SPONGE CITY THEORIES AND APPLICATIONS: A STUDY OF THE LANDSCAPE PLANNING IN LEINEFELDE-WORBIS

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ABSTRACT

With the process of urbanization, a lot of cities are faced with various environmental problems, many of which are associated with stormwater. To deal with these problems, landscape planning in urban areas needs to incorporate new sustainable development concepts, and one of them is the concept of sponge city.

This thesis systematically studies the sponge city concept, from both the theoretical and practical aspects. The theoretical part begins with the concept descriptions including the definition, objectives, and application processes. Thereby it brings the idea of bioretention (which is the basic practice in the sponge city concept), as well as some basic concepts related with bioretention. Then it introduces the stormwater treatment train, which integrates a variety of rainwater management facilities based on the idea of bioretention, to create a systematic approach to effective stormwater management. Major facilities to form the stormwater treatment train are also discussed in detail, including green roof, permeable pavement, planter, filter strip, swale, rain garden and pond.

The practical part is based on a landscape planning project in the city of Leinefelde-Worbis, the south of which is going to hold the Landesgartenschau 2024, which gives this area an opportunity to be re-planned, with a sustainable development concept. The project site is to be planned as a "garden city", which will be completely built after the Landesgartenschau 2024. After the analysis to the basic site conditions (including the location, topography, buildings, subsoil, air and water environment), the stormwater issues in this area are discussed in detail, including the causes of water problems, categories of water pollutants, sources and impacts of water pollution. According to the analysis and discussion, major strategies to deal with the stormwater issues at the site are developed.

Based on the theoretical study and the site strategies, a new urban planning for the site is provided, in the principles of "low-impact development". The first part is the concept plans, including a master plan, an overall structural plan (to plan different areas of the private properties for the residents, the streets for the circulation, and the public green spaces for recreation and rainwater management), and a sustainable stormwater management plan (to re-design the site levels and to provide a new drainage plan). The second part include detailed designs for different public area elements (streets, garden, park, parking lots, and other open green spaces), as well as proposals for private property designs in the future. In addition, scientific calculations for the water quantity control, systematic analysis for the water quality control, and further considerations for the plant selection, have also been provided in detail.

Through the study of literatures and applications on the sponge city concept, it is hoped that this thesis will provide a systematic summary of related theories of the sponge city concept, and an effective approach to deal with stormwater treatment issues at similar sites.

Key words: Sponge City, Stormwater Management, Landscape Planning, Low-impact Development, Water Pollution, Bioretention, Stormwater Treatment Train

CONTENT

CHAPTER 1 INTRODUCTION

1.1 STUDY BACKGROUND

With the rapid development of human civilization, the environmental problems coming with urbanization are becoming more and more serious for humans living on the earth. As can be seen from human daily life, these problems include air pollution, global warming and one that can never be ignored – stormwater issue.

According to some studies, humans have been fascinated with water since a distant past when humans evolved from ape-like creatures that once lived a semi-aquatic life by some water bodies in Africa. In that period, ancient humans fed on some hunted food like fish. This left humans a nature to be attracted to water.[1] The civilization of human beings originated from a region called Fertile Crescent, surrounded by the famous rivers – Nile, Tigris and Euphrates, and later spread all over the world. Nowadays, most important cities are set by the banks of waterways, such as New York, London, Hong Kong, Singapore, Tokyo, Paris, Berlin, Rome, Shanghai and so on.[2] (Figure 1-1, 1-2)

Figure 1-1: Huangpu River in Shanghai, China

Figure 1-2: Seine River in Paris, France

Water has been playing an essential role in human daily life for a long time, especially in the field of garden design. In East Asia, water is one of “the four basic elements” that compose Chinese Classical Gardens (Figure 1-3), which have great influences on some other Asian garden styles such as Japanese Gardens.[3] For the ancient cultures in the Middle East, where the idea of designing gardens for entertainment originated, water

1 Dunnett & Clayden, 2007 (pg. 18)
2 Venhaus, 2012 (pg .119)
3 Zhou, 1990

was an indispensable element in garden design.[4] In the centre of a typical Islamic garden, a geometric pond usually is placed to present the significance of water in Islamic culture, which emerged in a desert climate.[5] In the western countries, such as France and Italy, water elements (such as fountains) are often designed in gardens to entertain the visitors (Figure 1-4).[6]

