PREDICTING AQUATIC PHOSPHORUS LEVELS:
A SOUTHEAST MICHIGAN CASE STUDY

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ABSTRACT

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In this investigation, the current state of the art is examined to predict phosphorus levels for a case study in southeast Michigan. This case study examined four approaches to managing phosphorus: the first two approaches utilize bioswale and bioretention separately to treat stormwater runoff; third approach applies bioswale and constructed wetland (in a series) to purify stormwater; and fourth approach utilize bioretention and constructed wetland (in a series) to clean stormwater. Results of these approaches showed that of best management practices (BMPs) in a series worked incredibly better than single BMPs. The third and fourth approaches can help reduce phosphorus level to meet the requirement of EPA, while other two treatments cannot. This result showed that the pre-treatment and served drainage areas were main constraints of the performance for phosphorus removal by low impact development strategies in this project. Other physical constraints in this project were summarized included topography, precipitation, soil, and land use types.

Key words: Environmental Design, Urban Planning, Landscape Architecture, Phosphorus Removal, Site Hydrology, Urban Design.

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CHAPTER 1 INTRODUCTION

As an alternative clean water resource, stormwater also can be generally treated as an easy and effective way to conserve potable water resource and reduce the usage of surface water. With simple management protocols and good catchment management practices, stormwater is preferred to be harvested, managed, and stored on site, and it could be used for multiple purposes, such as outdoor irrigation, indoor toilet, bathroom, and laundry (WVDEP, 2012). Moreover, stormwater runoff ought to be controlled in developed urban areas because stormwater runoff from developed urban areas always contain contaminates such as litter, pathogens, and other chemicals. The pollutants may have negative impacts on quality of local water, local ecosystem, and human health (EPA Victoria, 2012). Thus, many new concepts and strategies of stormwater runoff management are created to seek an integrated way benefiting society, environment, and human being.

As one of them, Low Impact Development (LID) is a widely used concept applied for harvesting stormwater and recharging groundwater in developed urban areas. By using design technologies, LID can mimic natural hydrology and create a functionally equivalent hydrologic regime (SMCOG, 2008). The overall goal of LID is providing sustainable management of water resource, and this goal can be achieved by various ways. They are diminishing impervious surface, narrow roads and sidewalk width, and increasing micro-scale retention/detention areas, such as bioretention, vegetated swale, filtrated trench, pond, and green roof (SMCOG, 2008). Other design strategies are also included to protect environmentally sensitive areas, such as riparian buffers, constructed wetlands, steep slope, flood plain, and woodlands (SMCOG, 2008).

Low Impact Development (LID) is a cost-effective way and simple to be learned and used by designers, developers, engineers, and even property owners. Instead of post-construction, stormwater management is increasingly applied in the pre-design phases (SMCOG, 2008). However, scientific calculation of LID strategies always be ignored by designers and practitioners. Lack of integrated calculation methodology of LID and unclear calculation steps often lead to an invalid designs and makes the outcomes of LID hard to be estimated statistically. The main data of effectiveness for LID strategies are measured by plenty of experiment reports, which only represent a mean value in national level and cannot reflect the real results case by case. In Hyde's reclaiming riparian design (2013) of Rouge River at Detroit in Michigan, Low Impact Development (LID) strategies are employed in master plan to control quantity and quality of stormwater runoff. However, the name of LID strategies is blurred and no calculation method is provided to examine whether his design is appropriate and effective for this site or not.

This study will investigate the influences of urbanization on the quality and quantity of stormwater runoff， with an overview of LID strategies. The efficiency of bioswale, bioretention, and constructed wetlands are also reviewed in second chapter. In the third chapter, site inventory and design description are introduced. Based on the information, the blurry LID strategies will be changed to the explicit strategies. Four possible combinations of LID are used to calculate their efficiency of phosphorus removal in selected site. Results of four treatments will be shown in the fourth chapter. Finally, discussions about how to select, adjust, and improve the efficiency of LID strategies are presented in last chapter. This study also provides several recommendations for designer, future researchers and governors.

Therefore, based on Hyde's design, this study aims at:

(1) clarifying LID strategies used in Hyde's design;

(2) presenting an integrated calculation system for the efficiency of LID strategies in this project;

(3) through evaluating post-concentration of phosphorous treated by LID, examining the validity and practicability of LID usage in Hyde's design;

(4) finally, providing recommendations for designers, future researchers, and government officials.

CHAPTER 2 LITERATURE REVIEW

2.1 Stormwater Management Practices

2.1.1 Impact of Urbanization

The influence of human activities on the Earth's physical and biological systems is throughout the history, and it becomes a global issue for the past decades as the immediate urban expansion (Li, 2012). Today more than 80% of the earth surface has been covered by man-made facilities, and almost 40% of ice-free land surfaces are covered by transformed landscapes, such as cropland, pasture, and human habitats (DeFries, Asner, & Foley, 2006). In the United States, the rate of urban sprawl has been twice the rate of population growth in the past two decades, and the majority of the population settled in suburban and urban areas (USEPA, 2007). Between 1982 and 1997, the increase of developed land was 34% while the increase of population was only 15% (USEPA, 2007). This rapid growth and development stimulate the land transformation, especially in urban areas, and result in highlighted negative social and environmental impacts. Satterthwaite *et al.*, (2007) lists major impacts of urbanization, and they show that urban expansion exacerbates the overall risks of human and environmental health. These impacts include:

- High-density populations caused the concentrations of solid and liquid wastes in urban areas.
- Huge part of population lived in areas without official land-use control, and they had little attention to health and safety standards.

- Mainly developed land covered by impermeable surfaces, and little open spaces and water bodies remained.
- Inadequate planning and poor design did not consider about current and future hazards.
- City governments and urban economies are unable to cope with sudden movements of people into a city in response to crises elsewhere.

Urbanization profoundly influenced the surface water and groundwater moves and exchanges, the quality and quantity of stormwater runoff, and the ultimate conditions of nearby water bodies. The appearances of build environment, road density, and the ratio of pavement coverage to open space initially determine stormwater runoff related consequences (NRC, 2009). Raudolph (2012) demonstrated that the increase of imperious surfaces (roads, parking lots, rooftops) associated with urban development prevent infiltration of rainfall into soil; and therefore produce more runoff. This has significantly changed the natural flow patterns, resulting in lower infiltration rates, higher runoff peak flows, and higher flood risks (Li, 2013).

As mentioned above, the changes resulted from urbanization have dramatic effects on the natural water cycles and water resources, which can be summarized as following (SEMCOG, 2008); outcome first and then explained:

- Increased flooding and property damage. As the land for construction in urban areas continues to expand, some small water bodies such as ponds, lakes, and reservoirs are filled for building constructions; at the meanwhile, flood retention areas are occupied. The changes increase the risk, the frequency of severe urban flooding, and potential damages to public and private properties (SEMCOG, 2008).

- Impaired water quality. Although carefully controlled, heavy metals, eroded sediment, motor oil, animal waste, fertilizers, and pesticides are largely absorbed into stormwater, and are sent directly into local rivers and lakes through natural channels or drainage systems. These constituents have negative impacts on water quality and aquatic ecosystems. Sediment is a major carrier of contaminants and will cloud over the waterway, decreasing light penetration in stream, harming fishes and macro-invertebrate communities, and smothering fish eggs (NRC, 2009). Nutrients, such as phosphorus and nitrogen, can cause algae blooms, which may block the sunlight, reduce levels of dissolved oxygen in the water, and numeral fishes died due to anoxia (ECDEP, 2009). Toxic substances can accumulate in a stream and threaten water quality, so that they will kill fish and other aquatic lives (ECDEP, 2009). Bacteria and viruses can lead to diseases of fishes and humans via both ingestions and dermal contacts (NRC, 2009).
- Degradation of stream channels. The loss of natural features can cause a higher velocity of stormwater runoff flashing through urban areas. This condition is flashy flows, and it results in widening and deepening water channels, eroding stream banks and stream beds more frequent and heavily, and declining stream substrate qualities (SEMCOG, 2008).
- Less groundwater recharge and dry weather flow. Impermeable surface can impede stormwater infiltration and impact on groundwater recharge. Groundwater is a major supporter of surface water. With replenishment of groundwater, the rivers and lakes can keep a steady flow, especially during dry seasons. The reduction of stream flow in dry

weather can cause negative impacts on aquatic lives and recreational opportunities (SEMCOG, 2008).

- Increased water temperature. Water temperature is a major factor to select what kind of organisms can live in rivers and lakes (USGS, 2014). Stormwater runoff achieves a higher temperature when it flows through the impervious surfaces and warmed by the sun. The warmer runoff can affect the temperature of receiving rivers and lakes and cause a shock to the aquatic lives that require cold-water conditions (SEMCOG, 2008). In addition, water temperature influences on the rate of chemical reaction—"higher temperatures can dissolve more minerals from the rocks it is in and will therefore have a higher electrical conductivity."(USGS, 2014)
- Loss of habitat. The erosive flows and warmer water will cause a decrease of biodiversity and total amount of fishes and aquatic insects (SEMCOG, 2008).
- Decreased recreational opportunities. Stormwater runoff can decrease water quality, increase temperature, and decrease diversity of aquatic ecosystem. All these negative impacts result in decreased recreational opportunities (SEMCOG, 2008).

