than unaltered reaches. **Based on these results, it is important for prospective designers to carefully consider the long-term impacts of instream structures when developing future channel-restoration projects.**

Thompson, R. and S. Parkinson (2011). "Assessing the local effects of riparian restoration on urban streams." New Zealand Journal of Marine and Freshwater Research **45**(4):625–636.

Riparian zones mediate chemical and biological exchanges between streams and the terrestrial environment. In urban systems, these zones are often heavily modified by removal of native vegetation and bank disruption. Management agencies have made considerable investments into restoring riparian vegetation through replanting. We investigated the potential for riparian plantings to restore invertebrate communities, by comparing open and forested (replanted) reaches over winter within three urban streams in Melbourne, Australia. Clear differences in aquatic habitats, food resources and fauna were evident between reaches. Algal biomass on artificial substrates did not differ significantly between reaches. Open reaches had higher abundances of taxa reliant on autochthonous production as the primary food resources (e. g. gastropods, chironomids and oligochaetes), while forested reaches displayed a higher diversity of invertebrate taxa associated with allochthonous resources. We conclude that riparian plantings may have some positive effects on streams, even without broader catchment improvements in water quality and hydrology.

Violin, C.R., et al. (2011). "Effects of urbanization and urban stream restoration on the physical and biological structure of stream ecosystems." Ecological Applications **21**(6):1932–1949.

Streams, as low-lying points in the landscape, are strongly influenced by the stormwaters, pollutants, and warming that characterize catchment urbanization. River restoration projects are an increasingly popular method for mitigating urban insults. Despite the growing frequency and high expense of urban stream restoration projects, very few projects have been evaluated to determine whether they can successfully enhance habitat structure or support the stream biota characteristic of reference sites. We compared the physical and biological structure of four urban degraded, four urban restored, and four forested streams in the Piedmont region of North Carolina to quantify the ability of reach-scale stream restoration to restore physical and biological structure to urban streams and to examine the assumption that providing habitat is sufficient for biological recovery. To be successful at mitigating urban impacts, the habitat structure and biological communities found in restored streams should be more similar to forested reference sites than to their urban degraded counterparts. For every measured reach-and patch-scale attribute, we found that restored streams were indistinguishable from their degraded urban stream counterparts. Forested streams were shallower, had greater habitat complexity and median sediment size, and contained less-tolerant communities with higher sensitive taxa richness than streams in either urban category. Because heavy machinery is used to regrade and reconfigure restored channels, restored streams had less canopy cover than either forested or urban streams. Channel habitat complexity and watershed impervious surface cover (ISC) were the best predictors of sensitive taxa richness and biotic index at the reach and catchment scale, respectively. Macroinvertebrate communities in restored channels were compositionally similar to the communities in urban degraded channels, and both were dissimilar to communities in forested streams. The macroinvertebrate communities of both restored and urban degraded streams were correlated with environmental variables characteristic of degraded urban systems. Our study suggests that reach-scale restoration is not successfully mitigating for the factors causing physical and biological degradation.

Walsh, C.J., et al. (2005). "Stream restoration in urban catchments through redesigning stormwater systems: looking to the catchment to save the stream." Journal of the North American Benthological Society **24**(3):690–705.

