The Big Picture – Evaluating Stormwater BMPs Through the Life Cycle Lens

B. Kirk[1], R. Roseen[2], and C. Etnier[3]
1. Rubenstein School of Environment and Natural Resources, University of Vermont; Burlington, VT
2. Dept. of Civil and Environmental Engineering, University of New Hampshire; Durham, NH
3. Stone Environmental Inc.; Montpelier, VT

ABSTRACT
In response to heightening stormwater standards, increasingly intensive stormwater management has been applied to increasingly smaller catchments and development activities. To achieve these higher standards a host of structural and non-structural stormwater best management practices (BMPs) are being developed, recommended, and applied prescriptively with little regard to their net environmental performance. Even where BMP treatment performance and design is defined by removal rates of criteria pollutants within a watershed context, the direct impacts of construction, the indirect impacts of embodied materials and energy, the fate of pollutants captured, and changes in performance over the life of the system, are typically ignored. This is likely due to a lack of information regarding such impacts. A life cycle assessment (LCA) methodology has previously been developed to systematically evaluate the long-term, indirect, and cumulative non-monetary impacts of human activities, by accounting for all of the materials and energy consumed and substances emitted to air, water, and soil, from the initial extraction of raw materials needed through the decommissioning and disposal of the system at the end of its life. As such, LCA may provide a truer quantification of the net or total environmental benefit of employing specific stormwater BMPs or general policies. In this paper LCA is used to compare four conventional and low-impact designs under evaluation at a BMP performance verification center in New England. The impacts of the life cycle inventories of design and construction (cradle to gate) are assessed using the US EPA TRACI model.

INTRODUCTION
Stormwater regulation and the standards of management and design practice have continued to evolve, with some lag, in accordance with achievements in the understanding of the cumulative effects of development and human activities on hydrology, erosion, and water pollution. Over the last three decades the goals of stormwater management, initially focused on flood control, have gradually broadened to include water quality, which continues to be defined by an increasingly larger number of criteria pollutants. As water resource pressures in US population centers increase nationwide, recharging local aquifers has become yet another objective. And as a result of the US EPA's National Pollution Discharge Elimination System (NPDES) phase I followed by phase II regulations, heightened stormwater standards have been applied to smaller and smaller catchments and development activities. To achieve these higher standards a host of structural and non-structural stormwater best management practices (BMPs) are being developed, recommended, and applied prescriptively with little regard for their net environmental performance.

Numerous research efforts have and continue to provide designers and decision-makers with information about the basic treatment performance and in some cases cost of implementing structural and non-structural BMPs. Following the adoption of NPDES Phase II, which heavily promotes the use of BMPs, several attempts were made to quantify the long-term and cumulative financial costs, through life-cycle costing (Heaney, Sample et al. 2002; Muthukrishnan, Madge et al. 2004). Life cycle costing of BMPs has also since been coupled with treatment performance as a next step in design optimization (Taylor 2003; Wossink and Hunt 2003; Lampe, Andrews et al. 2005). Yet, a question which remains largely unknown and untested is, what are the long-term, indirect, and cumulative non-monetary impacts of providing stormwater management, which when combined with traditional measures of stormwater management performance, may provide a truer quantification of the net or total environmental benefit of employing stormwater BMPs.

The environmental life cycle assessment (LCA) method has been used to answer, systematically, questions regarding the long-term, indirect, and cumulative non-monetary impacts of human actions. In the broadest sense, the life cycle is considered from “cradle to grave,” meaning the direct and indirect provisions of raw materials, manufacturing, and transportation; use, maintenance, and reuse; and finally decommissioning or disposal. The environmental impacts include materials and energy used and releases of substances to the air, water, and soil. In the evaluation of projects with direct environmental priorities such as water treatment, LCA may be used to prevent or reduce unanticipated “problem shifting” or the substitution of an environmental problem in one medium or location to another medium or location. For this reason LCA has the potential to provide an appropriate foundation for conducting a holistic assessment of stormwater treatment systems which considers “up-stream” as well as downstream impacts.