2.1.2 Conventional Stormwater Management

Current stormwater management practices are dominated by a typically traditional concept—"Stormwater runoff is undesirable and must be removed from the site as quickly as possible to achieve good drainage (Roy, 2000)." Instead of reducing stormwater peak flow by decreasing runoff volume, the primary goal of conventional stormwater management is to quickly reduce the quantity of stormwater runoff. Traditional stormwater management collects stormwater runoff through roofs, gutters, curbs, and pipes. Although stormwater runoff may be heavily polluted, it often be conveyed directly into the nearest receiving water body (Ahiablame, Engel, & Chaubey, 2012). This approach increases the risk of deteriorating downstream water quality by transporting pollutants into the receiving waters (Ahiablame, Engel, & Chaubey, 2012). This conventional approach is usually known as conventional development (CD) or end-of-pipe practices, and usually it includes centralized stormwater management ponds, conveyance piping systems, pond/curb inlet structures, constructed concrete roadside ditches, and curb and gutter infrastructure (Ahiablame, Engel, & Chaubey, 2012).

Due to urbanization and deficiency of conventional development (CD), rapid hydrologic changes (increase in volume and frequency of stormwater runoff and the decrease of runoff travel times) cause more frequently serious natural disasters, such as urban flooding and algae bloom, and result in tremendous economic loss, heavy non-point pollution, and health issues in U.S. (Roy, 2000). Conventional development (CD) should not the only solution to deal with these problems, and a systematic approach needs to apply for mitigating the new problems through sustainable technologies and concepts.

2.2 Low Impact Development Overview

2.2.1 Low Impact Development

The origins of Low Impact development (LID) relate to the conservation movement stemmed from India and England in the mid-19th century, and people started to preserve local forests based on scientific principles (Barton, 2002). Then, this movement immediately spreads to the United States. Headed by Henry David Thoreau and George Perkins Marsh, the ideas that human activity had detrimental impacts on the land and ecosystem values preached in nationwide in the United States (Benedict & McMahon, 2006). At about the same time, Frederick Law Olmsted explored the multi-function of natural landscapes to mediate the interrelationship between people and nature, and he applied his theory into design greenways and parks (Eisenman, 2013). In the 1858 plan for New York City's Central Park, for example, Frederick Law Olmsted designed a large and unbroken green space to provide fresh air for the city, which also presented the remedy function of nature (Eisenman, 2013). Olmsted noticed that urban living led to many physical and mental diseases, and national parks could provide a health, relax environment as well as cultural and spiritual benefits for people (Eisenman, 2013).

In the early 1900s, with the appearance of automobiles, parks were too small to meet the social demands, therefore parkways were treated as important ways to link ecosystem together and, at the same time, to reduce the negative impacts of urbanization (Benedict & McMahon, 2006). In the same period, Greenbelts were developed into community level, such as schools, roads, facilities, and green infrastructures were utilized as portions to supply gray infrastructure (Benedict & McMahon, 2006). In 1970, the establishment of the United States Environmental Protection

Agency boosted the legalization of environmental protection actions and encouraged interdisciplinary developments. The team comprised with biologists, ecologists, developers, governors, urban planners, and designers started to recognize that preserving isolated natural areas was not enough. Later, green infrastructure became a comprehensive concept, which combined with sustainable development, ecosystem management, and regional planning (Benedict & McMahon, 2006).

In the early 1990s, the new concept, Low Impact Development (LID), was first implemented in an integrated statewide green infrastructure system in Maryland State, USA (USEPA 2000a). This first broad definition of LID was coined by Simon Fairlie in 1996 in Britain: “A low impact development is one that, through its low negative environmental impact, either enhances or does not significantly diminish environmental quality (Fairlie, 1996).” He later stated several LID criteria in 1996, including “integrated whole-site management and use, reversibility, minimized resource consumption, renewable resource use, on-site waste processing, and seeking an overall positive environmental impact (CCW, 2002)”. Based on his concept, the common perception of LID can be generally used for stormwater harvesting, low carbon housing design, renewable energy generation, and waste minimization worldwide. However, the application of LID in the United States mainly focused on rainwater harvesting, like its original definition coined by Prince Geoge’s County, Maryland (1999): “mimic the predevelopment site hydrology by using site design techniques that store, infiltrate, evaporate, and detain runoff” (Struck & Lichten, 2010). In 2010, LID was redefined by the U.S. Environmental Protection Agency (USEPA) as “an approach to land development (or re-development) that works with nature to manage stormwater as close to its source as possible (USEPA, 2010)."

The basic goal of LID is to recover the hydrology system of a developed site as close as its pre-developed natural condition (Ahiablame, Engel, and Chaubey, 2012). Based on this primary goal, several specific goals are applied in practices to help LID replicate natural water cycle. They are minimizing total runoff volume; controlling peak rate of runoff; maximizing infiltration and groundwater recharge; maintaining stream base flow; maximizing evapotranspiration; and protecting water quality (SEMCOG, 2008).

Conventional stormwater design criteria focuses on preventing flooding caused by high-intensity but less-frequency storm event, and it does not involve stormwater quality management and ecosystem protection (SEMCOG, 2008). These weaknesses of conventional stormwater management can be improved and supplied by LID. LID focuses on reducing constant peak rates of runoff for larger storms, and also minimizes runoff volumes increased for the much more frequent and smaller storms (SEMCOG, 2008). Hood et al. (2007) compared lag time characteristics of LID with CD, and found that LID had a significantly greater performance than CD by comparing runoff volume, peak discharge, and runoff coefficient. Although it cannot completely replace CD, LID is proved to work better for smaller storms with shorter durations than CD does (Qin, Li, & Fu, 2013). LID utilizes a variety of natural and artificial structures to reduce the volume and peak flow of runoff, filter out its pollutants, and mimic natural process. For instance, plant materials and soil layers filter runoff, potential pollutant uptake by selected vegetation, and biodegradation of pollutants by soil microbial communities (NCHRP, 2006; COE, 2011). Thus, LID positively facilitates the balance of natural hydrologic system. With these approaches, LID can minimize the negative impacts of urbanization and alleviate the global climate changes (Pyke et al., 2011).

The ‘best management practices’ (BMPs), as a subcategory of LID, are often applied to achieve the objectives of natural resource protection in practices. Generally, LID can be classified into two types, nonstructural BMPs and structural BMPs (SEMCOG, 2008). Nonstructural BMPs, with less artificial construct in their forms, are preventing stormwater runoff from the site. It is more flexible to be used in broadly locations (SEMCOG, 2008). Nonstructural BMPs contain several strategies, including: cluster development, minimization of soil compaction, minimization of total disturbed area, protection of natural flow pathways, protection of riparian buffer areas, protection impervious surfaces, and stormwater disconnection (SEMCOG, 2008). Structural BMPs, on the other hand, aimed to mitigate stormwater-related impacts after they have occurred and applied in locations where was more explicitly suitable for their physical form (SEMCOG, 2008). Structural BMPs consist of bioretention/rain gardens, capture reuse (rain barrels, cisterns, and tanks), constructed filter (dry wells, infiltration basins, infiltration trenches), detention practices (dry/wet ponds), level spreaders, native re-vegetation, pervious pavement, planter boxes, riparian buffer restoration, soil restoration, vegetated filter strip, vegetated roof, vegetated swale, and water quality devices (SEMCOG, 2008).

2.2.2 Principle of Smart Growth and LID

The potential of LID is maximized when incorporated with other approaches, and smart growth is one of them. In fact, the birth of smart growth comes with the conservation movement.

Many design elements of smart growth could date back to the early 1900s. For instance, Clarence Perry's concept of neighborhood unit (1920) defined neighborhood as a component of a town and initially separated pedestrians and vehicle traffics (Burchell, Listokin, & Galley, 2000). Nine years later, based on Perry's concept, Clarence Stein and Henry Wright designed innovatively pedestrian-orientated and other feathers in project of Radburn, NJ (Burchell, Listokin, & Galley, 2000). In the 1964s, Congress passed the Wilderness Act, which protected federal wilderness not to be occupied by expanding settlement and artificial mechanization (Benedict & McMahon, 2006). This growth control action and the growth management revolution in the 1970s and 1980s continued effecting on the compact development, housing and neighborhood development, walkable and transit-accessible development in United States over the next two decades (Knaap, 2004; Goetz, 2005).

