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Evaluation of Complete Environmental Impacts of Stormwater Best Management Practices with Life-cycle Assessment

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ABSTRACT

In this study, the environmental impacts of several types of best management practices (BMPs) for stormwater runoff control were estimated and analyzed with life-cycle assessment. Each structural stormwater BMP has different characteristics in terms of contaminant mitigation mechanism, contaminant removal effect, components, and design layout. This study evaluated four representative types of stormwater BMPs including dry swales, bioretention basins, wetland basins, and filter strips. In terms of each stormwater BMP type, environmental damage in the construction stage and environmental benefits in the operation stage were estimated. The considered environmental impact categories consisted of global warming, smog, acidification, eutrophication, respiratory effect, ecotoxicity, and fossil fuel depletion. Environmental impacts by construction inventories and activities were estimated with SimaPro 9.2.0 software. For assessment of environmental impacts by stormwater runoff control, the International Stormwater BMP Database (BMPDB) statistics of contaminant removal performance and the Traci method were used for analysis. Results showed that sand, gravel, mulch, cement, and transportation for the construction of stormwater treatment system are major factors resulting in the most significant environmental impacts for all stormwater BMP types. In most cases, the resulting environmental pollution was offset by pollutant removal, carbon storage, and sequestration effects that occurred during the operational life of the BMPs. However, pollution due to eutrophication was not reduced in the dry swale and bioretention basin. These results suggest that life cycle assessment is a useful design tool to implement eco-friendly stormwater runoff management and improve the performance through the design and operational life cycle of stormwater BMPs.

Keywords: stormwater BMP, life-cycle assessment, environmental impact, International stormwater BMPDB

1 INTRODUCTION

The Georgia Department of Transportation (GDOT) has constructed and operated a range of best management practices (BMPs) for stormwater management. The design of stormwater BMPs is optimized to manage both stormwater quantity and quality, and can lead to environmental benefits through treatment of stormwater runoff from roads and highways. Due to the diversity of BMP design, pollutant removal can vary as a function of treatment mechanism and arrangement. Field performance of stormwater BMPs has been widely studied, with particular focus on contaminants including total and suspended solids, nutrients, and dissolved metals (Bedan and Clausen 2009; Zarezadeh et al., 2018). While BMPs are effective at removal of pollutants from overland flow, the construction of stormwater BMPs, along with the associated soil disturbance, can have adverse environmental impacts due to material manufacture, transportation of construction materials, and operation of construction equipment. Consequently, understanding of the comprehensive environmental impacts of stormwater BMPs requires analysis of both the operation and construction phase to capture life cycle impacts.

While constructed BMPs produce positive environmental impact in terms of reduced contaminant transport during the operational lifetime, the construction of BMPs can contribute to air pollution, global warming, water pollution, smog, acidification, and eutrophication. Therefore, during stormwater BMP design and implementation, in-depth analysis in terms of the balance of environmental impacts is necessary, and can be performed using complete life-cycle assessment of stormwater BMPs.

Life-cycle assessment is typically used as a technique to evaluate environmental impacts caused by all products and processes over successive life cycle stages. Previous studies have applied life cycle assessment to study environmental aspects according to implementation of a selected stormwater BMP type (Kirk et al., 2006; Flynn and Traver 2011; Xu et al., 2017; Brudler et al., 2019). However, few studies have compared environmental impacts between different stormwater BMP types. In general, each stormwater treatment system has different properties that vary over the life cycle stages, such as construction inventories, different performance, such as contaminant removal efficiency. Therefore, it is important to assess each cradle-to-cradle environmental impact for optimal design and selection of a site specific stormwater treatment system. Notably, there exist a variety of models available for life cycle impact assessment (LCIA) that consider multiple impact categories (e.g., CML 2002, EPS 2000, Impact 2002+, IPCC, LIME, LUCAS, MEEuP, ReCiPe, Swiss Ecoscarcirty 07, and TRACI (ILCD Handbook 2010; Matthews et al., 2015). Note that the IPCC method is focused on climate change only.

The objective of this research was to estimate the environmental effects of several types of stormwater BMPs during the construction and operation phases and compare results as a function of BMP type. In this study, life-cycle assessments were conducted for four types of stormwater BMP including dry swales, bioretention basins, wetland basins, and filter strips using statistics of contaminant removal performance from the International Stormwater BMP Database.