The University of New Hampshire’s Stormwater Center currently operates and monitors twelve structural stormwater BMPs in parallel. The direct comparability of the systems combined with Center’s detailed monitoring and construction records have presented an ideal opportunity for conducting a life cycle comparison of stormwater BMPs, prompting a partnership with the University of Vermont’s Redesigning the American Neighborhood (RAN) Program. The on-going product of this partnership is a comparative economic life cycle cost analysis and environmental life cycle assessment of the conventional, low-impact development, and pre-manufactured designs in operation at the Stormwater Center (SC). This paper reports and discusses some of the initial findings of the RAN/SC Life Cycle Study.

METHODS

The life cycle assessment concept encompasses several variant methods designed for a variety of decision-making situations and in its attempt to be holistic, the calculation procedure often becomes complex, greatly increasing the chance of wrong or misleading results (Baumann and Tillman 2004). In response to such issues, the International Standards Organization established a standardized LCA method beginning in 1996. The ISO 14040 series standards outline the major procedural steps of LCA most commonly followed for comparisons of process and product alternatives and documentation of industry-wide “eco-profiles.” The RAN/SC Life Cycle Study adheres to the ISO framework described in Table 1.

Table 1. Life Cycle Assessment Framework

ISO Life Cycle Assessment Framework	
1. Goal and Scope Definition	Establish objectives; methods; temporal, spatial, and technical system boundaries; functional unit and criteria (impact categories); map all relevant human and natural material and energy flows.
2. Life Cycle Inventory (LCI)	Catalogue all resources used and emissions for each process, product, or activity. Process flow and/or input/output modeling may be necessary to calculate material and energy flows.
3. Life Cycle Impact Assessment (LCIA)	Determine the environmental consequences. Classify the inventory into pre-defined impact categories and characterize the magnitude of each element's contribution to the impact categories. (Further aggregation, normalization, and valuation is optional)
4. Interpretation	Determine the dominance, sensitivity, and uncertainty of results. (Interpretation can be conducted with without LCIA)

GOAL AND SCOPE

The LCA procedure begins with the definition of the goal and scope, establishment of the functional unit (the unit used for comparisons, e.g., 100 m^2 of roof for an LCA of roofing materials), system boundaries, and the extent and method of calculation to achieve the information necessary for decision-making. The eventual goal of the RAN/SC Life Cycle Study is to compare the total environmental, human health, and economic impacts of all twelve treatment units (TUs) from construction, through operation, maintenance, and decommissioning. The goal of this paper is to provide an initial look at the first half of the study, for which four of the twelve TU's were selected for comparison (Table 2).

Table 2: Stormwater BMPs Compared

BMP General Descriptions					
Treatment Unit	*Unit Type*	*Design Source*	*Arial Dimensions*	*Volumes*	*Treatment Function*
ADS Water Quality and Infiltration Device	Manufactured Device	Advanced Drainage Systems (ADS)	A1: 1.5m x 6.1m A2: 6.1m x 12.2m	Treatment: 92m^3	A1: Physical A2: Physical - Chemical
Retention Pond (Wet Pond)	Conventional	New York State Stormwater Design Manual	14.0m x 21.3m (approx.)	Forebay: 23m^3 Perm. Pool: 92m^3	Physical - Settling
Bioretention	Low Impact Design	New York State Stormwater Design Manual	Filter Bed: 20.4m x 10.7m Top Width: 21.6m x 14.0m	Forebay: 23m^3 Filter: 92m^3	Physical - Chemical and Biological
Gravel Wetland	Low Impact Design	Custom	Filter Beds (2): 4.6m x 9.8m Top Width (2): 11.3m x 17.1m	Forebay: 23m^3 Wetland: 92m^3	Physical - Chemical and Biological

