J. of Ecotechnology, 2005 (1) : pp.1-8

Water management for eco-friendly urban and highway construction

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Abstract

The paper briefly reviews the urbanization, including highway construction, impact on the hydrology and aquatic ecosystem. The emphasis is to discuss recent advances in various engineering measures, i.e., best management practices or BMPs, which would help mitigate the negative impacts and help restore the aquatic biological integrity. These BMPs include vegetative practices such as bioretention cells, grassed swales, and constructed wetlands, with emphasis on the low impact development (LID) practices, which are gaining nationwide adaptation in recent years. Such BMPs can be integrated into the landscape and therefore also offer aesthetic benefits. The paper also discusses a number of issues that needed to be addressed before a full watershed implementation of BMPs in Taiwan.

Keywords: urbanization impacts, stormwater management, low impact development, best management practices, bioretention cells, swales, constructed wetlands, implementation strategies.

Introduction

It has long been recognized that urbanization, including highway construction, can cause a significantly negative, sometimes even irreversible, impact on the ecosystem. For example, a poorly planned urban development could contribute to the loss of habitat, which represents a severe threat to the impacted region's biodiversity. Specifically, studies have shown that the degradation of physical and chemical qualities of water, attributed to urbanization, directly affects fish population in rivers, streams and other water bodies. Numerous studies have also shown that urbanization plays a significant role in the degradation of water quality. It is, therefore, imperative to minimize the impact of urban development including road construction on water quality in order to protect the integrity of the ecosystem.

The Clean Water Act (CWA) is the cornerstone of surface water quality protection in the United States. The primary goal of the CWA is "to restore and maintain the chemical, physical, and biological integrity of the nation's waters." In 1987, the US Congress amended the CWA to initiate a national effort on nonpoint source pollution (NPS) control. Under Section 319, states address the NPS problem by identifying and quantifying the extent of NPS pollution, and developing and implementing management strategies for its control. Most recently, the US Environmental Protection Agency (USEPA) has instituted the Total Maximum Daily Load (TMDL) program, which calls for the integrated control of both point and nonpoint sources of pollution in a watershed. Currently, the TMDL program is the main driving force behind the water quality management activities in watersheds throughout the United States.

Watershed management measures commonly include structural and nonstructural best management practices (BMPs). Structural BMPs are engineered facilities that detain, filter or retain pollutant-carrying stormwater runoff, such as bioretention cells, detention ponds, constructed wetlands, grassed swales and strips or buffers, and underground treatment tanks. Nonstructural BMPs are management practices aimed at reducing the generation of pollutants at their sources, such as street cleaning, land use control and nutrient management. Under the premises that biological integrity can be attained when the physical and chemical properties of water bodies are adequately maintained, the implementation of watershed BMPs is, therefore, an important step in reaching the goals outlined in the CWA.

This paper reviews the impact on the aqueous environment due to urban development and highway construction, and describes best management practices that help mitigates such impacts, especially certain practices pertaining to the "green" or "eco-friendly" types of practices such as bioretention cells, swales, buffer strips and constructed wetlands. The emphasis is on how to manage "water" for eco-friendly urban construction and road building.

Impact of Urbanization and Highway Construction

The major impact of urbanization on the water environment can be summarized as follows:

- Hydrology – Higher flood peaks, larger runoff volume, faster flood flows, less evapotranspiration, and less groundwater recharge.
- Water quality – Larger wastewater volumes, enhanced sediment and erosion processes, and stormwater runoff pollution.
- Aquatic biological integrity – Habitat loss, biodiversity, toxicity, etc.

Figure 1 depicts the hydrologic impact of urban development.