2 METHODOLOGY

2.1 Scope

The primary functions of stormwater BMPs are reduction of contaminant concentration through sorption, infiltration, and/or biodegradation, and control of stormwater runoff volume; however, the design characteristics of BMPs are optimized for site specific characteristics. Due to significant differences in design, the cost of installation and long term maintenance can also vary signficiantly. Standardized pollutant removal efficiencies, construction costs, and maintenance burdens for seven BMP designs commonly used in the state of Georgia demonstrate a wide range in performance and costs (Table 1). For example, infiltration trenches can remove pollutants with high performance, but construction and long term maintenance costs are high compared to other stormwater BMP types. Therefore, for optimal performance of a stormwater BMP, the cost efficiency and environmental impacts need to be evaluated using life-cycle assessment (LCA).

Table 1. *Properties of Stormwater BMPs (GDOT, 2020)*

	Pollutant Removal Rates for Design Purpose				Costs	
BMP Type	**TSS**	**TP**	**TN**	**Metals**	**Construction Cost**	**Maintenance Burden**
Bioretention Basin*	85%	80%	60%	95%	Med-High	Med
Enhanced Dry Swale*	80%	50%	50%	40%	Med	Med
Enhanced Wet Swale	80%	25%	40%	20%	High	Low
Filter Strip	60%	20%	20%	40%	Low	Low
Infiltration Trench	100%	100%	100%	100%	High	High
Sand Filters	80%	50%	25%	50%	High	High
Wetland Basin	80%	50%	30%	50%	Low	Low

Notes: * indicates stormwater BMP with an open underdrain.

In this study, the life-cycle analysis of the selected stormwater BMPs focused on environmental impacts. Because each stormwater BMP is designed with different components and main objectives, BMPs are chosen for treatment using different physical, chemical, and biological processes, with varying removal mechanisms resulting in the differences in the environmental impact. Consequently, the four stormwater BMP types (dry swale, bioretention basin, wetland basin, and filter strip) were analysed with LCA to normalize the environmental impact across designs (Figure 1). While a full life cycle analysis includes the phases of construction, operation, maintenance, and decommissioning, in this study, only the construction and operational phases were considered (Figure 2). For analysis of the construction phase, material, equipment, and transportation were considered. In the operational phase, contaminant removal by treatment method (e.g., air pollutant removal, carbon storage, and carbon sequestration) were evaluated.

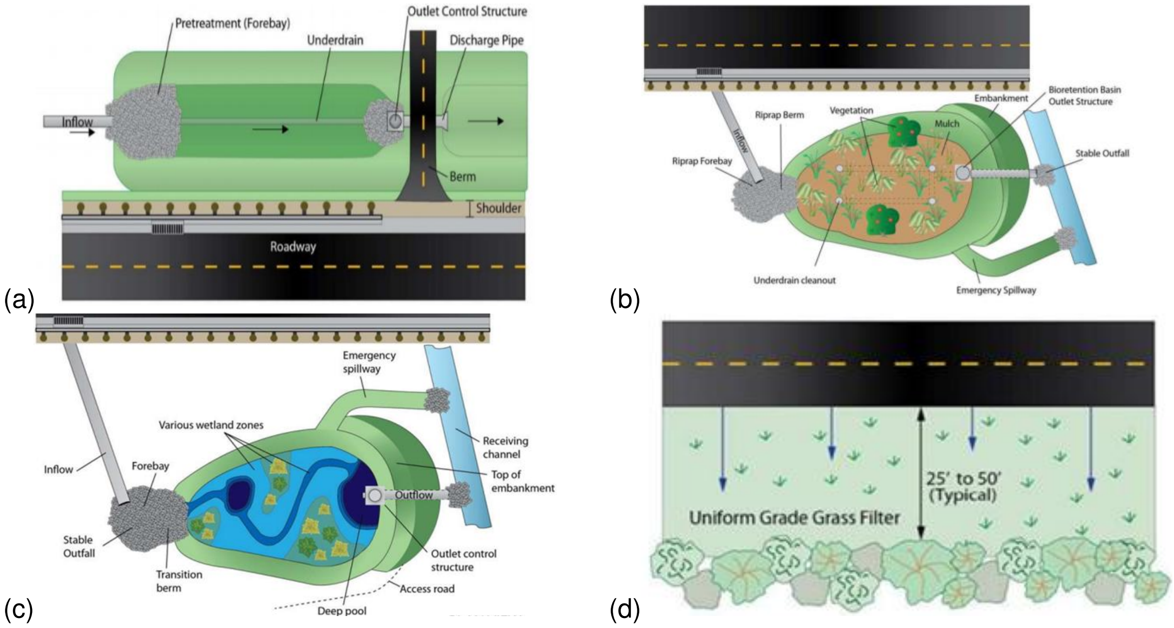

Figure 1. *Schematic drawings of stormwater BMPs: (a) dry swale; (b) bioretention basin; (c) wetland basin; (d) filter strip (GDOT, 2020).*