Combined with the principles of urbanism and sustainable development, Smart Growth is defined by EPA as "development that serves the economy, the community, and the environment. It changes the terms of the development debate away from the traditional growth/no growth question to how and where should new development be accommodated" ("Community Initiatives.", n.d.). Without affecting the speed of economic development, smart growth strives to produce environmental, economic, societal, and health benefits with several practices, such as encouraging compact and mixed-use communities, providing more transportation options, preserving open spaces and environmental habitats, protecting water and air quality, reducing greenhouse gas emissions and decreasing energy consumption in multiple ways (USEPA, 2011). Several specific principles are followed by smart growth, including (COEC, 2009):

- Taking advantage of compact building design;
- Creating a range of housing opportunities and choices;
- Create walkable neighborhoods;
- Foster distinctive and attractive communities with a strong sense of place;
- Preserve open space, farmland, natural beauty, and critical environmental areas;
- Strengthen and direct development towards existing communities;
- Provide a variety of transportation choices;
- Make development decisions predictable, fair, and cost effective; and
- Encourage community and stakeholder collaborations in development decisions;

Considering the aspect of stormwater management, smart growth practices can benefit the natural water cycle with the strategies that minimize impervious surfaces and improve water detention (COEC, 2009). Thus, the coordination of LID and smart growth may maximize the management of stormwater runoff and contribute to preserve natural watershed areas in different levels. Based on this idea, LID was developed closely to smart growth and improved in a community level to make better use of existing landscapes and create more compact, walkable, and mixed land use in a developed area (USEPA, 2011). The relationship of LID and smart growth can be reflected in their principles. For example, the principles of smart growth that relate to compact building design and preserving natural features directly link to nonstructural LID (SEMCOG, 2008). Influenced by smart growth, some of the main principles of LID are listed below (Roy, 2000; Qin, Li, & Fu, 2013; &SMCOG, 2008); principles first and then explained:

- Promote natural sensitive design in the pre-construction phase to create a hydrologic multifunctional landscape. In order to optimize stormwater benefits, LID should be considered into the community planning and design process as early as possible. Significantly, LID should limit the disturbances of a sensitive site by reducing the amount of stormwater runoff control.
- Manage stormwater as close to the source as possible with micro-scale practices disperse the site. Concentrate stormwater runoff to BMPs, as close to the generation point as possible, is an essential element for LID. LID cannot only be used to distribute the traditional sites, such as communities and new development sites, but also can be used in combined sewer systems, along transportation corridors, and at brownfield sites.
- Focus on prevention rather than mitigation and remediation. As an essential component of LID, nonstructural practices emphasize preserving natural features, clustering development, and minimizing impervious surfaces. Nonstructural BMPs usually are considered first to maximize environmental benefits in design processes and prepare for using structural BMPs.
- Manage stormwater as a resource, not a waste. Stormwater provides people alternative potable water, and it is a vital natural resource related to groundwater recharge, stream base flow, and lake and wetland heaths. LEED programs also demonstrate the principles as stormwater should be collected on-site and be designated as an important part of gray water used for irrigation and toilet flushes.
- Make maintenance a priority. Maintenance should be considered when selecting a LID

technique. The maintenance of LID usually is a longer term and can help LID to achieve a higher performance but less cost when contrast to conventional systems. An optimal LID should suit for both the nature conditions of the site and the owners/ operators who implement future maintenance activities.

- Encourage public education and participation in environmental protection. Education programs should include training programs for the maintenance of LID, community volunteers delivering relevant information throughout the project life cycle, and ongoing involvement of owners, developers, and operators with community groups.

In order to be flexibly applied and broader used into new development and re-development projects, LID principles are currently being incorporated into regulatory mandates, Federal and State regulators, which can lead LID into a standardized development procedures (COEC, 2009).

2.2.3 Benefits of LID

Applications of LID provide many benefits to developers, environment, and communities (SEMCOG, 2008). Some of these benefits can be identified as actual and quantitative savings, such as economic benefits; while others are more intangible qualitative interests, such as environmental, social, and aesthetic benefits that are difficult to assign a quantitative value.

For builders and developers, LID costs less than CD to construct and maintain. Based on the cost comparisons for 17 different case studies across United States, EPA found that cost saving of LID ranged from 15% to 80% compared with CD (SEMCOG, 2008). LID often needs less land clearing, grading, infrastructure costs, and potentially save more construction time

(SEMCOG, 2008). LID, such as bioretention or bioswale, occupies less space than traditional stormwater ponds and create multi-purpose landscaping to increase lot yields (BIAOW, 2013). When applied LID in developed areas, it has more flexibility and simplicity to integrated in site designs, and it can preserve more developable lands than CD (COEC, 2009). Additionally, LID can enhance property values and increase marketability, which lead to fast sales as well as reduce energy consumption and water treatment costs (COEC, 2009). A study conducted by Trust for Public Land and the American Water Works Association found that forest cover in a watershed can positive impact on the water supply treatment costs. According to this study, every 10% increase in forest cover will cause about 20% decrease in water treatment costs (USEPA, 2007).

LID also significantly benefits community and environment. As an advanced and eco-friendly strategy, LID coordinates the built environment with the natural environment in a better way (COEC, 2009). The multiple functions created by LID can enhance green neighborhoods, increase recreational opportunities, provide environmental education chances, reduce urban flooding risks, and contribute to higher quality of human life through increasing livability, sense of place, and aesthetics (SMCOG, 2008; COEC, 2009). The hydrologically functional landscape can significantly reduce the amount of pollution, protect stream channel from erosion, cool down water temperature, protect aquatic ecosystems, and preserve sensitive habitat (SMCOG, 2008; COEC, 2009).

2.3 Evaluation of LID Practices

Despite the performance of LID measured in field or laboratory studies, even evaluated by modeling tools, there is no standardized efficacy of LID practices can be used to estimate its performance in all locations (Qin, Li, & Fu, 2013; Lee et al., 2012). The performance of LID practices usually is affected by human activities, watershed scales, and climate conditions, such as snow melting, or rainfall intensities, frequency, and duration (Qin, Li, & Fu, 2013; SMCOG, 2008). Additionally, location, size, and type of LID practices, design method, implementation, and maintenance frequency can also influence on its performance (Qin, Li, & Fu, 2013; Lee et al., 2012; Subhasis, Nejadhashemi, & Woznicki, 2012).

Some studies attempt to use modeling tools to help selection and evaluation of LID practices. After (or By) utilizing Soil and Water Assessment Tool (SWAT) model to evaluate the non-point source pollution reduction by applying several BMPs, Lee et al. (2010) found that vegetated filter strip can reduce 24.8%, 5.4%, and 5.6% for sediment, total nitrogen (TN), and total phosphorus (TP) loading, respectively; while the same situation riparian buffer system would reduce 20.1%, 8.9%, and 9.4% for sediment, TN, and TP loadings, respectively. Another study showed that the placement of LID in the watershed affects the efficiency of the pollution reduction in SWAT model (Subhasis, Nejadhashemi, & Woznicki, 2012). The result represented that the performance of BMPs will be different in vary locations, and native grass and terraces were generally the most effective BMPs in compared to others (Subhasis, Nejadhashemi, & Woznicki, 2012). However, some studies also showed that LID structure may have influences on pollutant concentration, which cannot be forecasted in models (Rao, et al., 2009). Flores-Lo′ pez et al. (submitted for publication) compared both results from laboratory and models, and they found the baseflow phosphorus (P) concentration could decrease by as much as 38%, as cattle crossings were installed, but this result was not shown in model. Rao et al. (2008) found that the dramatic reduction in P levels caused by the installation of the cattle crossing cannot be forecast in Variable Source Loading Function (VSLF) model. Several other models occurred in recent decades to simulate the effectiveness of BMPs, such as the Generalized Watershed Loading Function (GWLF) model, the Spatially Referenced Regressions on Watershed Attributes (SPARROW) model, and the Long-Term Hydrologic Impact Assessment (L-THIA) model (Rao, et al., 2009). However, there is a lack of a comprehensive modeling system available for systematically selection and evaluating the location, type, and cost of LID strategies (Lee et al., 2012).

Other researchers attempt to evaluate the efficient of various types of LID by field and laboratory studies. The performance of Bioretention, Bioswale, and Constructed Wetland for reduction of total suspended soil (TSS), TN, and TP will be reviewed separately in next several paragraphs.

2.3.1 Bioretention

Bioretention, also known as rain garden, has been used as one of BMPs since 1992 (USEPA, 1999). Bioretention utilizes soil and vegetation to attenuate stormwater runoff and remove water pollution from it (Ahiablame, Engel, & Chaubey, 2012). Soil layers contribute to the storage and filtration of stormwater runoff, and plants serve to filter and transpire stormwater runoff (SEMCOG, 2008). Native and perennial plants that resist drought, tolerate saturated soils, and resist insects and diseases are usually cultivated in bioretention (BIAOW, 2013), at the same time, plants that are properly designed add attractive features and enhance aesthetic values in community (SEMCOG, 2008). Rain garden (usually refers to smaller-scale bioretention) can be modified to accommodate small residential and commercial settings, while bioretention can also be used for agricultural water quality improvement or as a part of larger LID series (SEMCOG, 2008; Ahiablame, Engel, & Chaubey, 2012). Graying Stormwater Project, MI, is an example of integrated project that combines bioretention with conventional stormwater management (SEMCOG, 2008). This $1.2 million project includes 86 bioretentions and attempt to eliminate approximately 80% of stormwater pollutions in the future (SEMCOG, 2008).