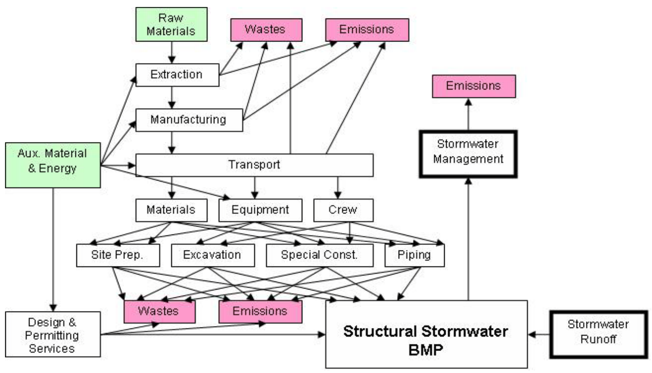
Chosen primarily on the basis of objective direct comparability, each system was designed to manage and treat runoff from 0.4 ha (1 acre) of parking lot and to meet equivalent performance criteria, including treatment of the water quality volume, detention of the channel protection volume, and attenuating the 0.9, 1, and 10-year storm to pre-development conditions. The similar design basis provides the foundation for the life cycle functional unit. For the results reported in this paper, the functional unit is the management and treatment of stormwater runoff from 0.4 ha (1 acre) of impervious surface for one year, with reference to the New York State stormwater design criteria, precipitation characteristics of Durham, NH, and the runoff pollutant characteristics of the University of New Hampshire's West Edge Parking Lot.

The life cycle impacts calculated from this functional unit are limited by boundaries set in both the inventory analysis and impact assessment phases. Temporally, the systems are assumed to be in operation for 30 years, over which the impacts of construction are annualized (without discounting). Spatially, all operations occurring within the Stormwater Center's watershed (e.g. construction and treatment) were modeled using site and process specific data whenever possible, and all operations occurring outside the watershed boundary (e.g. production of fuels and materials) have been modeled using U.S. national average data. For transportation of equipment, personnel, and materials to the site, the distances used are site-specific, but the emissions per unit distance are based on U.S. national averages. Likewise for construction equipment, the equipment hours, flywheel power, and loading factors are site-specific, but the emissions per (operating flywheel) kW-hour are based on U.S. national averages. The boundaries of the technical-economic system considered in this paper are defined as, "cradle to gate" plus the impacts of the stormwater treatment processes – including all activities related to construction, production of materials, transport of materials, and the effluent discharged from the stormwater TUs. Clearly missing from this analysis are all activities associated with the maintenance and repair over each TU's life cycle as well as decommissioning of the system at the end of its useful life. Other technical boundary assumptions include the exclusion of all physical components and activities that would be identical amongst the alternatives, most notably the influent and effluent piping. Lastly, the spatial boundaries for the impact assessment phase were established for the continental U.S., thus the characterization of the life cycle inventory into environmental and human health impacts is also based on U.S. national averages.

BMP LIFE CYCLE INVENTORY

The bulk of work for any life cycle assessment is the development of the life cycle inventory in which the quantities of material and energy resources and emissions flowing across the previously defined technical-economic system boundary are calculated. This is generally conceptualized in a material flow diagram (Figure 1) and quantified through material flow analysis (MFA). The MFA is typically conducted through a series of process and product calculations, often based on either monetary budgets or cost models.

Figure 1: Simplified Material Flow Diagram – "Cradle to Gate" with Treatment Performance



The foundation for the construction LCI of each TU was built from the original monetary construction budget and design documents adjusted for as-built changes. Each budget line item was translated into RS Means unit costs from which construction activity productivity data could be obtained (RSMeans 2005). The emissions and fuel consumption of construction equipment activities were calculated using the US EPA's 2005 release of the NONROAD emissions inventorying model and the loading factors and fuel consumption rates catalogued in the Caterpillar Performance Handbook (CAT 2004; USEPA 2005). Emissions and resource consumption of off-site activities such as material production and design services were calculated using Carnegie Mellon University's Environmental Input-Output Life Cycle Assessment Model (EIO-LCA) through a tiered-hybrid life cycle calculation procedure (Suh and Huppes 2005; GDI 2006). And emissions and fuel consumption factors for on-road transportation were obtained from the 2003 release of the US EPA's MOBILE 6.2 emissions inventorying model (USEPA 2003).