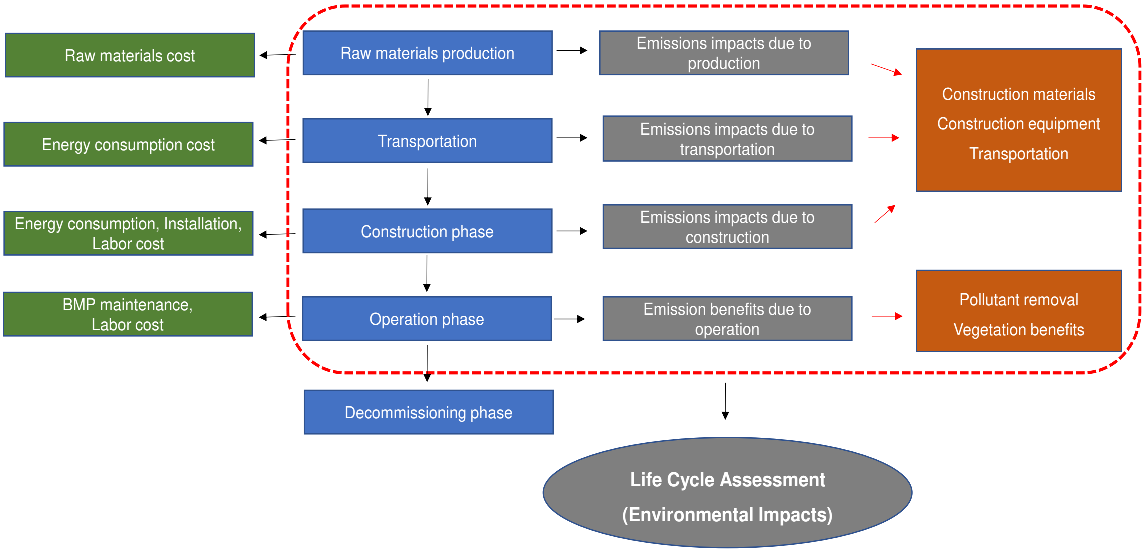

Figure 2. *System boundary diagram of stormwater BMP.*

2.2 International stormwater BMP database

Because contaminant removal efficiencies vary in the operational phase, the International Stormwater BMP Database was used to gather data on pollutant removal efficiencies (Clary et al., 2017) for the LCA study. Typical formats for the performance data include inflow concentration and outflow concentrations of total suspended solids, bacteria, metals, and nutrients from the BMP, with differences assumed to be the percent of contaminants removed and retained within the BMP. In this study, the tested database included the median concentrations of contaminants at influent and effluent (total suspended solids, metals: copper, lead, zinc, and nutrients: phosphorous and nitrogen) as a function of stormwater BMP type (Table 2).

Table 2. *Concentration of Contaminants at Influent and Effluent by International Stormwater BMP Database (Clary et al., 2017)*

Pollutants		Dry swale	Bioretention basin	Wetland basin	Filter strip
TSS [mg/L]	In	28.60	40.60	31.00	44.00
	Out	24.00	10.00	14.10	19.00
Cu [µg/L]	In	11.70	9.20	7.26	23.00
	Out	11.10	5.70	3.32	7.20
Pb [µg/L]	In	3.95	3.16	2.37	7.37
	Out	3.95	0.32	1.30	3.76
Zn [µg/L]	In	42.60	49.80	47.63	98.00
	Out	35.00	12.00	20.00	24.0
TP [mg/L]	In	0.12	0.13	0.16	0.14
	Out	0.20	0.24	0.12	0.17
TN [mg/L]	In	0.76	1.24	1.48	1.40
	Out	0.85	1.04	1.42	1.13

2.3 Stormwater runoff volume

For evaluation of pollutants removal impacts by stormwater treatment, stormwater runoff volume was estimated using average rainfall for a 30 year period (1981-2010) according to rainfall history of Atlanta, Georgia, USA by the National Weather Service (NWS). The drainage area and operational life for the life-cycle assessment were assumed as 0.4 hectares (1 acre) and 30 years in all stormwater BMPs, respectively. Given the drainage area and rainfall, the estimated stormwater runoff volume for the total operational period was 5.1x10^6 L (Table 3).