A large number of studies have well documented the performance of bioretention in laboratory conditions (Hunt et al. 2007; Trowsdale and Simcock, 2010; Chapman and Horner 2010; Ahiablame, Engel, & Chaubey, 2012). These studies usually report high performance of bioretention for removing TSS, TN, and metal pollutants from stormwater. For example, based on the survey conducted by Davis et al. (1997), EPA credited that bioretention can remove 49% of total nitrogen (TN), 65%-87% of total phosphorus (TP), 64%-95% of Zinc (Zn), 70%-95% of lead (Pb), and 43%-97% of Copper (Cu) (USGPA, 2014). Chapman and Horner (2010) also proved that street-bioretention system can filtrate and evapotranspiration about 48% of runoff, and closer to 74% of runoff can retain. Based on the reduction of runoff, they estimate that roughly 87% of TSS, 67% TP, 63% of TN, 86% of Pb, 80% of Cu and Zn, and 92% of motor oil were removed by this system. However, the efficiency of bioretention may be affected by composition of bioretention media and its construction activities (Ahiablame, Engel, & Chaubey, 2012). Hunt et al. (2007) found that the effluent concentrations of TSS, TN, TP, Cu, Pb, and Zn were respectively reduced 60%,32%, 31%, 54%, 31%, and 77% than influent concentrations, which presented a generally lower efficiency of bioretention than other studies. Ahiablame et al (2012) compared several bioretention laboratory studies and concluded that the reduction of sedimentation and nutrition by bioretention systems could range from 0% to 99%. Thus, further studies still needed to figure out the conditions and affecters that would influence on performance of bioretention.

2.3.2 Bioswale

Bioswales (vegetated swale) are broad shallow channels partially provide pretreatment of stormwater and convey stormwater to subsequent BMPs (University of Florida, 2008). Because of these functions, they usually replace or support the conventional curbs and gutters nearby the road (Ahiablame, Engel, & Chaubey, 2012). Pretreatment of bioswale can also improve the pollutant removal efficiency of any other BMPs (SEMCOG, 2008). While check dams of bioswale obtain stormwater volume, grasses, shrubs, and trees slow down, filter, and infiltrate stormwater runoff (SEMCOG, 2008). Bioswale can perform stably in different seasonal conditions, and often be adopted in both urban settings and agricultural environments (Ahiablame, Engel, & Chaubey, 2012).

The efficiency of bioswale swings within a range (Ahiablame, Engel, & Chaubey, 2012; Majed et al, 2004; Abu-Zreig et al., 2001). Ahiablame et al (2012) reported that bioswale could lessen 14% to 98% of nutrients and TSS, and up to 93% of metals. Xiao and McPherson (2011) reported that bioswale could reduce runoff by 88.8% and the total pollutant loading by 95.4%.

The similarly high performance also can be found in other studies: Abu-Zreig et al. (2004) stated that bioswale can reduce 68%-98% TSS; in another article, they found the bioswale could remove TP up to 79% (Abu-Zreig et al., 2003). However, Vertraeten et al. (2006) reported that because of the overland flow convergence and catchment scale, the sediment reduction is only 17% when adopted riparian bioswales at the riverside. Some studies pointed out that this range could result from variable sedimentation processes, swale length, slope, vegetation density, and water residence time in bioswale (Ahiablame, Engel, & Chaubey, 2012; Mazer, Booth, & Ewing, 2001; Abu-Zreig et al., 2004).

2.3.3 Constructed Wetland

With the increasing human population and urban sprawl, natural wetlands are gradually damaged by human activities to satisfy the demands of economic development. A study shows that around half of natural wetlands have disappeared due to human activities all over the world since 1900 (OECD, 1996), and this loss of natural wetlands caused markedly negative impacts on water birds habitats and aquatic ecosystems (Van Zant, 2005). In Michigan, the total wetlands area was up to 11 million acres in the past, however, the number of that degrades to 3-5 million acres; because of the deterioration of soil properties, hydrologic regime, and vegetation, only one-quarter of the original 100,000 acres of coastal wetlands remain (SEMCOG, 2008). As one of important components of these artificial habitats, constructed wetlands can provide a synthetical method for stormwater management as well as waterbirds conservation.

Constructed wetlands are artificially multi-functional stormwater treatment systems, which provide open spaces, natural beauty, and habitats for wildlife and human beings (SEMCOG, 2008). Comprising of shallow/deep mush ponds, channels, micro-pool, aquatic vegetation, and soil, constructed wetlands have been extensively utilized to treat nonpoint source pollutants, such as urban runoff, agricultural pollution, and acid mine drainage (USEPA, 2000b). Constructed wetlands include two classifications, which are subsurface flow (SSF) system and free surface flow (SF) system, and both of them use emergent/submergent plants to enhance the control of stormwater pollutions (USEPA, 2000b). Besides the selection of aquatic plants, pond size, shape, temperature, loading, and vegetation also can influence on its performance (Iowa Department of Natural Resources, 2007).

Constructed wetlands also show an unstable performance in many studies. In the observation study of constructed wetland, Birch et al. (2004) claimed that the removal efficiency of TSS ranged between -98% and 46%, and the removal efficiency of TP and total kjeldahl nitrogen (TKN) were 12% (range -14% to 39%) and 9% (range -34% to 58%). These results are supported by other investigators (Grismer et al., 2003). Grismer et al. (2003) found that chemical oxygen demand removal rates ranged from 49% to 79%, while tannin removal ranged from 46% to 78%, and the greater removal rates occurred during the spring non-crush period. High effectiveness of constructed wetland is also observed in many studies (Mashauri, 2000; Borin and Tocchetto, 2006). Mashauri (2000) reported the high removal efficiencies of constructed wetland: 80% for TSS, 66% for chemical oxygen demand (COD), 91% for faecal coliforms (FC) and 90% for total coliforms (TC). Borin and Tocchetto (2006) also declaimed that constructed wetland could remove up to 90% TN. The amount of pollutants removed by aquatic systems was also measured in some studies (Sim et al., 2008; Zimmels Y. et al., 2004; Oporto et al., 2006). Sim et al. (2008) figured out the efficiencies of various aquatic plants used in constructed wetland to remove nutrition pollutants. In their report, the Common Reed from the constructed wetland system could reduce 42.1%TKN and 28.9% P, while Tube Sedge could reduce 26.1%TKN and 17.4% P (Sim et al., 2008). Zimmels Y. et al. (2004) stated aquatic plants could improve smell, pH, and turbidity in a short time by its high sorption ability and high rate of reproduction and floating capability. Moreover, they suggested using cascade or stepwise treatment process to increase the ability of turbidity in this system.

2.3.4 Conclusion

In conclusion, from the reviewed materials above, it is easy to find that the efficiency of LID can be affected by a large number of factors. The performance of BMPs is unstable and should be discussed case by case. Moreover, few investigations have explored the efficiency of LID performance in Michigan, thus, further studies are needed in this subject area.

CHAPTER 3 METHODOLOGY

3.1 Site Description

3.1.1 Site Selection

The site selected for this project is located in riverside of the City of River Rouge, Michigan, close to the confluence of Rouge River and Detroit River. The total area of River Rouge is 3.24 square miles, which consists of 2.65 square miles of land and 0.59 square miles of water. Currently, land use in this city is primarily industrial occupation, high and medium residential development, and scattered commercial enterprises (Hyde, 2013). This site belongs to the largest watershed in Southeastern Michigan, which contains 404 lakes and ponds in the basin ranging in sizes from less than an acre to 670 acres (Beam, & Braunscheidel, 1998). Due to the industrial pollution and nonpoint source pollutants carried by runoff, over fifty fish species, ninety birds species, as well as plenty of mammals and aquatic invertebrates lived in this watershed are threatened by decreasing water quality. According to Beam and Braunscheidel (1998), the Water quality ranged from poor to slightly better than poor in this most downstream stretch before entering the Detroit River, and the poor water quality is mainly caused by the excessive level of nutrient (total phosphorus), dissolved oxygen, and bacteria. Besides flooding risk, protecting water quality of Rouge River and Detroit River is of most priority and has great importance to fish population, riparian habitat, and human contact (Beam, & Braunscheidel, 1998). Thus, the water pollution problem urges the researches of stormwater management strategies. These problems also make this site an excellent location to be studied. Other reasons for choosing this site are mentioned by Hyde (2013):

> "…The site also happens to be located along one of the world's largest freshwater coastal marshes, the Lake St. Clair and Lake Erie system. Much of this important ecosystem was destroyed by human settlements and agriculture within the region. Destruction continues today through development and water pollution."
>
> "…Size was another determining factor of site selection. To accomplish successful restoration of a coastal wetland, significant land area is necessary. A large area is also necessary to implement the stormwater management techniques used in this study. This site is approximately 1,000 acres in size."
>
> "…The City of Detroit and its suburbs are in drastic need of revitalization projects to retain and attract residents, especially River Rouge. Projects of a similar nature have been occurring recently along the Detroit River, making this project ideal for creating habitat corridor linkages. Lastly, this location was chosen based upon its convenience for the researcher as the area is very familiar." (Hyde, 2013)

Figure 1 showed the location of this project.