Figure 1-3: Chinese Classical Garden, Suzhou **Figure 1-4: French Baroque Garden, Versailles**

Humans are fascinated with water bodies due to many reasons, such as the advantages of transportation, energy production and recreation.[7] With the progress of industrial revolution, humans started to become more and more powerful in the control of water supply. In the late 19th century, "centralized drinking and waste water disposal system" was introduced into human daily life "in the wake of devastating choleras and typhus epidemics".[8] Also during this period, the urbanization had made many cities grow apart from this essential life force. Many rivers, streams and brooks were transformed into inhabited land due to the social development. The emerging sanitation systems started playing an important role in urban society, and this resulted in severe deterioration of the urban river water quality. With the appearance of more and more water problems in the past decades, people started to reflect on these environmental issues.[9]

As one of the indispensable elements in human daily life, water is supporting the nature in a continuous movement known as the hydrological cycle that includes some major

[4] Dunnett & Clayden, 2007 (pg. 9)
[5] Harigaya, 1977
[6] Schröer & Enge, 1992
[7] Venhaus, 2012 (pg. 119)
[8] Kenney, 1997 (pg. 53)
[9] Dunnett & Clayden, 2007 (pg. 19)

processes such as evaporation, condensation, precipitation, infiltration, surface runoff and subsurface flow.[10] (Figure 1-5) However, since the land surfaces have been changed due to the urbanization movement, the natural processes of the hydrological cycle were deeply influenced.

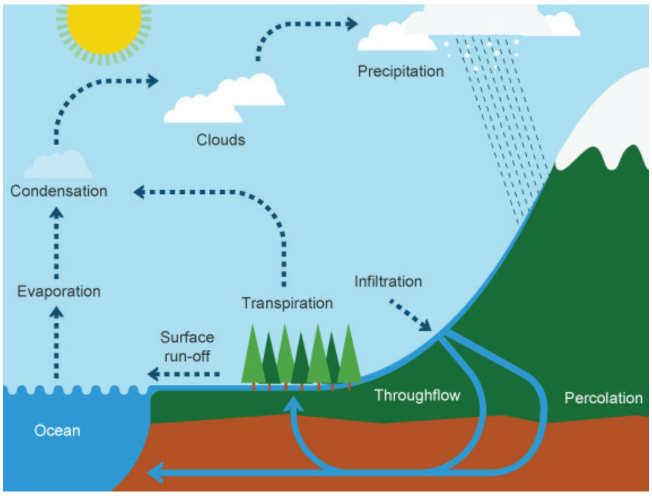

Figure 1-5: the Hydrological Cycle[11]

In urban areas, sealed land surfaces are created everywhere: house roofs, streets and roads, parking areas, squares and so on. These sealed surfaces have formed an impermeable layer on the earth and prevented rainwater from moving into the soil, which eventually blocks the natural way by which water infiltrates into the earth to join in the system of groundwater.[12]

In addition, sealed surfaces will force rainwater to flow from where it falls to other surrounding places. The water concentrates in another area in large amounts, thereby leading to the threat of flooding.[13] The rate of rainwater runoff in urban areas, whose surfaces are sealed with high proportion of impermeable materials, is twice or three times that in vegetated areas.[14] In the meantime, high rates of runoff will cause erosion and damage too.[15]

Moreover, rainwater runoff from urban areas can be a major source of water pollution,

[10] Dunnett & Clayden, 2007 (pg. 32-33)
[11] NMSB, 2019
[12] Dunnett & Clayden, 2007 (pg. 34)
[13] Dunnett & Clayden, 2007 (pg. 34)
[14] Daley, 2003
[15] Dunnett & Clayden, 2007 (pg. 34)

since the contaminants from urban surfaces can be transported with the runoff into nearby receiving waters, such as streams, rivers, lakes, seas and so on. Due to this, the quality of natural water resources on which human daily life depends will be deteriorated.[16]

Figure 1-6 shows the situation of a natural green space, which presented a beautiful scenery after a violent stormwater event in Hunan, China, July, 2017. On the contrast, the same stormwater event had brought a disastrous flood with large amount of polluted water into a developed urban area in Hunan, China, July 2017, as shown in Figure 1-7.