Table 3. *Characteristics of BMP System for Estimation of Stormwater Runoff Volume*

Average rainfall (NWS)	Drainage area	Operational life	Stormwater runoff volume
126 cm	0.4 hectares	30 years	5.11E+06 L

3 CASE STUDIES

3.1 Analysis of construction phase

For evaluation of environmental impact during BMP construction, construction inventories including material volume, equipment, and transportation (ton-km) were determined based on standardized BMP design (Table 4), assuming 0.4 hectares.

Table 4. *Material Inventories of Stormwater BMPs*

Material Inventory	Dry swale	Bioretention basin	Wetland basin	Filter strip
Mulch [kg]	366	1,956	9,273	756
Sand [kg]	138,074	84,588	42,294	23,677
Cement [kg]	1,231	82	1,363	558
Graded gravel [kg]	13,039	36,241	106,754	1,861
Stone [kg]	2,337	4608	-	-
Seedlings [each]	-	149	1,454	-
Non-woven fabrics [kg]	25	74	14	4
Excavated material [m^3]	137	106	120	23
Transportation [t·km]	6,949	5,515	6,606	1,189

Environmental impacts of the estimated construction inventories were evaluated with SimaPro 9.2.0 software. In this study, the TRACI method, which an environmental impact assessment tool with a US-focused model, was applied. The TRACI method considers environmental impact categories including climate change, acidification, eutrophication, smog, ecotoxicity, human toxicity, and resource consumption (Bare 2002; Bare et al., 2012; Flynn and Traver 2013; Matthews et al., 2015). Additionally, SimaPro's Ecoinvent Database and the United States Life Cycle Inventory (US LCI) Database were utilized for calculation of environmental impacts.

The computed environmental impacts by each stormwater BMP type included global warming potential, smog, acidification, eutrophication, respiratory effects, ecotoxicity, and fossil fuel depletion (Table 5 and Figure 3). The results indicate that the filter strip BMP led to the least environmental impact in all impact categories due to the smallest construction material inventory when compared to other types of stormwater BMPs. In contrast, the wetland basin showed the highest environmental impact in all categories. Comparing the material inventories of the dry swale and bioretention basin with the wetland basin, the volume of mulch and gravel were high in the wetland basin but the sand volume was relatively low; however, because sand and gravel typically cause similar environmental impacts per unit mass, the implication is that mulch contributed to the difference in environmental impact of the wetland basin. In addition, comparing the dry swale with the bioretention basin, dry swale caused somewhat larger environmental damage in all impact categories except ecotoxicity and fossil fuel depletion, which is attributable to a larger volume of cement used in the construction.

Table 5. *Environmental Impacts by Construction of Stormwater BMP*

Impact category	Dry swale	Bioretention basin	Wetland basin	Filter strip
Global warming potential [kg CO_2 eq]	3.2E+03	2.4E+03	8.5E+03	1.4E+03
Smog [kg O_3 eq]	3.4E+02	2.9E+02	8.3E+02	1.3E+02
Acidification [kg SO_2 eq]	1.9E+01	1.8E+01	6.5E+01	9.1E+00
Eutrophication [kg N eq]	2.5E+00	2.4E+00	3.8E+00	5.9E-01
Respiratory effect [kg $PM_{2.5}$ eq]	1.8E+00	1.6E+00	3.9E+00	6.0E-01
Ecotoxicity [CTUe]	1.4E+04	1.4E+04	2.4E+04	3.2E+03
Fossil fuel depletion [MJ surplus]	3.0E+03	5.0E+03	1.4E+04	1.4E+03