Restoration of streams degraded by urbanization has usually been attempted by enhancement of instream habitat or riparian zones. Such restoration approaches are unlikely to substantially improve instrearn ecological condition because they do not match the scale of the degrading process. Recent studies of urban impacts on streams in Melbourne, Australia, on water chemistry, algal biomass and assemblage composition of diatoms and invertebrates, suggested that the primary degrading process to streams in many urban areas is effective imperviousness (EI), the proportion of a catchment covered by impervious surfaces directly connected to the stream by stormwater drainage pipes. The direct connection of impervious surfaces to streams means that even small rainfall events can produce sufficient surface runoff to cause frequent disturbance through regular delivery of water and pollutants; where impervious surfaces are not directly connected to streams, small rainfall events are intercepted and infiltrated. We, therefore, identified use of alternative drainage methods, which maintain a near-natural frequency of surface runoff from the catchment, as the best approach to stream restoration in urban catchments and then used models of relationships between 14 ecological indicators and EI to determine restoration objectives. Ecological condition, as indicated by concentrations of water-quality variables, algal biomass, and several measures of diatom and macroinvertebrate assemblage composition, declined with increasing EI until a threshold was reached (EI = 0.01-0.14), beyond which no further degradation was observed. We showed, in a sample catchment, that it is possible to redesign the drainage system to reduce EI to a level at which the models predict detectable improvement in most ecological indicators. Distributed, low-impact design measures are required that intercept rainfall from small events and then facilitate its infiltration, evaporation, transpiration, or storage for later in-house use.

Walters, D.M., et al. (2009). "Environmental indicators of macroinvertebrate and fish assemblage integrity in urbanizing watersheds." Ecological Indicators **9**(6): 1222–1233.

Urbanization compromises the biotic integrity and health of streams, and indicators of integrity loss are needed to improve assessment programs and identify mechanisms of urban effects. We investigated linkages between landscapes and assemblages in 31 wadeable Piedmont streams in the Etowah River basin in northern Georgia (USA). Our objectives were to identify the indicators of macroinvertebrate and fish integrity from a large set of best land cover (n = 45), geomorphology (n = 115), and water quality (it = 12) variables, and to evaluate the potential for variables measured with minimal cost and effort to effectively predict biotic integrity. Macroinvertebrate descriptors were better predicted by land cover whereas fish descriptors were better predicted by geomorphology. Water quality variables demonstrated moderate levels of predictive power for biotic descriptors. Macroinvertebrate descriptors were best predicted by urban cover (-), conductivity (-), fines in riffles and local relief (+). Fish descriptors were best predicted by embeddedness (-), turbidity (-), slope and forest cover (+). We used multiple linear regression modeling to predict descriptors using three independent variable sets that varied in difficulty of data collection. "Full" models included a full range of geomorphic, water quality and landscape variables regardless of the intensity of data collection efforts. "Reduced" models included GIS-derived variables describing catchment morphometry and land use as well as variables easily collected in the field with minimal cost and effort. "Simple" models only included GIS-derived variables. Full models explained 63-81% of the variation among descriptors, indicating strong relationships between landscape properties and biotic assemblages across our sites. Reduced and simple models were weaker, explaining 48–79% and 42–79%, respectively, of the variance among descriptors. Considering the difference in predictive power among these model sets, we recommend a tiered approach to variable selection and model development depending upon management goals. GIS variables are simple and inexpensive to collect, and a GIS-based modeling approach would be appropriate for goals such as site screening (e.g., identification of reference streams). As management goals become more complex (e.g., long-term monitoring programs), additional, easily collected field variables (e.g., embeddedness) should be included. Finally, labor-intensive variables (e.g., nutrients and fines in sediments) could be added to meet complex management goals such as restoration of impaired streams or mechanistic studies of land use effects on stream ecosystems. Published by Elsevier Ltd.

Weber, C. and A. Peter (2011). "Success or Failure? Do Indicator Selection and Reference Setting Influence River Rehabilitation Outcome?" North American Journal of Fisheries Management **31**(3):535–547.