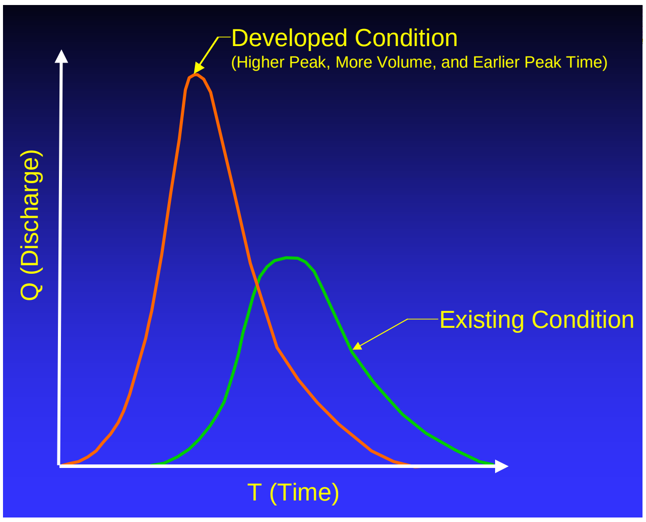

Figure 1. Hydrologic Impact of Urbanization

Highway construction impacts include excessive sediment yield during construction and runoff pollution from pavements and right-of-ways. For example, hydrologic changes due to site cleaning, grading, increased imperviousness and landscape maintenance can cause stream channel instability, which could lead to stream bank erosion and habitat degradation (Federal Highway Administration or FHWA, 2000). Also, runoff containing deicing compounds is toxic to fish, plants and other wildlife. Other harmful pollutants in highway runoff include nutrients, herbicides, trace metals, and oil and grease. Some forms of petroleum hydrocarbons have been found to be carcinogenic. In addition, highway culverts at stream crossings could hinder the movement of aquatic fauna.

Practices for Eco-friendly Urban Development and Highway Construction

One of the most prominent examples of eco-friendly stormwater management practices in the United States is what is generally called 'Low-Impact Development', or LID. LID is an innovative technological approach to stormwater management and ecosystem protection where hydrologic controls are integrated into every aspect of a site's design to mimic the predevelopment hydrologic regime (Coffman, 2004). LID focuses on how to design developed areas in a manner that maintains ecosystem and hydrologic functions. LID maintains or restores the hydrologic regime and manages stormwater by fundamentally changing conventional site design to create an environmentally and hydrologically functional landscape that mimics all natural watershed hydrologic functions (volume, frequency, groundwater recharge, evaporation and discharge).

LID techniques are simple and effective, and are significantly different from conventional engineering approaches, which emphasize the piping of water to low spots removed from the development area as quickly as possible. Instead, LID uses micro-scale techniques (sometimes known as 'ultra-urban' techniques) to manage precipitation as close to where it hits the ground as possible. Instead of large investments in complex and costly engineering strategies for stormwater management, LID strategies integrate green space, native landscaping, natural hydrologic functions, and various other techniques to generate less runoff from developed land. This involves strategic placement of linked lot-level controls, such as bioretention cells, buffer strips, swales, and other ultra-urban best management practices (BMPs) that are designed to address specific pollutant loads as well as stormwater timing, flow rate, and volume issues.

One of the primary goals of LID design is to reduce runoff volume by infiltrating rainfall water to groundwater, evaporating rainwater back to the atmosphere after a storm, and finding beneficial uses for water rather than exporting it as a waste product down storm sewers. The result is a landscape functionally equivalent to predevelopment hydrologic conditions, which means less surface runoff and less pollution damage to lakes, streams, and coastal waters. LID practices include such techniques as bioretention cells or rain gardens, grass swales and channels, vegetated rooftops, rain barrels, cisterns, vegetated filter strips and permeable pavements. Many of these techniques both reduce runoff volume and filter pollutants from water before it is discharged into receiving watercourses.

Grassed Swales

Swales are grassy depressions in the ground designed to collect storm water runoff from streets, driveways, rooftops and parking lots. Two general types of grassed swales are generally designed: 1) a dry swale, which provides water quality benefits by facilitating stormwater infiltration, and 2) a wet swale, which uses residence time and natural growth to treat stormwater prior to discharge to a downstream surface water body. Both dry and wet swales demonstrate good pollutant removal, with dry swales providing significantly better performance for metals and nitrate. (FHWA, 2000). The primary pollutant removal mechanism is through sedimentation of suspended materials. Therefore, suspended solids and adsorbed metals are most effectively removed through a grassed swale. Both dry and wet swales demonstrate good pollutant removal, with dry swales providing significantly better performance for metals and nitrate. Dry swales typically remove 65 percent of total phosphorus (TP), 50 percent of total nitrogen (TN), and between 80 and 90 percent of metals. Wet swale removal rates are closer to 20 percent of TP, 40 percent of TN, and between 40 and 70 percent of metals. The total suspended solids (TSS) removal for both swale types is typically between 80 and 90 percent. In addition, both swale designs should effectively remove petroleum hydrocarbons based on the performance reported for grass channels (FHWA, 2000). Table 1 shows the pollutant removal efficiencies for some grassy and vegetated swales used for stormwater conveyance and treatment in the United States.