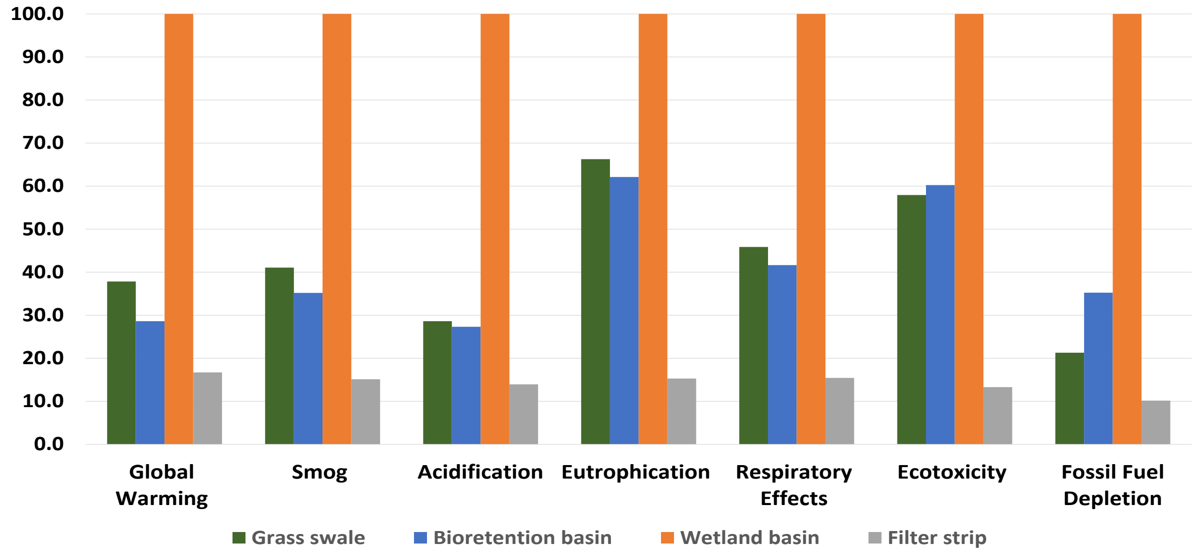

Figure 3. *Relative environmental impact in terms of stormwater BMP type.*

Comparison of the contribution of construction materials to each environmental impact was analysed as a function of BMP type (scaled to 100% for comparison) (Figure 4). Sand, gravel, cement, mulch, and transportation were primary factors that contributed to environmental impacts, with sand and gravel used in construction contributing to eutrophication, respiratory effect, and ecotoxicity. In contrast, cement and mulch caused significant impact in global warming, smog, and acidification. In particular, the influence of cement was large in the dry swale and filter strip due to concrete used in their drainage structures. However, the contribution of cement was not relatively big that when compared to the wetland basin due to the substantial quantities of mulch (energy and transportation intensive with fossil fuel depletion) when compared to other stormwater BMP types. The stormwater treatment benefit in terms of eutrophication impact can be improved by increasing phosphorus removal efficiency thorough filters amended with sorptive agents (Zhang et al., 2008; Kandel et al., 2017; Ulrich et al., 2017; Erickson et al., 2012). In addition, alternative materials can be considered in design; for example, copper slag and quarry dust can be used as replacement of sand for concrete (Al Jabri et al., 2009; Lohani et al., 2012). Cement use can be reduced with fly ash, silica fume, or ash from timber (Elinwa and Mahmood, 2002).