The treatment unit operation inventory was calculated independently of the construction inventory and was more empirically derived. The operational inventory was defined by the total annual discharge of ten pollutants monitored by the Center's staff. Each total annual discharge was estimated using the Simple method ($L = R*C*A$, where L represents the annual pollutant load) (CWP 2003). The pollution concentration, C, was based on the median annual event mean concentrations measured for each pollutant from each unit during twelve events from September 8th, 2004 to August 13th, 2005. The annual runoff, R, was calculated using the annual normal precipitation for Durham, NH; a factor of 0.9, representing the fraction of rainfall events generating runoff; and a runoff coefficient of 0.83 for 100% parking lot surface. The area, A, representing the functional unit, is given as 0.4 ha.

IMPACT ASSESSMENT

To characterize the inventory of each BMP, a predefined impact assessment method developed by the US EPA's National Risk Management Research Laboratory was used. The 2006 version of the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) classifies the impacts of 960 chemical emissions into nine impact categories. Each category does not represent an actual damage caused by the emission, but rather its potential to cause damages (Bare, Norris et al. 2003). The nine impact potentials include global warming, acidification, eutrophication, human health – cancer, human health – noncancer, human health – criteria air pollutants, ecotoxicity, smog formation, and ozone depletion. Eight of the nine impacts are expressed as equivalents of a particular chemical emission. For example, emissions causing global warming potential are calculated as kilograms of CO_2-equivalents. The magnitude of effect of each emission in the inventory on each impact potential is determined by a characterization factor relating to the impact category unit (e.g. kg CO_2-e). The characterized results are then normalized with respect to US conditions by dividing by the US national per capita contribution to each impact category (Lippiatt 2002). In an attempt to value and compare the cumulative impacts appropriately, the normalized impacts were weighted using qualitative valuations established by the US EPA's Science Advisory Board and quantified in accordance with the method applied by the Building for Environmental and Economic Sustainabilty (BEES) LCA tool (Lippiatt 2002). Additionally, the impacts of fossil fuel depletion have been characterized, normalized, and weighted according to BEES (Lippiatt 2002).

RESULTS

The 30 year cumulative impacts of the four BMPs as characterized by TRACI are listed in Table 4, and represent aggregations of the largest and most damaging flows of substances recorded into and out of the technical-economic system, i.e. to and from the environment.

Table 4: Characterized Structural Stormwater BMP Life Cycle Impacts

"Cradle to Gate" and Treatment Effluent Impacts Over 30 Year Life Cycle for a 0.4 ha (1 acre) Parking Lot									
Impact Categories	*Global Warming*	*Acid.*	*Eutroph.*	*Fossil Fuel Depletion*	*Human Health*	*HH-Criteria Air Pollutants*	*Ecotoxicity*	*Smog*	*Ozone Depletion*
Units	*kg CO2-e*	*H+ moles-e*	*kg N-e*	*MJ surplus energy*	*kg toluene-e*	*microDALYs*	*kg 2,4 D-e*	*kg NOx-e*	*kg CFC 11-e*
ADS	44900	9940	30.8	58500	1160	3.70	0.0775	203	0
Wetpond	9520	2930	292	12300	1480	1.54	306	67.0	0
Bioretention	27700	6450	71.5	37600	1330	2.97	0.0840	134	0
Gravel Wetland	27500	8100	27.9	30600	1420	4.23	0.0810	181	0