Table 1 - Pollutant removal efficiencies for grassy swales (from FHWA, 2000)

Design	Pollutant Removal Efficiencies (%)					
	TSS	Metals	Nutrients			Source
			TN	NO_3	TP	
Grassed channel	68		23	-2	43	City of Austin (1995)[1]
Vegetated swale (61-m)	21-95	-	-	-	32-85	Yu, et al., (1993)[2]
Vegetated swale (30-m)	49	13	-	-	33	Yu, et al., (1994)[2]
Grassed swale	30	11	-	-	Neg.	Yu and Kaighn (1995)[1]
Grassed swale	-	(-25)-92	(-14)-25	-	(-48)-48	Yousef, et al., (1985)[1]
Grassed swale (61-m)	83	30-72	-	-	29	Kahn, et al., (1992)[2]

[1] Removal efficiencies based on concentrations
[2] Removal efficiencies based on mass loading.

Bioretention Cells

One of the key LID techniques is a bioretention cell (sometimes referred to as a “rain garden”). Bioretention is a terrestrial-based (up-land as opposed to wetland), water quality and water quantity control practice using the chemical, biological and physical properties of plants, microbes and soils for removal of pollutants from storm water runoff. Some of the processes that may take place in a bioretention cell include: sedimentation, adsorption, filtration, volatilization, ion exchange, decomposition, phytoremediation, bioremediation, and storage capacity (Prince George’s County, 2002). Figure 2 shows a typical bioretention system.

Figure 2. Typical 'Rain Garden' Bioretention System

Bioretention systems are more than simply creative landscaping. They are engineered systems that have been designed and installed to promote the biological, physical and chemical treatment of stormwater runoff, as well as to promote the infiltration of stormwater runoff in order to help restore the character of the natural hydrologic cycle of the area. Bioretention cells are comprised of six basic components (USEPA, 2000). These are:

- Grass buffer strips that reduce runoff velocity and filter particulate matter,
- Sand bed that provides aeration and drainage of the planting soil and assists in the flushing of pollutants from soil materials,
- Ponding area that provides storage of excess runoff and facilitates the settling of particulates and evaporation of excess water,
- Organic layer that performs the function of decomposition of organic material by providing a medium for biological growth (such as microorganisms) to degrade petroleum-based pollutants. It also filters pollutants and prevents soil erosion,
- Planting soil that provides the area for stormwater storage and nutrient uptake by plants. Often the planting soils contain some clays which adsorb pollutants such as hydrocarbons, heavy metals and nutrients, and
- Vegetation (plants) that function in the removal of water through evapotranspiration and pollutant removal through nutrient cycling.

Figure 3 shows a schematic drawing of a typical bioretention cell constructed to transport stormwater runoff from a parking lot.

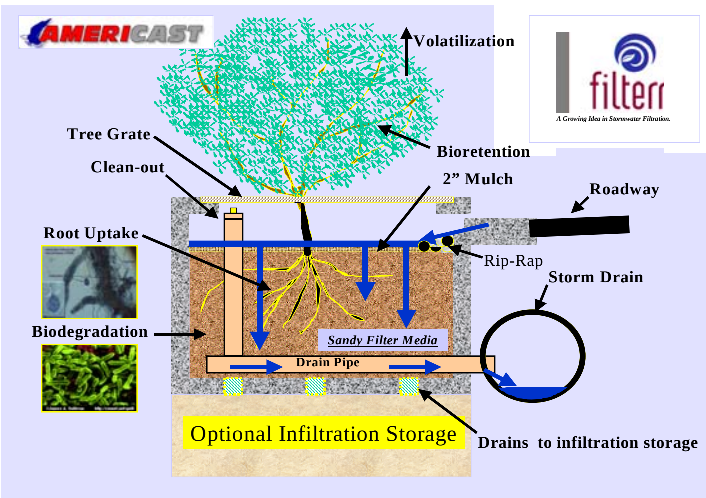

Figure 3. Schematic of a Bioretention Cell

The various pollutant transport and transformation processes active in a bioretention are illustrated in Figure 4.

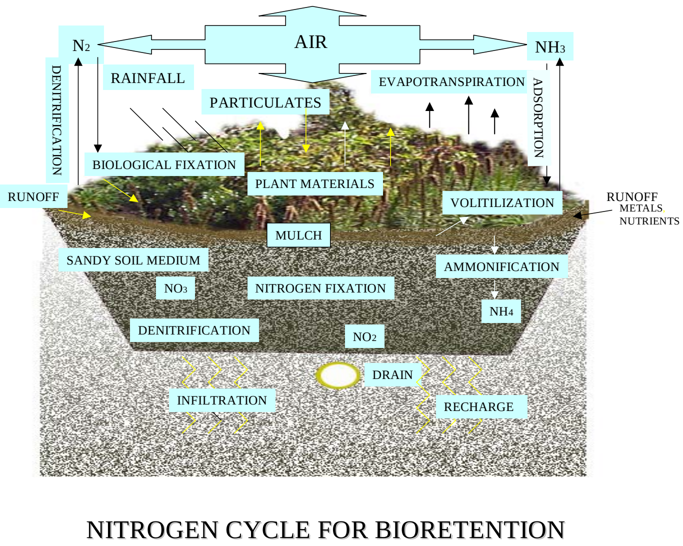

Figure 4. Nitrogen Cycle in a Bioretention Cell (Source: USEPA, 2000)