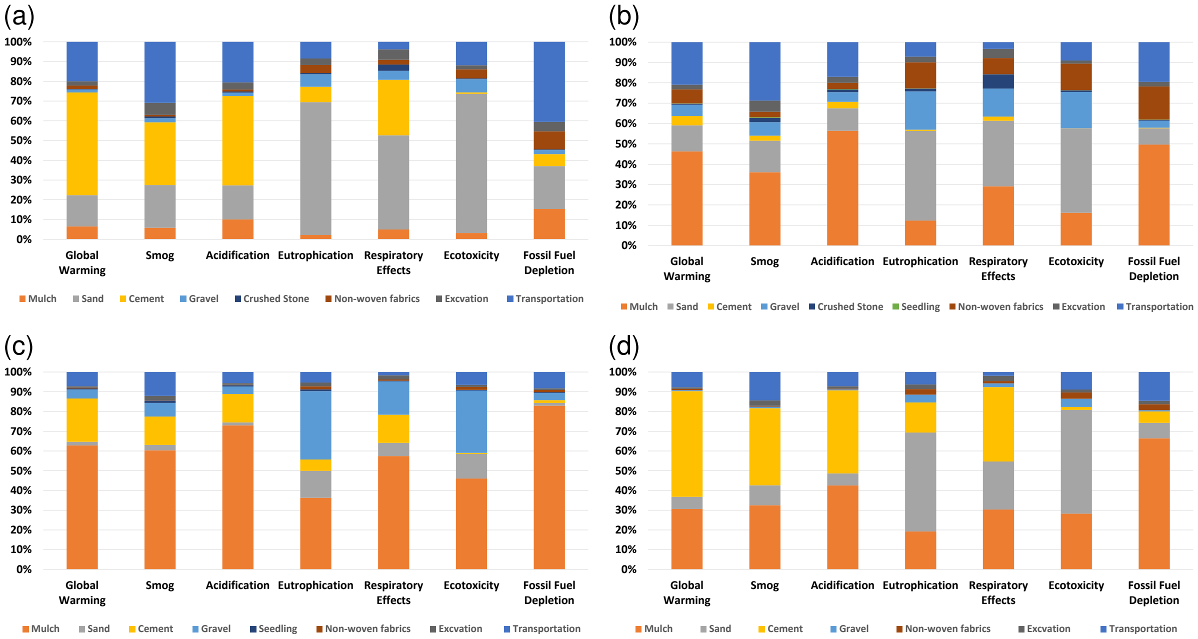

__Figure 4.__ Contribution of material to each environmental impact categories: (a) dry swale; (b) bioretention basin; (c) wetland basin; (d) filter strip

3.2 Analysis of operation phase: Stormwater BMP management benefit

The environmental benefit of operation of the stormwater BMPs occurs through removal and retention of contaminants in the BMP, and the removal percentages were estimated using the data from the International Stormwater BMP Database assuming 30 year lifespan for removal (Table 6). Overall, the filter strip showed high removal of most pollutants, while the dry swale showed the lowest performance for reducing contaminant concentrations. In terms of suspended solids, the bioretention basin demonstrated good performance due to its effective treatment mechanisms for sediment removal (e.g., filtration and sedimentation). In some cases, the results showed negative values, which indicated increases of pollutant concentration at the outlet compared to the inlet (i.e., the BMP increased pollutant outflow concentration), which has been documented for phosphorous in dry swales, bioretention basins, and filter strips (Clary et al., 2017). Contrary to these stormwater BMP types, the wetland basin showed substantial reduction of total phosphorous for its operational life.

***Table 6.** Pollutant Removal by Stormwater BMP Management for Operational Life*

Pollutants	Dry swale	Bioretention basin	Wetland basin	Filter strip
TSS [kg]	705	4691	2591	3832
Cu [kg]	0.09	0.54	0.60	2.42

Pb [kg]	0.00	0.44	0.16	0.55
Zn [kg]	1.17	5.79	4.24	11.34
TP [kg]	-12.26	-16.86	6.13	-4.60
TN [kg]	-13.80	30.66	9.20	41.39

Evaluation of the environmental impacts resulting from the estimated pollutant reduction were evaluated using the TRACI model (Table 7), and demonstrated that removal of heavy metals had a positive impact on ecotoxicity as would be expected (positive outcome for all four BMPs); however, the export of nutrients from a dry swale and a bioretention basin negatively impacted eutrophication. The net results for contaminant removal in a filter strip (decreasing for all contaminants except phosphorous) showed positive performance environmental benefits for both eutrophication and ecotoxicity.

Table 7. *Environmental Benefits by Stormwater BMP Management per 0.4 Hectares of Stormwater BMP for Operational Life*

Impact category	Dry swale	Bioretention basin	Wetland basin	Filter strip
Eutrophication [kg N eq]	-1.03E+02	-9.27E+01	5.38E+01	7.30E+00
Ecotoxicity [CTUe]	5.00E+04	2.53E+05	1.97E+05	5.72E+05

3.3 Analysis of operation phase: Vegetation benefit

During the operational phase, vegetation within the stormwater BMP will result in environmental benefits through carbon storage, carbon sequestration, and air pollutant removal, with pollutants of concern including ozone (O_3), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and particulate matter less than 2.5 microns ($PM_{2.5}$) (Table 8) (Nowak et al., 2006; Nowak et al., 2014). In order to estimate the vegetation benefits of the BMPs, the initial vegetated cover area per 0.4 hectare of drainage area was assumed to be 0.15 hectare in all cases according to Nowak (2010) (ratio of tree cover of Atlanta = 36.7%). Based on the data of the contiguous US, each pollutant removal amount attributable to vegetation were estimated, and the environmental impacts including smog, acidification, eutrophication, and respiratory effect were calculated with TRACI model (Table 9). Reduction of nitrogen dioxide had an influence on all impact categories, whereas reduced sulfur dioxide improved the acidification and respiratory effect. Removal of ozone and particulate matter less than 2.5 microns improved smog and respiratory effects, respectively. Benefits of the utilization of carbon by vegetation were estimated based on data analysed by Urban Forest Effects (UFORE) model (Nowak, 2010). The values of atmospheric carbon reduction per acre of vegetation were 15.9 tons and 0.55 tons per year, respectively. When integrated over the operational life of the BMP, 11,891 kg of total carbon would be reduced by this effect. Finally, global warming potential was estimated using EPA's Greenhouse Gas Equivalencies Calculator (Table 9), and the avoided global warming potential was equivalent to CO_2 emission by 1,338 gallons of gasoline consumption.