Figure 1-6: Flooding in Green Space, China

Figure 1-7: Flooding in Urban Area, China

In natural flooding processes, the function and biodiversity of aquatic and terrestrial ecosystems is maintained. Some benefits such as creating critically important habitat, supplement of groundwater, returning nutrients to the land, and replenishment of topsoil are brought about by floodwaters. However, as mentioned above, sealed paving in urban areas will not only result in the decrease of groundwater as well as the increase of surface runoff, but also cause some severe problems such as pollution in receiving waters. All these consequences will threaten the human daily life.[17]

In this case, stormwater is not a resource but also a threat for the environment at site. When it is captured, stored and cleansed through treatment facilities it can be utilized in different ways and bring various environmental and economic benefits, while when it is wasted it may cause flooding and water pollution.

[16] Venhaus, 2012 (pg. 119)
[17] Venhaus, 2012 (pg. 119)

Therefore, the relationship between water and human beings is changing: water may not always be a renewable resource in the control of human beings. On the contrary, it can be a potential threat to humans, if necessary precautions are not taken in time. In this case, the traditional ways to deal with water issues must be changed, and new sustainable approaches to the harmony between human civilization and natural water system must be created.[18]

The sponge city concept is one of the theories and practices that bring the opportunities to integrate modern urbanization and low-impact development, in the consideration of stormwater quantity and quality control.

1.2 THESIS STRUCTURE

The structure of this thesis consists of three major parts: the theoretical part to systematically study on the sponge city concept including related literatures review and scientific analysis, the practical part based on the project of the landscape planning in Leinefelde-Worbis, and the conclusive part that discusses the results of the study and gives recommendation for future work.

Chapter 1 briefly introduces the background and outlines the structure of the study, thus developing the main study objectives.

Chapter 2 describes the definition, objectives, processes and main practices of the sponge city concept, and introduces other related concepts as well as major facility elements applied in the sponge city concept.

Chapter 3 brings the description of the project site in Leinefelde-Worbis City, including the background of the project, and analysis of the site. Then it raises the water issues related to this project and site strategies for the issues.

Chapter 4 moves into the planning and design part, based on the analysis from previous chapters. This chapter consists of the overall concept plans, detailed designs for the public space, proposals for the private properties, considerations for the bioretention system volume, analysis of the pollution purification, and considerations for the plant selection.

[18] Dunnett & Clayden, 2007 (pg. 9)

In Chapter 5 makes a conclusion of the study in both theoretical and practical way, and gives recommendation for future work.

1.3 MAIN OBJECTIVES

This study aims to systematically analyse the related theories of the sponge city concept, and provide scientific and effective approaches, based on the theoretical analysis, to the problems of water pollution caused by stormwater runoff from urban residential areas to receiving waters, such as streams, rivers, lakes, or other water bodies, through a series of practical applications in a landscape planning project.

CHAPTER 2 SPONGE CITY THEORIES

2.1 SPONGE CITY CONCEPT

2.1.1 Concept Definition

The earliest version of the "sponge city" concept was used in a paper named *Sponge Cities and Small Towns: a New Economic Partnership*, which was published in 2005 to described the relationship between urbanization and population.[19] In the year 2013 at the China Central Work Conference on Urbanization, the "sponge city" concept was proposed again with a new connotation as "a new urban development program to manage effectively urban rainwater"[20]. Therefore the term "sponge city" has a new definition as "cities that are able to adapt flexibly, like sponges, to changes in the environment, such that they absorb, store, permeate and purify rainwater, and are able to make use of the stored water when needed"[21].

Figure 2-1: Typical Sponge City System[22]

[19] Budge, 2005
[20] Liu et al., 2017
[21] Shao et al, 2016
[22] Go Chengdu, 2015

The new definition of the sponge city concept shares a similar connotation with some other concepts that are also used in different areas of the world, such as “Low-impact Development” (the U.S.A. and Canada), “Blue-green Infrastructure” (the U.S.A.), “Best Management Practices” (the U.S.A.), “Water-sensitive Urban Design” (the Middle East and Australia), “Sustainable Urban Drainage Systems” (the U.K.), “Blue Green Solutions” (the E.U.) and so on.[23]