Laboratory and some limited field tests have shown good removal capabilities of some pollutants such as 80 – 90% for total suspended solids (TSS); 40 – 50% for total phosphorus (TP), and 50 – 90% for heavy metals (FHWA, 2000, Yu and Wu, 2004). One significant advantage for using bioretention cells as a water management measure in urban areas is the fact that bioretention cells can be designed as part of the urban or highway landscape.

Ecological Detention Systems

LID technologies are generally applicable for small-scale contributing areas. For large drainage areas (e.g., greater than 0.5 hectares) bioretention may not be practical due to its storage capacity limitations. In these cases larger systems, such as ponds and wetlands are generally used to treat stormwater (Center for Watershed Protection, 1996). Such larger stormwater management structures include retention ponds, detention ponds, and constructed wetlands. These practices, when properly designed and maintained, can enhance the aesthetic values of the landscape and also help mitigate some of the negative impact of development on the ecosystem.

An example of a constructed stormwater treatment wetland for a highway application is given in Figure 5 below. Both detention ponds and constructed wetlands have shown good to excellent pollutant removal capabilities. For example, removal rates of 60 – 90% for TSS, 50 –80% for TP, and 30 –60% for metals have been reported (FHWA, 2000, Yu et al., 1994). High removal rates have also been reported for constructed wetland systems (FHWA, 2000)

Figure 5. Constructed Wetland in a Highway Medium

In addition to pollutant removal, constructed wetlands offer the most potential for creating the ancillary benefits of wildlife habitat, public recreational uses such as bird watching and nature study, and surface runoff flow retention.

Summary of Pollutant Removal Efficiencies of Various BMPs

Since the use of BMPs was promoted in the mid-1980's, numerous laboratory as well as field tests have been conducted to test the pollutant removal efficacies of different types of BMPs. Currently a joint effort is being made by the American Society of Civil Engineers (ASCE) and the US Environmental Protection Agency (USEPA) to develop and maintain a comprehensive national and international database on BMPs. The ASCE/EPA BMP database now includes several hundred BMPs and is being expanded to include LID-type of BMPs. Table 2 below is a recent list of median efficiencies of major types of BMPs.

Table 2 - Median Pollutant Removal (%) of Stormwater Treatment Practices (Center for Watershed Protection, 2000)

	TSS	TP	Sol P	TN	Nox	Cu	Zn
Stormwater Dry Ponds	47	19	- 6.0	25	4.0	26[1]	26
Stormwater Wet Ponds	80	51	66	33	43	57	66
Stormwater Wetlands	76	49	35	30	67	40	44
Filtering Practices[2]	86	59	3	38	-14	49	88
Infiltration Practices	95[1]	70	85[1]	51	82[1]	N/A	99[1]
Water Quality Swales[3]	81	34	38	84[1]	31	51	71

[1] Fewer than 5 data points

[2] Does not include vertical sand filters and filter strips

[3] Refers to open channel practices designed for water quality

N/A = Data are not available

TSS = Total suspended solids; TP = Total phosphorus; Sol P = Soluble phosphorus;

TN = Total nitrogen; NOx = Nitrate and nitrite; Cu = copper; Zn = Zinc

Major Watershed Management Issues in Taiwan

Background

Taiwan is an island nation with a land area of 36,002 km^2 and a 1999 population of about 22 million. The topography is characterized by tall mountains in the middle and eastern, plains in the western and southern part of he island. The annual rainfall averages over 2,500 mm (about 98 inches) but distributes very unevenly throughout the year. Furthermore, on average almost 80% of the runoff goes into the sea because of the steep terrain and short lengths of the rivers and streams. Therefore in Taiwan reservoirs represent the major source of water supply. In 1999, there are more than 60 reservoirs, supplying roughly 70% of the total water usage in Taiwan.

In recent years, many reservoirs in Taiwan have been seriously impacted by excessive urbanization and industrialization in their watersheds. Highland farming, construction, lack of wastewater treatment and effective conservation practices all contribute to water quality problems such as siltation, eutrophication, etc. For example, a 1995 report estimated that the effective storage capacity of some reservoirs were down to only 75% of the design capacity due to siltation.