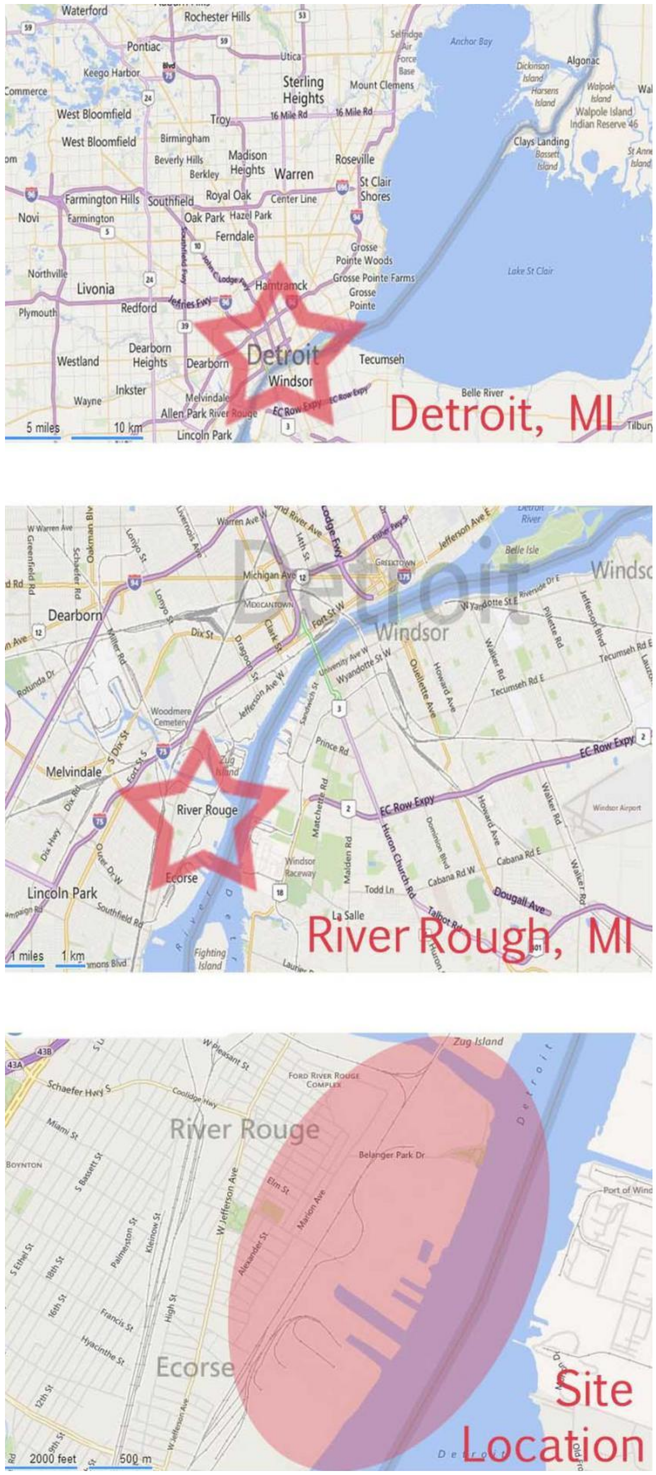

Figure 1. Selected site location (Bing data; revised).

3.1.2 Design Description

The location, topography, facilities, and landscapes utilized in this thesis are all based on Hyde's design. The original site of this project is industrial land, and the original topography is rather flat (Hyde, 2013). In contrast to current condition, in Hyde's thesis, this site is designed as a river-adjacent and mixed use green zone to prevent urban sprawl, promote sustainability, restore natural quality, protect biodiversity, manage quality and quantity of stormwater, and rebuild both natural and artificial wetlands (Hyde, 2013). Based on the concepts of biophilia, sustainability, new urbanism, green urbanism, smart growth, and LID strategies, Hyde (2013) attempted to "…investigate the relationship between human and non-human (natural) ecosystems within an urban residential environment…and how they can be better integrated…."

It is important to notice that several fractal-like patterns are used repetitively throughout the site (figure 2). Each pattern in Hyde's design is a function unit including mixed-use areas, residential areas, commercial areas, stormwater treatment strategies, open spaces, closed wetlands, and open wetlands. Redeveloped road network and public transportation systems connect within and between these patterns. "With the aid of light-rail, efficient bus routes, car-shares, and bike-shares, River Rouge could take advantage of the local connections and attract a significant population increase." (Hyde, 2013)

Figure 2. Master plan of Hyde's project.

The concept of repeatedly fractal-like patterns also is reflected in the coastline design at this site. The natural coastline was transformed into several repetitive curve gulfs, and each gulf connects directly with an open wetland. The curve gulf can prevent coast wetlands from tide erosion and water pollution of Detroit River, at the same time provide great recreational opportunities for residents. The functions of these curve gulfs are also mentioned by Hyde (2013): “this fractal coastline was essential in restoring the wetlands that once existed on site, and protecting them from rough river conditions…The decision to shape the coast in this manner also remedies part of the problem of the post-industrial soil.”

Because of the repeated fractal-like patterns, this project can be divided into three parts geographically. Each part are grouped by similar functions, land uses, building types, hydrology, landscapes, and LID strategies. To simplify our research, this thesis only chooses one area of this site to: (1) explore LID strategies utilized in Hyde’s design; (2) estimate the efficiency of LID strategies based on the reduction of phosphorus in stormwater runoff; (3) provide valid options of LID strategies for this design. The chosen site is shown in figure 3.

Figure 3. Selected pattern for LID study (uncovered part is the site chosen for this thesis).

Figure 4 presents the land uses of this part. Red dash lines are the boundary of the selected site. Yellow blocks represent residential uses and open spaces between buildings. These areas are intended as high residential development areas with seven or more dwelling-units per acre, and each residential block is bounded by open space mimicking natural landscapes (Hyde, 2013). Pure commercial buildings and mixed-uses land (Orange blocks) are located at the western edge of this site. These mixed-use areas employ/utilize traditional urban landscapes (Hyde, 2013). Several heavily forested parks and wetlands (green blocks), scattered in western and northern edges of this site, provide green spaces and recreational opportunities for the residents, while restoring the habitat for wildlife (Hyde, 2013). Two proposed filtration channels (blue line) are also shown in figure 4, one is located in the middle of residential areas and terminates at the large Riverview Plaza, and another one traverses a forest and connects with the coastal wetland.

Figure 4. Original Land Use in Hyde's Design.

3.1.3 Hydrology

The topography of the peninsula is designed like a funnel, with a higher elevation in edge of its coastline while lower elevation in the central area. Instead of pouring directly into river, stormwater can slowly concentrate from the peninsulas toward the collection pond located in mainland through terraced filtration channels (Hyde, 2013). Figure 5 presents the hydrology schematic designed by Hyde (2013). Several tanks and treatment pools also proposed by Hyde (2013). However, considering their small surfaces, tanks and treatment pools merely contribute to quite micro-scale watershed and make little difference to the stormwater treatment of entire site. Therefore, it is assumed that the effects of these tanks and treatment pools are close to zero for the entire site and can be ignored in this thesis. Additionally, because the stormwater should be cleaned before discharging into the wetlands and the river (Hyde, 2013), it is assumed that the stormwater runoff of the entire site should be fully treated by filtration channels.

Figure 5. Hydrology Schematic Designed.

3.2 Identification of Filtration Channels

Hyde (2013) used the term of “filtration channel” to describe the LID strategy utilized in his project, and the structure and function of this “filtration channel” were presented as: “sitting within or strolling between the residential blocks users will be exposed to the stormwater treatment process through a sequence of artificial wetlands.” Hyde described the treatment stages of “filtration channel” as “water cascades for aeration, and a wetland of plants selected to remove heavy-metals”, and then [xx is/are] “followed by the pathogen removal terraces” (Hyde, 2013). However, “filtration channel” is not a specific term in LID. There is no corresponding category for it. This blur of “filtration channel” will cause difficulties when estimating its efficiency and application in reality. Thus, this study will find the closest LID strategy to integrate this design to his design. If the LID strategy adapts to the project ecologically well, it will be used to estimate the efficiency; whereas, other LID strategies, which are similar to Hyde’s description, will be recommended for this project to seek a higher efficiency of pollutions removal.

According to the term “artificial wetlands” and the description above, the “linear wetland swale” of LID is the closest LID strategy to this linear, small-scale and planted “filtration channel”. Linear wetland swale is a smaller constructed wetland that can provide runoff filtering and treatment during the conveyance process. It cannot reduce quantity of runoff because of the lack of infiltration and retention process. Normally, a constructed wetland must serve a drainage area of at least 10 acres and need a constant inflow to maintain its biological health (SEMCOG, 2008). Comparing to normal constructed wetlands, linear wetland swale serves for smaller drainage areas (not exceed 5 acres), and is utilized in the high water table of the coastal plain

(SEMCOG, 2008). However, there are three limitations to apply the linear wetland swale into this project. First, the linear wetland swale is commonly used in small drainage areas, while the drainage area in this project is up to over 300 acres. Second, in this project, the linear wetland swale locates in a residential area, but usually the linear wetland swale is not utilized in residential or commercial settings because this permanent shallow pool may become a potential area for mosquito breeding ("Grassed Swales," 2014). Third, the linear wetland swale is commonly constructed near the water table and intersects shallow groundwater to maintain a plant community (SEMCOG, 2008). As mentioned before, the topography of this peninsula is designed like a funnel, with a higher elevation of its coastline edges and lower elevation in the central area, which means the bottom of this linear wetland swale should avoid reaching the water table. In other words, this linear wetland swale lacks a permanent water source to maintain its biological health. Therefore, because of the large drainage area, neighborhood contexts, and the topography of this site, it is not appropriate to apply linear wetland swales in this project.