2.1.2 Main Objectives

According to the paper *“Sponge City” Concept Helps Solve China’s Urban Water Problems*, the sponge city concept follows three main objectives as following[24]:

1. Conservations for the original water bodies and other natural resources in a sustainable way, which means using sustainable methods to protect water bodies such as streams, rivers, ponds and lakes from contamination and other kinds of damages, especially those originating from the constructions in urban areas;

2. Remediation for the contaminated or damaged water bodies and other natural resources in an ecological way, which means applying ecological solutions to recover the injuries the natural landscape suffer from the process of urbanization;

3. Applications of the “low impact development” concept, which means combining a series of stormwater treatment practices with the processes of urbanization to create an ecological and economic way of development.

2.1.3 Application Processes

To realize the three objectives, the sponge city concept is applied through six processes as following[25]:

1. Rainwater infiltration: natural surfaces have been replaced by impermeable surfaces during the development of urbanization, and the sponge city concept aims to transform the impermeable surfaces back into permeable surfaces that permit water infiltration during and after rainfall events;

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23 Sieker, 2019; Dunnett & Clayden, 2007 (pg.37-38)
24 Liu et al., 2017
25 Liu et al., 2017

2. Rainwater detention: when stormwater events happen, it is easy to accumulate large amount of runoff in urban areas, thereby leading to flooding problems, and the sponge city concept aims to slow down the runoff through a series of stormwater treatment practices, so that the peak flow of runoff can be reduced;

3. Rainwater retention: the traditional way to manage stormwater is to transport it through local drainage systems to receiving waters, and when the amount of rainwater exceeds the water delivery capacity of drainage systems, the overflow will cause several problems, while in a sponge city system, the rainwater can be stored in a series of stormwater treatment facilities, thereby bringing the reduction of runoff volume and the preparation for future use;

4. Rainwater purification: as mentioned above, the rainwater is directly drained into the combined drainage systems in some urban areas, and the waste water overflow from drainage systems during stormwater events, thereby leading to water pollution problems, while sponge city systems aim to increase the natural infiltration capacity of rainwater, by diverting stormwater from the sewer systems through vegetation, soil and other natural spaces to trap, filter and release excess rainwater before it is directed into receiving waters, thereby improving the water quality in natural waterbodies;

5. Rainwater utilization: in traditional stormwater management systems, rainwater is treated as waste water and drained away, but in sponge city systems, rainwater is regarded as a resource that can be directed to supplement the groundwater resource, or be stored in various rainwater harvesting systems for future reuse during dry seasons;

6. Rainwater discharge: in order to solve the stormwater conveyance problems in urban areas, the sponge city concept also aims to update urban drainage pipes, interconnect natural water systems, and separate surface drainage systems and underground pipeline systems, in order that if rainwater cannot be absorbed completely, it can be discharged through separated and high-capacity drainage systems as soon as possible.

2.2 APPROACHES TO SPONGE CITY

2.2.1 Bioretention

2.2.1.1 Basic Description

The basic idea for the sponge city concept is the applications of “bioretention” (also named “biofiltration”[26]). Bioretention is a land-based practice using the chemical, biological and physical properties of vegetation, microorganism and soil to deal with the water issues including its quality and quantity in a targeted area. Practically, bioretention applies a model which provides places for the collection, infiltration, filtration, detention, storage and drainage of runoff with the cooperation of plants, soils and microorganisms.[27]