Table 8. *Average Air Pollutant Removal per Square Meter of Tree Cover (Nowak et al., 2014)*

Pollutants	Contiguous US	Urban areas	Rural areas
NO_2 [g/m^2]	0.55	0.70	0.55
O_3 [g/m^2]	5.49	5.40	5.49
$PM_{2.5}$ [g/m^2]	0.27	0.28	0.27
SO_2 [g/m^2]	0.35	0.34	0.35
Total	6.66	6.73	6.66

Table 9. *Total Vegetation Benefits per 1 Acre of Stormwater BMP for Operational Life*

Global warming potential [kg CO_2 eq]	Smog [kg O_3 eq]	Acidification [kg SO_2 eq]	Eutrophication [kg N eq]	Respiratory effect [kg $PM_{2.5}$ eq]
4.36E+04	8.53E+02	3.28E+01	8.22E+00	1.32E+01

3.4 Complete life-cycle environmental impact

Combining the environmental impacts resulting from the construction and operation phases of the BMPs over their design life resulted in negative value (environmental damage) during construction phase and positive values (environmental benefits) during the 30 year operational life due to stormwater treatment and vegetation impacts (Figure 5). Overall, the results demonstrated that all stormwater BMPs resulted in environmental benefits during their operational life in global warming potential, respiratory effects, and ecotoxicity. Implementation of stormwater BMPs also showed treatment improvements in the impact categories of smog and acidification. However, in the case of a wetland basin, the environmental damage caused by construction did not offset in terms of acidification during its operational life, and barely offset in the case of smog impact, which means that wetland basins need more time to reach the break-even point resulting in environmental benefit. In the case of dry swales and bioretention basins, deterioration of eutrophication impact was accelerated as operation activities resulted in nutrient export. In contrast, the wetland basins and filter strips showed positive operational impacts that offset issues caused during construction. One of the main causes of eutrophication in dry swales and bioretention basins is the export of phosphorous and nitrogen due to soil media with high nutrient content (Chahal et al., 2016; Clary et al., 2017; Hurley et al., 2017). Additionally, dissolved nitrate, nitrite, and phosphorous are not effectively removed by filtration process (Lin et al, 2009; Osman et al., 2019). Some proceses, such as nitrification, ammonification, and plant decomposition, can lead to accumulation and export of nutrients (Cho et al., 2009; Clary et al., 2017).