> Recovery indicators play a crucial role in the evaluation of river rehabilitation projects. Various types of biological indicators are used to address different ecosystem attributes (structure, composition, and function) at different levels of the biological hierarchy (population, guild, and community). Indicator values are evaluated against reference information from various sources, representing the conditions to be achieved (near-natural references) or to avoid (degraded references). We studied the extent to which investigators' conclusions on project outcome were influenced by the indicator and reference types used. We analyzed 40 selected studies dealing with the recovery of riverine fish assemblages after active rehabilitation of physical habitat and lateral connectivity. In 32 (80%) of the 40 studies, fish response was measured at the population level. Structural and compositional indicators dominated (31 and 24 studies, respectively), while functional indicators were underrepresented (5 studies). Eighteen studies used multiple indicator types for a given ecosystem attribute, a given hierarchical level, or both. Among these studies, we found only very limited evidence that project outcome differed among different indicator types (1 study). In contrast, highly heterogeneous results were found within the different indicator types at the level of the individual study (i.e., indicators addressing the same hierarchical level and ecosystem attribute resulted in different evaluations of project outcome). Such heterogeneity was related to the spatiotemporal variability of the results and species-specific responses to physical habitat rehabilitation. Most studies (73%; 29 studies) used a single type of reference, and the majority focused on degraded conditions. Among the 10 studies that applied multiple reference types, one-third (3 studies) showed inconsistent results (i.e., one reference comparison produced a positive assessment for a given indicator, whereas the second comparison indicated that the endpoint was not achieved). We discuss the implications of inconsistent project outcomes for future monitoring activities.

Whiteway, S.L., et al. (2010). "Do in-stream restoration structures enhance salmonid abundance? A meta-analysis." Canadian Journal of Fisheries and Aquatic Science **67**:831–841.

> Despite the widespread use of stream restoration structures to improve fish habitat, few quantitative studies have evaluated their effectiveness. This study uses a meta-analysis approach to test the effectiveness of five types of instream restoration structures (weirs, deflectors, cover structures, boulder placement, and large woody debris) on both salmonid abundance and physical habitat characteristics. Compilation of data from 211 stream restoration projects showed a significant increase in pool area, average depth, large woody debris, and percent cover, as well as a decrease in riffle area, following the installation of in-stream structures. There was also a significant increase in salmonid density (mean effect size of 0.51, or 167%) and biomass (mean effect size of 0.48, or 162%) following the installation of structures. Large differences were observed between species, with rainbow trout (*Oncorhynchus mykiss*) showing the largest increases in density and biomass. This compilation

highlights the potential of in-stream structures to create better habitat for and increase the abundance of salmonids, but the scarcity of long-term monitoring of the effectiveness of in-stream structures is problematic.

Woolsey, S., et al. (2007). "A strategy to assess river restoration success." Freshwater Biology **52**(4):752–769.

1. Elaborate restoration attempts are underway worldwide to return human-impacted rivers to more natural conditions. Assessing the outcome of river restoration projects is vital for adaptive management, evaluating project efficiency, optimising future programmes and gaining public acceptance. An important reason why assessment is often omitted is lack of appropriate guidelines.

2. Here we present guidelines for assessing river restoration success. They are based on a total of 49 indicators and 13 specific objectives elaborated for the restoration of low- to mid-order rivers in Switzerland. Most of these objectives relate to ecological attributes of rivers, but socio-economic aspects are also considered.

3. A strategy is proposed according to which a set of indicators is selected from the total of 49 indicators to ensure that indicators match restoration objectives and measures, and that the required effort for survey and analysis of indicators is appropriate to the project budget.

4. Indicator values are determined according to methods described in detailed method sheets. Restoration success is evaluated by comparing indicator values before and after restoration measures have been undertaken. To this end, values are first standardised on a dimensionless scale ranging from 0 to 1, then averaged across different indicators for a given project objective, and finally assigned to one of five overall success categories.

5. To illustrate the application of this scheme, a case study on the Thur River, Switzerland, is presented. Seven indicators were selected to meet a total of five project objectives. The project was successful in achieving 'provision of high recreational value', 'lateral connectivity' and 'vertical connectivity' but failed to meet the objectives 'morphological and hydraulic variability' and 'near natural abundance and diversity of fauna'. Results from this assessment allowed us to identify potential deficits and gaps in the restoration project. To gain information on the sensitivity of the assessment scheme would require a set of complementary indicators for each restoration objective.

Zalewski, M., et al. (1998). "The importance of the riparian ecotone and river hydraulics for sustainable basin-scale restoration scenarios." Aquatic Conservation: Marine and Freshwater Ecosystems **8**(2):287–307.