Consider to the shape, slope, vegetation condition, neighborhood setting, and topography of the site, two highly similar LID strategies, bioswale and bioretention, are recommended to replace linear wetland swales. At the same time, because the drainage area is over 100 acres and a large volume of runoff need be treated, a third option is also proposed to enhance the overall efficiency. In this option, open natural wetland could replace a constructed wetland. Stormwater runoff will firstly flow to bioswale/bioretention, then be treated in constructed wetland and be cleaned up before discharging into the gulf. Thus, four treatments will be estimated in the following section: (1) stormwater runoff is treated by bioswale; (2) stormwater runoff is treated by bioretention; (3) stormwater runoff is treated by bioswale and constructed wetland (in a series); (4) stormwater runoff is treated by bioretention and constructed wetland (in a series). The locations of bioswale/bioretention and constructed wetland are shown in figure 6.

Figure 6. Locations of Bioswale/Bioretention and Constructed wetland.

3.3 Calculations

3.3.1Calculating Runoff

Runoff curve number method, sometimes referred as Technical Release 55 (TR-55) is perhaps the most widely used method in the United States to calculate the total volume of stormwater runoff. It is first developed by Soil Conservation Service (SCS) in 1975, and then incorporates current SCS procedures (Cronshey, 1986). It particularly can be used urbanizing watersheds and small watersheds. In this method, stormwater runoff is calculated by following equation:

$$Q = \frac{(P-0.2S)^2}{(P+0.8S)} \qquad \text{(Equation 1)}$$

Where:

Q = runoff volume (in.)

P = rainfall (in.)

S= potential maximum retention after runoff begins (in.)

S is determined by the soil types and cover conditions of the watershed, and can be represented by the runoff curve number (CN):

$$S = \frac{1000}{CN} - 10 \qquad \text{(Equation 2)}$$

Therefore, runoff volume (Q) dependent on two variables: rainfall (P) and runoff curve number (CN).

Rainfall (P) relates with location, frequency, and duration of stormwater events. This site locates in Wayne County, and belongs to zone 10 of Michigan (SEMCOG, 2008). The seasonal distribution of precipitation in this region is fairly even, and the annual rainfall of this site is on average of 31.33 inches (Beam & Braunscheidel, 1998). According to the design criteria, LID strategies are required to treat 2-year storm event and completely drain out runoff within 48 hours (SEMCOG, 2008). Thus, the rainfall intensity used for this calculation is a 2-year, 24-

hours event in zone 10, Michigan (SEMCOG, 2008). Based on the data of Rainfall Frequency Atlas in the Midwest, rainfall (P) of 2-year, 24-hours duration in zone 10 is 2.26 inches (SEMCOG, 2008).

CN are determined by land cover type, hydrologic condition, antecedent runoff condition (ARC), and hydrologic soil group (HSG) (SEMCOG, 2008). To adjust CN into this project, cover types and hydrologic soil group (HSG) of this site are particularly needed. HSG of this site is group C, and this kind of soil has a slow infiltration rate (*Rogue River Watershed Project: Rogue River Watershed Management Plan*, 2000). Based on Hyde's design and TR-55, this site can be separates/divided into five cover types: urban districts for commercial or business uses, residential districts with average lot size more than 1/7 acre, road area, forests in good condition, and water bodies. According to TR-55, the curve number of soil group C of urban district (commercial or business uses), residential districts (average lot size is 1/7 acre or more), impervious road areas, forests (with good condition) are 94, 90, 98, and 74, respectively.

Total stormwater runoff can be calculated using following equation:

$$V = Q*A*28.317 \qquad \text{(Equation 3)}$$

Where:

V = runoff volume (L)

Q = runoff volume measured by depth (In.)

A = surface area of different types (sf.)

Table 1 shows the rainfall intensity, hydrologic soil group, surface areas of different cover types, runoff volume from different cover types, and total runoff volume. Based on the calculation, runoff volume from urban districts, residential districts, forests, and roads, are about 52 million liters, 29 million liters, 20 million liters, and 56 million liters, respectively. The total runoff volume from this site is about 157 million liters.

Wayen County	2-year, 24-hours rainfall (in.) is 2.26 inches				
Hydrologic Soil Group is C					
Site Conditions	Urban Districts	Residential Districts	Forests	Roads	Total
CN	94	90	74	98	
Area (sf)	1121215.83	774596.54	1440486.68	973451.29	4309750.34
S (In.)	0.64	1.11	3.51	0.20	
Q (In.)	1.64	1.32	0.48	2.03	5.470
Runoff Volume (L)	52099204.6	28930670.07	19500246.53	56017362.27	156547483.5

Table 1. Runoff Calculation Results

3.3.2 Calculating Phosphorus Loadings

According to the survey conducted by US EPA in 1998, 35% of stream samples were found severely polluted, and 30% of them were mainly resulted from excessive nutrient loading (Faucette, 2011). Water quality degradation caused by nutrient is an increasingly common in recent years. Phosphorus (P) is one of the parameters commonly used to indicate the nutrition level and water quality (Beam, & Braunscheidel, 1998). Generally, the lower the total phosphorus loading in the water represents, the better water quality is. P is in very small amount in natural water bodies and, normally, will not cause harms to humans and aquatic organisms. However, due to urbanization and agricultural developments, overmuch P entering the surface water through stormwater runoff can elicit a rapid growth of algae, lessen dissolved oxygen, and cause fish and other aquatic organisms to suffocate and ultimately die. This process called eutrophication. Jon Burley stressed that this process could be calculated and predicted, and applied Carlson Index for Pelican Lake in the Ottertail Watershed, Minnesota (Burley, 1989). Moreover, property land-use forms and sensible management techniques can greatly retard this process (Burley, 1989).

In order to monitor stormwater quality throughout the country, a long-term stormwater quality data survey was conducted by Dr. R. Pitt of the University of Alabama and the Center for Watershed Protection in 2001. The National Stormwater Quality Database (NSQD) released in 2011 from this organization explicitly analyses the urban stormwater runoff characterization in various land uses, states, and EPA Rain Zones. At the time of writing in 2014, this database can be expected as the most reliable and specific source to estimate the phosphorus loadings in Detroit area.

This database contains data collected over a 10-year period from more than 8500 events in nationwide (The National Stormwater Quality Database, 2011). Separated by EPA Rain Zones, stormwater characteristics (TSS, TKN, TP, Cu, Zn, and fecal coliforms) are collected and summarized for each zone (The National Stormwater Quality Database, 2011). Significantly, Detroit happens to be one of the monitoring locations in zone 1, and the data collected from Detroit can highly reflect the stormwater quality of Hyde’s project. According to the total phosphorus (TP) concentrations for different land uses in this database, TP concentrations vary from 0.18 mg/L to 0.40 mg/L. Combined TP concentrations with runoff from different cover areas, it is simple to achieve the total phosphorus concentration through the following equation:

$$C = \frac{M}{V} \qquad \text{(Equation 4)}$$

Where:

C = phosphorus concentration (mg/L)

M = mass of phosphorus (mg)

L = volume of stormwater runoff (L)

Table 2 reflects the P loadings from various land uses, TP, and average phosphorus concentration in this site. According to NSQD, the phosphorus concentration from commercial areas is on average of 0.25 mg/L, and from residential areas and open spaces are on average of 0.40 mg/L and 0.18 mg/L, respectively. Thus, the total phosphorus load in this site is about 17.7 kg, and the TP concentration in the effluent is about 0.157 mg/L.

Two year, 24 Hours Rainfall				
Land Use	Commercial Area	Residential Area	Open Space	Total
Runoff Volume (L)	70771658.69	47603124.16	38172700.62	156547483.5
Total Phosphorus Concentrations (mg/L)	0.25	0.4	0.18	0.157
Total Phosphorus Load in Each Land Use (mg)	17692914.67	19041249.66	6871086.112	24564000.78

Table 2. Total phosphorus load, and average phosphorus concentration in this site.

Nutrient enrichment accompanies by a high P level, and 1.0 mg/L of P is the trigger leading to eutrophication (Faucette, 2011). In most unpolluted national streams, P loading ranges from 0.05mg/L to 0.1 mg/L (Flint River GREEN Notebook, 2011). According to the EPA water quality standard, for a river that flows into a natural lake or a reservoir, the P loading should not exceed 0.05 mg/L, and the phosphorus to the natural lake should be less than 0.025 mg/L. Whereas, for a river that does not flow into a lake, P should be controlled within 0.1 mg/l (Beatty, 2001). However, contrary to the small number required by EPA, in rule 60 of the Michigan Water Quality Standard, phosphorus concentration only requires to be within1.0 mg/L (Beatty, 2001). This standard recently has been concerned to be too loose to control water quality in Detroit River, which already caused the severe eutrophication in the downstream and Lake Erie (*Survey of States, Tribes and Territories Nutrient Standards*, 2003). Therefore, this study chooses the standard credited by EPA, and the phosphorus concentration of runoff should be controlled within 0.05 mg/L. Based on EPA water quality criteria, it is easy to conclude that this design will cause a high phosphorus loading rate (0.157mg/L). The onsite TP concentration of a

2-year, 24-hours storm event will exceed the baseline of 0.05 mg/L and may lead to the eutrophication if the stormwater flows directly into Detroit River. Moreover, this project needs LID strategies to treat stormwater runoff.