Major Issues

1. Laws and Regulations on Watershed Protection

For example, the current water pollution control act does not cover nonpoint source pollution. It does not address wetland protection either. There are many laws and regulations on the books, but enforcement has always been difficult, especially when citizen property rights are impacted.

2. Organizational Issues

Functions of different agencies sometimes overlap and not very well defined. Cooperation among agencies needs to be strengthened.

3. Water Quality Protection

Control of point sources is not adequate. Many studies on nonpoint source characterization and BMP efficiency have been done recently. However, full-scale implementation has not been started.

4. Citizen Concerns

Environmental awareness is still relatively low. Some residents in watersheds demand unreasonable "compensation" when their lands are taken for building conservation measures.

BMP Implementation Issues in Taiwan

Regulatory Framework

In the 1980's, Virginia environmental agencies tried to encourage various sectors to install BMPs on a "voluntary" basis. However, the strategy did not work very well. The current regulations established at the federal, state, and local levels serve as a "driving force" for nonpoint pollution control and therefore BMP implementation activities in the US. It seems that, in order to efficiently reach set goals for watershed water quality protection, a regulatory framework is needed. Requiring eco-friendly engineering practices for government-sponsored engineering projects, e.g., highway building is a very good strategy because this will set examples and generate valuable information for other potential implementations. For privately sponsored construction projects such as shopping malls and residential sites the developers might be persuade to use multi-purpose BMPs, such as wet ponds, to gain "aesthetic values" and water quality protection credits.

The regulatory framework could be established at either the central or the local government level, or both. Tax benefits could also be used as a motivational tool.

Cost and Maintenance

One of the key issues in BMP implementation is: who should pay for the construction and maintenance costs associated with the BMPs? In the US, for public construction projects including road building, BMP cost is part of the overall construction cost and the responsible agency (e.g., transportation departments in the case of highway construction) would maintain the facilities. For private projects, the developer would construct the BMPs and the users (e.g., homeowners associations in the case of residential developments) would be responsible for the maintenance costs.

BMP costs depend largely on the type of BMP and many other site-specific factors such as land value, labor and material costs, etc. The FHWA report in 2000 cited some preliminary costs for BMPs. For example, a bioretention cell system could cost about $25,000 per impervious hectare area served. On the other hand, swales and filter strips would cost much less, about $4,000 to $5,000 per impervious hectare served.

Technical Issues

Because nonpoint pollution problems are very site-specific, there is virtually no "one-size-fits-all" type of approach in controlling NPS pollution. Rainfall, and therefore runoff characteristics in Taiwan are quite different from those in the US. Factors such as topography, soil, agricultural practices (e.g., tea gardens are prevalent in Taiwan), climate, etc., all impact the selection and the design of BMP that are appropriate for Taiwan. Some of the most important design-related questions are:

- What should be the design frequency for storms? (In the US, a 10-year frequency is commonly used for runoff quantity control, whereas a 2-year or lesser storm is used for quality control). The sizing of BMPs and therefore their cost depend on the design frequency selected. The choice of an appropriate design frequency should be carefully determined with consideration given to both the economics and the degree of protection or treatment desired.

- Should the control of the “first-flush” of the runoff (usually the first 0.5 in or 13 mm runoff volume), which is adopted in many states in the US, be considered in Taiwan? The reason of choosing the first 0.5 in of runoff to treat is because literature data suggested that the first flush runoff generally contains a very significant amount of the total pollutant loads generated by a single storm. Such a phenomenon may or may not be the case in Taiwan.
- Should the underground type of BMPs such as bioretention cells, vault structures and sand filters be considered as preferred BMPs in Taiwan? These BMPs require little space and would be less vulnerable to vector problems, which should be a concern in Taiwan because of the warm weather year-round.
- What type of pollutant parameters should be considered as “priority” pollutants to be controlled? For example, given that water temperature is an important parameter for fish such as the Formosan Salmon, the design criteria of the BMPs then should include water temperature as a key parameter.

Other Issues

Other important issues relating to a full-scale BMP implementation include: special provisions for certain sectors in the society, e.g., BMP implementation for the agricultural sector, especially farmers, partnership with environmental groups, public education strategies, etc.

Conclusions

Urbanization, including highway construction, could cause significant negative impact on the aquatic ecosystem. There are a number of engineering practices, called BMPs, can be employed to mitigate these negative impacts. BMPs such as bioretention cells, vegetative buffer strips and swales, and constructed wetlands can be integrated into the landscape and therefore providing both water quality management and aesthetic benefits. The full implementation of BMPs in watersheds requires a well-planned strategy, which needs to address issues such as a regulatory framework, cost and maintenance, technical and other issues.

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