1. The effect of riparian ecotone functional complexity and stream hydraulics on an upland river ecosystem has been analysed.

2. The amount of nutrients retained by bottom sediment was lowest on a sandy substrate (range: 26-104 mg m(-2) P-PO4) and highest in wetland bays

(range: 558–5368 mg m(-2) P-PO4). A stream bed covered by Berula erecta had about three times higher retentive nutrient capacity ((x) over bar = 584 mg m -2 day(-1)) than did a sandy substrate (x) over bar = 205 mg m(-2) day(-1)).

3. The amount of allochthonous organic matter (CPOM) deposited on the stream bed decreased with current velocity. The trophic potential of CPOM, measured as total protein, was significantly correlated with the amount of deposited CPOM ($r = 0.863$; $p < 0.00001$) and depended on stream order.

4. Both invertebrate and fish biomass in the upland river were significantly correlated with calcium/bicarbonate (benthos: $r = 0.858$; $p < 0.006$; fish: $r = 0.918$; $p < 0.001$).

5. Fish biomass, diversity and species richness were highest in pools, lower in riffles and lowest in the run/transition zone.

6. Macroinvertebrate biomass was highest at an intermediate riparian ecotone complexity with an adequate supply of organic matter and incident light. Fish biomass followed the same trend, being lowest in heavily shaded areas and in open channels without riparian vegetation (range: 1-4.5 g m(-2)), but highest in ecotones of intermediate complexity (range: 1.6-92.8 g m(-2)). The 'cascading effect' of invertebrate density depletion, which was inversely related to fish biomass, was observed seasonally.

7. The above results indicate that riparian ecotone structure and the heterogeneity of the stream channel may regulate biodiversity, productivity and nutrient retention in the fluvial corridor. These quantitative data help to create alternative scenarios for sustainable river basin management. (C) 1998 John Wiley & Sons, Ltd.

APPENDIX B

Studies Categorized by Indicator Type

Table B-1. Literature Review Studies Categorized by Type(s) of Indicators Used.					
Study Reference	Hydrologic Indicators	Chemical Indicators	Physical Habitat Indicators	Biological Indicators	Miscellaneous
Ahiablame, 2013	✓	✓	✓		✓
Archer, 2002	✓	✓			
Bain, 2014	✓	✓	✓	✓	
Bedan, 2009	✓	✓	✓		
Beechie, 2008					✓
Boavida, 2012	✓	✓	✓	✓	
Booth 2005					✓
Booth, 2002					✓
Brasher, 2010	✓	✓			
Brederveld, 2011				✓	
Bryant, 1995	✓	✓	✓	✓	
Buchanan, 2012			✓	✓	
Bukaveckas, 2007	✓	✓	✓		
Burns, 2012					✓
Canobbio, 2013				✓	
Chang, 2014		✓	✓		
Clausen, 2007	✓	✓	✓		
Clements, 2010		✓	✓	✓	
Cockerill, 2014					✓
Cuffney, 2010	✓	✓	✓	✓	
DeGaspri, 2009	✓	✓	✓	✓	
Deletic, 2012	✓				✓
Dietz, 2008	✓	✓	✓		
Dietz, 2004		✓	✓		
Doll, 2014			✓	✓	
Fausch, 1995				✓	
Filoso, 2011		✓	✓		
Fletcher, 2014	✓	✓			
Fletcher, 2011					✓
Frissell, 1992			✓	✓	
Grimm, 2000			✓	✓	✓
Haase, 2013				✓	
Hammersmark, 2008	✓	✓			

Table B-1 (continued). Literature Review Studies Categorized by Type(s) of Indicators Used.