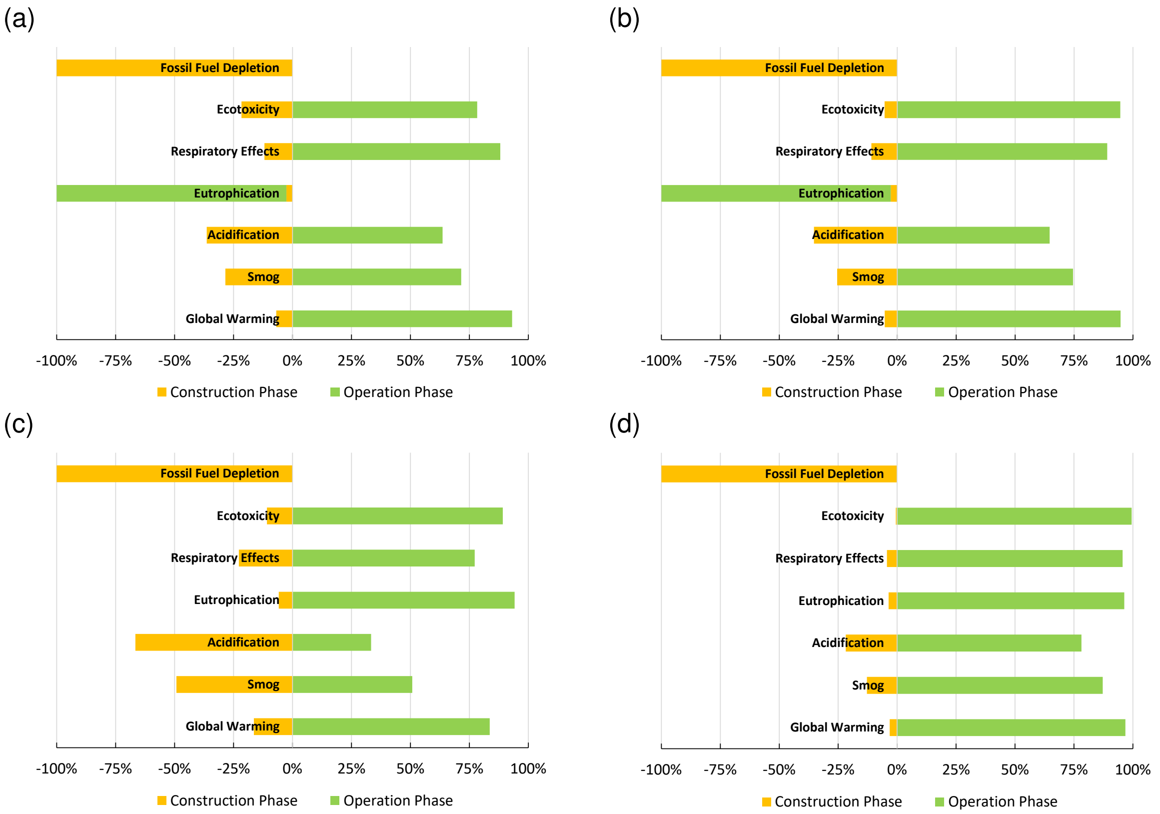

__Figure 5.__ Comprehensive Life-cycle Environmental Impacts of Stormwater BMP: (a) dry swale; (b) bioretention basin; (c) wetland basin; (d) filter strip.

4 SUMMARY AND CONCLUSION

The environmental impacts of four types of stormwater BMPs (dry swale, bioretention basin, wetland basin, and filter strip) were evaluated during their construction and lifetime operational phases. Data for the influent and effluent concentrations for the BMP types were gathered from the International Stormwater Database, environmental impacts from construction inventories/activities were estimated with SimaPro 9.2.0, and the TRACI method was used to determine environmental impact categories including climate change, acidification, eutrophication, smog, ecotoxicity, and respiratory effects. Based on the computed data, the following conclusions can be drawn:

1. During the construction phase, construction inventories caused several environmental damage for all four BMP types. The filter strip showed the least environmental impact due to the smallest amount of construction inventory. In contrast, wetland basins showed the highest environmental damage in all impact categories.

2. Construction inventories such as sand, gravel, mulch, cement, and transportation are the main contributors to environmental damages. Generally, sand and gravel caused significant impact on eutrophication, respiratory effect, and ecotoxicity. The negative contributions of mulch and cement were dominant in terms of global warming, smog, and acidification impact, and mulch and transportation resulted in significiant fossil fuel depletion; however, the primary factor in each stormwater BMP was slightly different according to the amount and relative proportion of each inventory.

3. In the case of mulch and cement, the environmental impact was large even though relatively small quantities were used when compared to sand and gravel. In addition, even small increases in material volume can cause substantial environmental impact. For example, the large volume of mulch required in the wetland basin caused significant impact on all categories, making consideration of alternative and materials important during the planning and design process.

3. In the operational phase, all stormwater BMPs resulted in environmental benefits through pollutant removal, carbon storage, and sequestration. Filter strips showed the highest environmental benefits by stormwater treatment, with the exception of eutrophication. Additional vegetation of stormwater BMPs (where possible) resulted in environmental benefits to global warming potential, smog, acidification, eutrophication, and respiratory effects.

4. Comprehensive life-cycle assessment showed that environmental damage was completely resolved within operational life of a filter strip, dry swale, and bioretention basin. However, the wetland basin needed more time than the 30 year operational life to offset environmental impacts from acidification. In the case of smog impact, the wetland basin could offset construction damage in just under the 30 years of operational life (projected break-even year: 29.1 years).

5. Comprehensive life-cycle environmental impacts of dry swales and bioretention basins implies that they can result in adverse impact due to export of nutrients and eutrophication, which must be considered during design.

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