3.3.3 Estimating LID Efficiency

The simple method is to predict storm pollutant export and estimate pollutant load removed by each BMPs. In this method, the post-development load of total phosphorus, the average BMP removal rate, and the drainage area served are needed in the equation:

$$LR = (Lpost)\ (BMP_{RE})\ (\%\ DA\ Served) \qquad \text{(Equation 5)}$$

Where:

LR = Annual total phosphorus load removed by the proposed BMP (lbs/year)

Lpost = Average annual load of total phosphorus exported from the post-developmentsite prior to development (lbs/year)

BMP_{RE} = BMPs removal efficiency for total phosphorus (%)

% DA Served = Fraction of the drainage area served by the BMP (%)

BMP_{RE} has been measured by many organizations and researchers in the United States. However, the efficiency of BMPs varies in different locations and surface conditions. Choosing valid data to estimating the efficiency of BMPs is an essential part of this calculation. In this thesis, the average BMPs phosphorus removal rates are from the report of *Stormwater Best Management Practices (BMP) Performance Analysis* prepared for EPA. This report presents a long-term performance curves for BMPs. These satisfying results collected from real examples were also inter-proved by EPA's Storm Water Mangement Model (SWMM) and BMP Decision Support System (BMPDSS). These comprehensive resources may promise the accuracy of BMPs efficiency. In EPA's report, the average TP removal rates relate to various land use types and the depth of runoff treated. Therefore, the particular efficiency of BMP that is suitable for this study area can be chosen for this study. The majority of this site is commercial land.

Additionally, because of the large drainage area in this site, the depth of runoff treated is assumed to be 2.0 inches for peak flow of the 2-year, 24-hour storm events. Therefore, according to EPA's report, the phosphorus removal rates are 89% of bioretention, 36% of bioswale, and 66% of constructed wetland.

Post-development phosphorus loading is determined by rainfall depth, runoff coefficient, land use conditions, the average phosphorus concentration, and the surface areas of the development site. Lpost can be calculated by following equation:

$$L_{post} = (P)\,(R_v)\,(C)\,(A)\,(0.20) \qquad \text{(Equation 6)}$$

Where:

Lpost = Average annual load of total phosphorus exported from the post-development site (lbs/year)

P = Rainfall depth over the desired time interval (inches)

Rv = Runoff coefficient, which expresses the fraction of rainfall which is converted into runoff = 0.05 + 0.009(Ipost)

Ipost = Post-development (proposed) site imperviousness (i.e., I = 75 if site is 75% impervious)

C = Flow-weighted mean concentration of the pollutant (total phosphorus) in urban runoff (mg/l)

A = Area of the development site (acres)

*0.20 is a regional constant and unit conversion factor

The annual rainfall depth in Detroit is over 31.33 inches. The imperviousness area is about 53.3% of this site, thus, the value of Ipost is 53.3. Runoff coefficient of this site is 0.53. The mean concentration of the total phosphorus during 2-year, 24-hours rainfall event in this site is 0.157 mg/L. The total surface area of this site is 105.73 acres. Therefore, utilizing these values into the equation 6, the average annual load of total phosphorus (Lpost) exported from this site is 55.13 lbs/year.

Fraction of the drainage area served by the bioswale or the bioretention (% DA Served) is 2.7%. Therefore, the two treatments of a single BMPs process can be estimated via equation 5. Table 3 shows the annual total phosphorus load removed by the proposed bioswale and bioretention (treatment 1 & 2).

BMP Group	Bioswale (Treatment 1)	Bioretention (Treatment 2)
Average TP Removal Rate (%)	36%	89%
Annual Removed Phosphorus LR (lbs/year)	0.54	1.32

Table 3. Annual total phosphorus load removed by each BMP.

Considering the treatment 3 and 4, the efficiency of BMPs in series should be calculated in a different way, another equation is utilized to calculate the overall efficiency of it:

$$R = L\ [(E1)+(1- E1)E2+(1-((E1)+(1- E1)E2)E3+\ldots] \qquad \text{(Equation 7)}$$

Where:

R = Pollutant Removal (lbs/year)

L = Annual Load from Simple Method (lbs/year)

E_i= Efficiency of the i^{th} practice in a series

Equation 7 can be used for estimating two treatments of BMPs series. In these two conditions, the fraction of the drainage area served by the filtration channel and constructed wetland (% DA Served) is 50%. Table 4 shows the results from the two treatments.

BMP Group	Bioswale & Constructed Wetland	Bioretention & Constructed Wetland
Annual Removed Phosphorus LR (lbs/year)	43.13	53.07

Table 4. Annual total phosphorus load removed by BMPs series.

CHAPTER 4 RESULTS

According to the calculations, total runoff volume from this site is about 157 million liters, and the annual phosphorus load in this site is 55.13 kg. Before being treated, phosphorus concentration contained in the runoff is 0.157 mg/L, which exceeds the EPA standard (0.05 mg/L). This may lead to the eutrophication, if the stormwater flows directly into Detroit River. After being treated by LID strategies, results of four treatments are separately shown as following:

Treatment 1. Bioswale is the only BMPs used to treat stormwater runoff in this watershed. The phosphorus removal rate of bioswale is assumed to be 36%. 0.54 lbs phosphorus can be removed from runoff per year, which is 0.97% of the annual total phosphorus exported from this site. After flowing through bioswale, the total phosphorus concentration decreases to 0.155 mg/L, which is still higher than the EPA's water quality standard (< 0.05 mg/L). In other words, this polluted stormwater only flowing through bioswale should not directly circulate to the open wetland and river.

Treatment 2. This treatment uses bioretention to treat stormwater, thus stormwater runoff ought to be purified before it reaches the open wetland. Bioretention can remove 89% of the phosphorus when the depth of treated runoff is 2 inches. After treated in bioretention, 1.32 lbs phosphorus can be removed from runoff per year, which is 2.4% of the annual total phosphorus exported from this site. However, the treated water still has a high phosphorus concentration

(0.153 mg/L), which exceeds the baseline of 0.05 mg/L, and the runoff cannot discharge directly into the open wetland and river.

Treatment 3. When an open wetland in this site is changed to constructed wetland, it is assumed that stormwater runoff should be treated in a series: first bioswale, then constructed wetland. The high phosphorus level in stormwater should reduce to a normal level before runoff flows into river. Bioswale and constructed wetland in this site can help reduce 43.13 lbs phosphorus from runoff per year, which is 78.2% of annual phosphorus load. The phosphorus concentration obviously decreases to 0.034 mg/L, which means the treated stormwater can discharge into Detroit River after treated by constructed wetland with limited potential of eutrophication.

Treatment 4. In this treatment, stormwater runoff will be treated in a series: first bioretention, then constructed wetland. This series BMPs can reduce 53.07 lbs phosphorus per year, which is 96.3% of the annual phosphorus load in this site. With this removal rate, the final phosphorus concentration will be 0.005 mg/L. The small number indicates that bioretention and constructed wetland work excellently when combine them together.

In summary, the different elements in four treatments include: BMPs types, sequence of BMPs, and drainage area served by BMPs. According to the results of four treatments, treatment 1 and 2 make little differences on phosphorus removal, and the phosphorus concentrations in runoff still exceed than the requirement of EPA. Thus, these are two ineffectual approaches for this site. Treatment 3 and 4 work well for phosphorus removal, and after treated by BMPs in a series, the phosphorus concentrations in runoff perfectly meet the requirement of EPA.

Therefore, treatment 3 and 4 are recommended for this site to manage stormwater runoff. Table 3 summarizes the results of four treatments.

Treatment	Removal Annual P (lbs)	TP removal rate (%)	P concentration in treated water (mg/L)
1. Bioswale	0.54	0.97	0.155
2. Bioretention	1.32	2.4	0.153
3. Bioswale & constructed wetland	43.1	78.2	0.034
4. Bioretention & constructed wetland	53.07	96.3	0.005

Table 5. Comparison of four treatments.

CHAPTER 5 DISSCUSSION

In Hyde's design (2013), phosphorus concentration contained in runoff (0.157 mg/L) exceed the EPA standard (0.05 mg/L). Therefore, the original design that treats the runoff only by a single BMP is not valid, and adjustment is needed for his design. This adjustment can be, but not limited to, BMPs in series shown in treatment 3 and 4. Comparing treatment 3 and 4 with the other two, BMPs in series obviously have a higher efficiency than any single BMP. It is probably because the pre-treatment process accomplished by the first BMP can enhance the entire performance of BMPs. Pre-treatment can easily reduce the overloads of pollutants, especially for reducing sediment, and decreases the erosion caused by high velocity of inflow. Thus, choosing the BMP that contains pre-treatment process increases its efficiency. In addition, the efficiency of BMPs has a correlation with pollutants' concentration, and the efficiency of the second BMP (in a series??) will decrease because of lessened pollutants' concentration (Burack, Walls & Stewart, 2008). Thus, the efficiency of BMPs in series is not equal to add two efficiencies of each BMP together.