Figure 2: Normalized Impacts

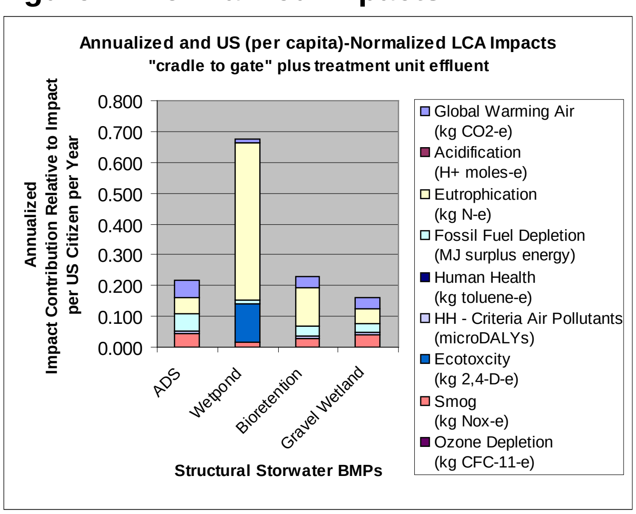
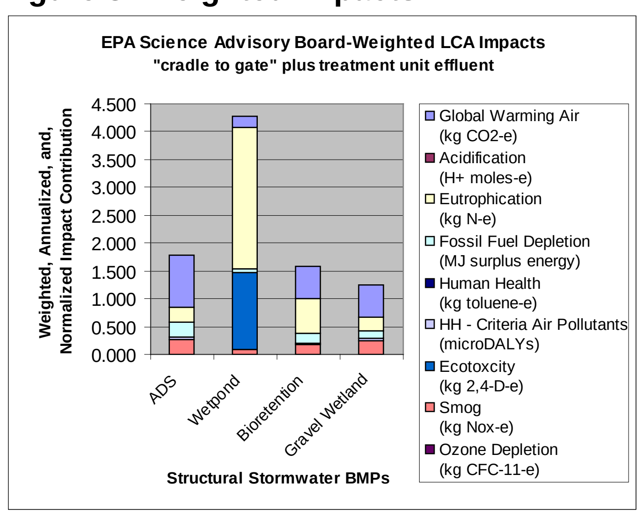
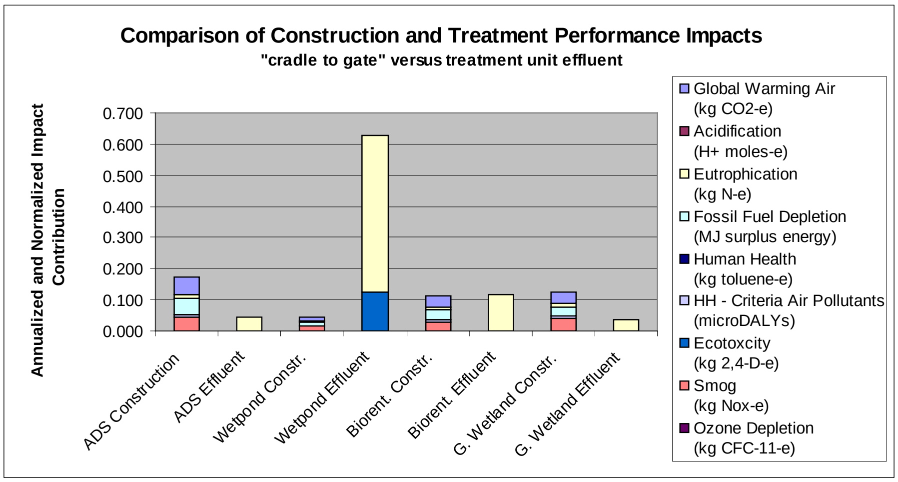


Figure 3: Weighted Impacts



The results in Figure 2 are annualized (total results divided by the 30 year life span) and normalized using US per capita normalization data to indicate the relative magnitude of each impact. The relative importance of each impact is then indicated in Figure 3, where the annualized and normalized results have been weighted according to values assigned by the US EPA Science Advisory Board. The cumulative values in Figure 3 also represent a total or net "score" for each BMP. However, because performance is so often defined by just the effluent performance it is helpful to separate the construction or "cradle to gate" impacts from the TU effluent impacts (Figure 4).