Study Reference	Hydrologic Indicators	Chemical Indicators	Physical Habitat Indicators	Biological Indicators	Miscellaneous
Heinrich, 2014				✓	
Henshaw, 2000			✓	✓	
Hilderbrand, 1997			✓	✓	
Hines, 2011		✓	✓		
Hood, 2007	✓	✓			
Jahnig, 2010				✓	
Jahnig, 2011					✓
Jansson, 2005					✓
Johnson, 2014		✓	✓		
Jordan, 2014				✓	
Kail, 2012		✓	✓		
Kaushal, 2012		✓	✓		
Kaushal, 2008		✓	✓		
Kemp, 2014				✓	
King County, 2014	✓	✓	✓	✓	
King, 2003		✓	✓		
King, 2008	✓	✓	✓	✓	
Klein, 2007	✓	✓	✓	✓	
Kondolf, 2011					✓
Kondolf, 1995					✓
Konrad, 2002	✓	✓			
Kristensen, 2011			✓	✓	
Kristensen, 2013			✓	✓	
Kurth, 2014	✓	✓	✓	✓	✓
Laasonen, 1998				✓	
Larson, 2001			✓	✓	
Lave, 2014					✓
Lawrence, 2013		✓	✓		
Lepori, 2005			✓	✓	
Levell, 2008			✓	✓	
Line, 2012	✓	✓	✓		
Lorenz, 2013				✓	
Lorenz, 2012				✓	

Table B-1 (continued). Literature Review Studies Categorized by Type(s) of Indicators Used.

Study Reference	Hydrologic Indicators	Chemical Indicators	Physical Habitat Indicators	Biological Indicators	Miscellaneous
Luderitz, 2011			✓	✓	
Matthews, 2010				✓	
Miller, 2010				✓	
Moerke, 2004a				✓	
Moerke, 2004b			✓	✓	
Montalto, 2007	✓				✓
Montgomery, 2003					✓
Moore, 2012	✓	✓	✓		✓
Morandi, 2014				✓	
Morley, 2002				✓	
Mueller, 2014				✓	
Murdock, 2004	✓			✓	
Nakano, 2006				✓	
Niezgoda, 2005					✓
Palmer, 2007					✓
Palmer, 2005					✓
Pander, 2013				✓	
Parasiewicz, 2013	✓				✓
Pess, 2014				✓	
Phillips, 2014		✓	✓		
Pitt, 2013	✓	✓	✓		✓
Pizzuto, 2000			✓	✓	
Potter, 1991	✓	✓			
Pretty, 2003		✓	✓	✓	
Purcell, 2009				✓	
Roberts, 2007		✓	✓		
Roni, 2002				✓	
Roper, 1998			✓	✓	
Roy, 2008		✓	✓	✓	
Roy, 2014	✓	✓	✓	✓	
Sansalone, 2013	✓				✓
Schiff, 2011				✓	
Schilling, 2002		✓	✓		

Table B-1 (continued). Literature Review Studies Categorized by Type(s) of Indicators Used.

Study Reference	Hydrologic Indicators	Chemical Indicators	Physical Habitat Indicators	Biological Indicators	Miscellaneous
Selbig, 2008	✓	✓	✓		
Selvakumar, 2010	✓	✓	✓	✓	
Shilla, 2011	✓	✓	✓		
Shuster, 2013	✓	✓			
Simenstad, 2006					✓
Sivirichi, 2011		✓	✓		
Smith, 2011				✓	
Smucker, 2014		✓	✓	✓	
Stewart, 2009				✓	
Stillwater Sciences, 2015	✓	✓	✓	✓	
Strange, 1999	✓	✓		✓	
Stranko, 2012				✓	
Sundermann, 2011				✓	
Suren, 2005				✓	
Talebi, 2014	✓	✓			
Thompson, 2002			✓	✓	
Thompson, 2011			✓	✓	
Violin, 2011			✓	✓	
Walsh, 2005		✓	✓	✓	
Walters, 2009	✓				✓
Weber, 2011				✓	
Whiteway, 2010				✓	
Woolsey, 2007		✓	✓	✓	
Zalewski, 1998				✓	

Study references in **Bold** are priority studies for the Redmond Paired Watershed Study.