In treatment 1 and 2, although there has a large gap between the efficiencies of bioswale and bioretention, they both make little difference to the entire phosphorus loading. It is probably caused by the large drainage area of this site. This result is also reflected in equation 5, the fraction of drainage area served by BMPs is an essential parameter, which indicates the area ratio of BMPs to entire project. Thus, it may not be physically possible to treat the large site with one BMP. The results may become better if dividing this large watershed into several smaller subareas for treatments. Moreover, the size of BMPs (treated runoff depth) is another parameter influencing on the efficiency of BMPs. According to the curve represented by EPA (2010), the performance of BMPs will enhance with increasing treated runoff depth. The treated runoff depth chosen for this study is an assumption based on the precipitation conditions and local standards and may not reflect the real situation. Hence, when be used in practices, the size of BMPs should be considered if there is a requirement of BMPs' performance.

From the factors used in the equations, it also can be found that several physical constraints potentially impact on the performance of BMPs in this project, such as soil types, impervious cover, and water table. The impact of soil types can reflect in runoff curve number and infiltration rates. Impervious cover level associated with soil types directly influences on total runoff volume. It also contributes to a higher concentration of several specific pollutants and markedly reduces the local water quality. The mean total suspended solid (TSS) will be significantly higher in industrial land than other land types, and recreational land will significantly lead to a higher concentration of Escherichia coli and enterococci (Stein, Tiefenthaler, & Schiff, 2008). Water table is another inevitable physical constraint that should be considered in this project. Again, the original BMPs designated for this project is linear wetland swales, and generally linear wetland swale are installed in coastal areas and plains areas. However, taking the specific topography of this site into account, the performance of linear wetland swale will be seriously affected without intersecting into water table in practice. Ground water can provide constant water source for wetland plants to maintain its aquatic system. Thus, the linear wetland swale is inappropriate to be utilized in this site.

Long-term performance of BMPs is affected by the intensity, duration, and frequency of storm events. A higher efficiency usually is achieved in smaller storm events by the same BMPs, probably because BMPs are designed to operate larger events than the average level. At the same time, rainfall depth over the desired time interval is an important fraction in equation 5 and equation 6, which influence the total phosphorus load and indirectly impact on the performance of BMPs. Therefore, BMPs project should take into account the precipitation condition.

As discussed above, there are many factors influence on the performance of BMPs. Physical constrains and hydrology conditions are the basic elements when selecting the type and size of BMPs. Some factors in equations can reflect the proper ways to adjust performance of BMPs to meet assigned objectives. Besides simple method, other practical methods estimate the efficiency of BMPs in series. Although not discussed in this study, the factors occurred in these methods should also be considered for chasing a better performance of BMPs.

5.1 Limitations

The efficiencies of three BMPs in this study are based on the EPA credited material. However, limited by the different locations and hydrology conditions, these efficiencies probably cannot reflect their exact efficiencies in practice. As mentioned in Chapter 2, the efficacy of BMPs occurs in a range, and there is no universal standard for it. It is certain that the efficacy of BMPs assumed in this study will not be inaccuracy unless measuring it after practicing. Therefore, the results of the study are based on another assumption that the mean value shown in EPA’s material can direct a mean performance in common situations.

The inaccuracy may occur in the calculation process, as the rainfall intensity are measured ages ago. This data is reported in *Low Impact Development Manual for Michigan* (2008), and authors of this book believe that it is the most reliable source of rainfall frequency data until 2008. However, this data was measured in 1992, and may not reflect the up-to-date precipitation conditions on this site. Additionally, the equations used in this study are based on other resources, and their validities are not examined for this particular study. Based on the above uncertain variables? , these equations cannot be the most effective method to calculate phosphorus level.

The results are limited by the BMPs types chosen for this project. The results can only reflect the performance of bioswale/bioretention tested by this method. Other BMPs may achieve a better performance for phosphorus removal, for instance, filtration trenches have a 100% of phosphorus removal rate. The study could be more accurate if the quantity of BMPs is larger, with a low, medium, and high efficiency and various combinations.

Additionally, extreme weather conditions are not considered in this study. Some BMPs, such as constructed wetland and linear wetland swale, will be affected by dry weather, because there is little or no baseflow in them to maintain their plants' ecosystem. For bioretention, bioswale, and buffers, cold weather may cause a lower performance because of the decrease of plant density and capacity. Thus, weather conditions and adaptable plants should be explored in further BMPs researches.

Finally, the water quality is evaluated via phosphorus concentration required by EPA, however, besides phosphorus and other pollutants, such as TSS, TN, TKN, Cu, Zn, and Pb, should also be used to measure water quality. Thus, more pollutants and water standards need to be explored in further studies.

5.2 Recommendations

For designers and developers, the practicability and validity of BMPs should be taken into account in early stage. It is necessary to check the land use as well as physical and hydrology conditions for the (study) site before selecting BMPs. Designer and developers should clarify the federal, states, and local regulations for both water quality and LID strategies. Then based on these regulations, they can set up a target for BMPs. This target can help adjusts the size, location, and efficiency of BMPs and reduce further maintenance and cost.

For governors, the water quality standard in Michigan is too “loose”. This standard has been proved to indulge excessive phosphorus discharging into rivers and result in the eutrophication in downstreams of Detroit River and Lake Erie. Comparing with other states and EPA, the water quality standard in Michigan states is too general. There is no specific standard to separately control the industrial outflow and stormwater drainage outflow. Thus, more “tight” and specific water quality standards should be laid down in Michigan.

5.3 Conclusions

LID strategies can be broadly used to improve stormwater quality and alleviate the negative impacts caused by urbanization. This strategy can effectively reduce pollutants load, recover natural water regime, and significantly enhance livability, sense of place, and aesthetic in community level. However, because of the unclear calculation steps, LID strategies usually are misused by many designers, especially college students. Thus, this study demonstrates an integrated method to estimate the efficiency of BMPs, and presents a simple and quick calculation system for designers to test their design plan of BMPs.

Based on Hyde's design, four treatments with different BMPs types are tested in this study. The results of this calculation system indicate that the original design of Hyde (2013) is not valid, and adjustments are necessary. Moreover, factors that influences on this result are explored in this study, and other two valid plans have been tested by this method and can be used for further adjustments.

This study also points out that the existing water quality standard in Michigan is too loose, and decision-makers should revise this standard from a sustainable perspective. A general procedure of selecting and adapting BMPs for designer and developers is also illustrated in this study, which can help designers reduce further errors from the primary stage. Thus, this study would serve as a good guide for designers to select, adjust, and apply BMPs in practice.

APPENDIX

APPENDIX: CALCULATION RESULTS

$$S = \frac{1000}{CN} - 10 \qquad \text{(Equation 2)}$$

	CN	S (In.)
Urban Districts	94	0.64
Residential Districts	90	1.11
Forests	74	3.51
Roads	98	0.20

Table 6. Results of Equation 2.

$$Q = \frac{(P-0.2S)^2}{(P+0.8S)} \qquad \text{(Equation 1)}$$

	P (In.)	S (In.)	Q (In.)
Urban Districts	2.26	0.64	1.64
Residential Districts		1.11	1.32
Forests		3.51	0.48
Roads		0.20	2.03

Table 7. Results of Equation 1.

$$V = Q*A*28.317 \qquad \text{(Equation 3)}$$

	Q (In.)	Area (sf)	Runoff Volume (L)
Urban Districts	1.64	1121215.83	52099204.6
Residential Districts	1.32	774596.54	28930670.07
Forests	0.48	1440486.68	19500246.53
Roads	2.03	973451.29	56017362.27
Total	5.470	4309750.34	156547483.5

Table 8. Results of Equation 3.

$$C = \frac{M}{V} \qquad \text{(Equation 4)}$$

	Runoff Volume (L)	Phosphorus Concentrations (mg/L)	Mass of phosphorus (mg)
Commercial Area	70771658.69	0.25	17692914.67
Residential Area	47603124.16	0.4	19041249.6
Open Space	38172700.62	0.18	6871086.11
Total	156547483.5	0.157	24564000.7

Table 9. Results of Equation 4.

$$L_{post} = (P)\ (R_v)\ (C)\ (A)\ (0.20) \qquad \text{(Equation 6)}$$

Lpost = 55.13 lbs/year
P = 31.33 (inches)
Rv = 0.53
Ipost = 53.3
C = 0.157 mg/L
A = 105.73 acres

Table 10. Results of Equation 6.

$$LR = (L_{post})\ (BMP_{RE})\ (\%\ DA\ Served) \qquad \text{(Equation 5)}$$

	Lpost (lbs/year)	BMP_{RE}	% DA Served	LR (lbs/year)
Treatment 1	55.13	36%	2.7%	0.54
Treatment 2		89%		1.32

Table 11. Results of Equation 5.

$$R = L\,[(E1)+(1-E1)E2+(1-((E1)+(1-E1)E2)E3+\ldots] \qquad \text{(Equation 7)}$$

	E1 (Efficiency of Bioswale or Bioretention)	E2 (Efficiency of Constructed Wetland)	Lpost (lbs/year)	Pollutant Removal (lbs/year)
Treatment 3	36%	66%	55.13	43.13
Treatment 4	89%	66%		53.07

Table 12. Results of Equation 7.

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