Figure 4: Construction vs. Treatment Performance Impacts



DISCUSSION

With nearly every calculation in LCA comes additional assumptions and subsequently increased subjectivity and error. For this reason it is useful to first review the raw impact assessment results (Table 4) prior to normalization and weighting to determine if any two or more alternatives in comparison have lower or higher emissions and resource consumption across all categories ranking them as unequivocally better or worse under those criteria. Unfortunately, there are no such clear distinctions and tradeoffs between impacts are unavoidable if a choice between alternatives is made. For such tradeoffs the normalization and weighting of impact categories can be helpful.

The normalized results indicate that the magnitude of annual eutrophication impact of the wetpond is nearly half of the eutrophication impacts per capita, while the cumulative impacts of the other alternatives are significantly less. As these results are weighted and the cumulative results are compared, the wetpond remains by far the poorest performer, but there is a slight shift in the ranking of the others. While the ADS unit appeared to perform slightly better than the bioretention unit in the normalization results, the high importance placed on global climate change by the Science Advisory Board, caused the weighted cumulative score to increase slightly above that of the bioretention unit. The higher global climate change score is due largely to the carbon dioxide emissions associated with plastic pipe manufacturing, upon which the ADS unit depends heavily. In both the normalized and weighted results the wetpond stands out as the having the highest net environmental impact, but although an apparent ranking among the net impacts of the other three alternatives is visible, their results are too close to determine an undoubtedly lowest net performer without further analysis of the uncertainty of results.

What may be more useful are the results in Figure 4 which disaggregate the normalized results into contributions of construction and effluent. Here it is revealed that wetpond actually has somewhat fewer "embodied" impacts resulting from construction than the other alternatives, and it is its poorer treatment performance which causes its relatively poor net performance. It is also interesting to note that, while the effluent impacts of the gravel wetland and the ADS unit are similar, there is a great degree of variation (nearly 1.4 times) in the construction impacts with respect to the cumulative effluent impacts, suggestive of the importance of determining and comparing the impacts of construction in addition to effluent quality.

The results above may be useful to decision makers interested in achieving broader water quality, environmental, or sustainability goals than those typically outlined in stormwater guidelines. These results may also be of interest to those responsible for environmental quality over a large regions, watersheds, or airsheds, particularly those which are heavily urbanized, consisting of a large percentage of impervious catchment areas or high population density. However, any decision maker considering the results of this study must recognize the limitations of the LCA method, the goal and scope defined within the study, the TRACI impact assessment characterization, and the weighting values used.
The most notable of these limitations include the exclusion of impacts associated with pollutants not measured, the exclusion of maintenance and decommissioning impacts, the lack of characterization factors for total suspended solids (TSS) and total petroleum hydrocarbons (TPH) emitted to water, and the subjectivity of impact valuation.

CONCLUSIONS

In comparison to the current and tradition measures of stormwater BMP performance, the life cycle assessment method, as applied in this paper, significantly broadens the purview of impacts considered spatially, temporally, and technically, providing new insight into the cumulative, direct, indirect, and long-term non-monetary impacts of structural stormwater BMPs. For designers, decision-makers, and agencies committed to achieving environmental quality and sustainability goals, these findings could result in a considerable broadening of the definition of performance used to evaluate BMPs for design, planning, and regulation. But before such determinations are made, the full BMP life cycle from “cradle to grave” should be evaluated; the impacts missing from the inventory (e.g. erosion during construction, water consumption, chemical species not measured, and retained pollutant fates) should be considered; the characterization of TSS and TPH should be added; and impact category weights for different classes of stormwater decision-maker values should be determined.

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