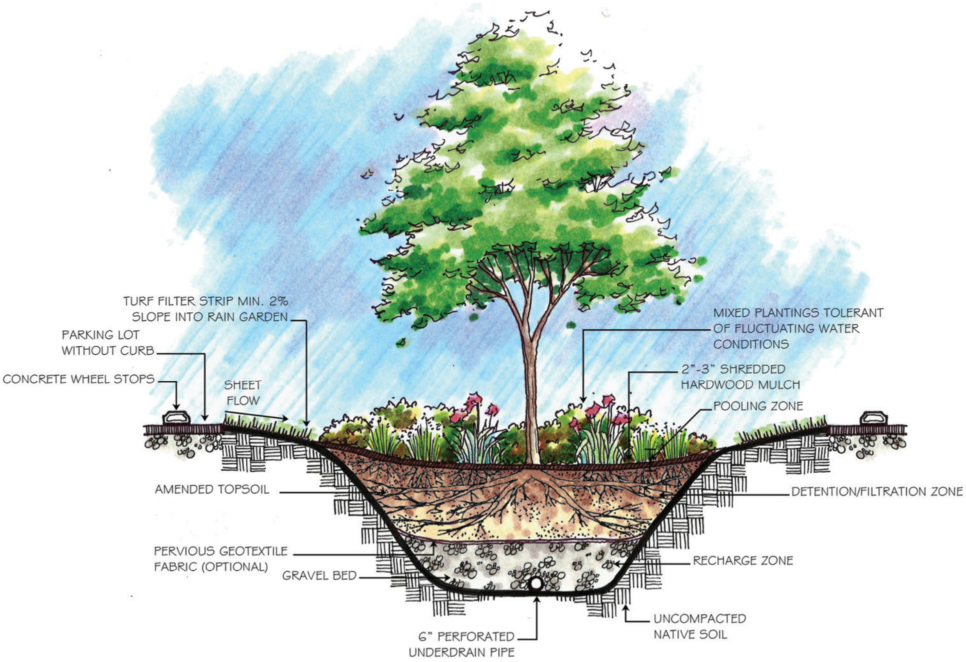

Figure 2-2: Typical Bioretention Cell[28]

2.2.1.2 Major Categories & Application Suitability

In general, there are three types of bioretention systems: “full infiltration system” with no underdrain (Figure 2-3), “partial infiltration system” with underdrain (Figure 2-4),

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[26] Venhaus, 2012 (pg. 150)
[27] Coffman & Winogradoff, 2002
[28] Wallover, 2015

and “no infiltration system” (Figure 2-5, also known as “biofilter system”) with both underdrain and impermeable liner. The biorentention system types depend on the native soil permeability (infiltration rate) and other physical constraints. The basic component in a bioretention system is the filter bed that consists of sands, fines, aggregates and organic materials. Other components include selected plants, a mulch ground cover or pavements, etc. The particles which would clog the filter bed should be removed before the runoff reaches the bioretention system by pre-treatments such as vegetated filter strip, setting forebay, or stone diaphragm.[29]

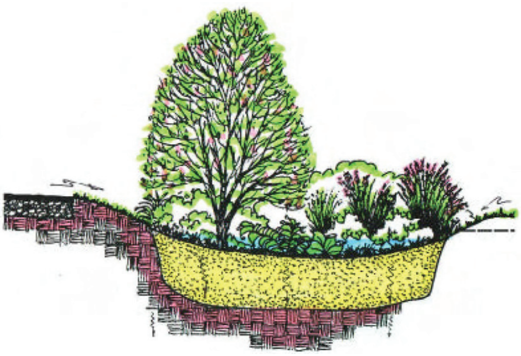

Figure 2-3: Full Infiltration System[30]

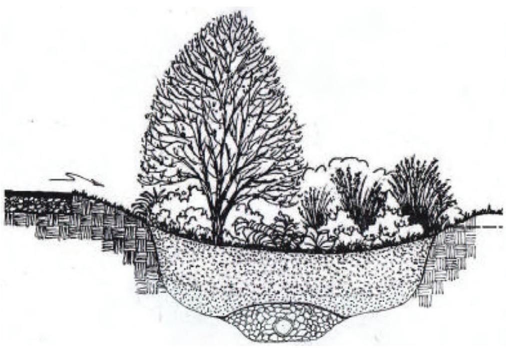

Figure 2-4: Partial Infiltration System[31]

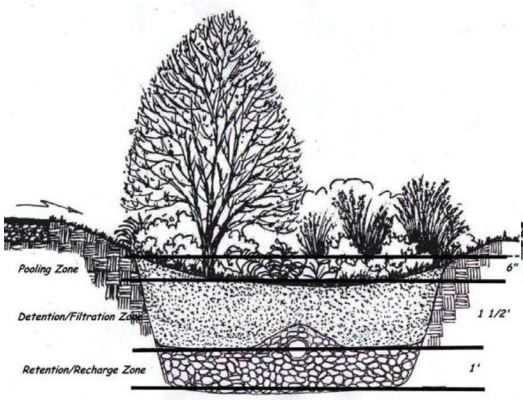

Figure 2-5: No Infiltration System[32]

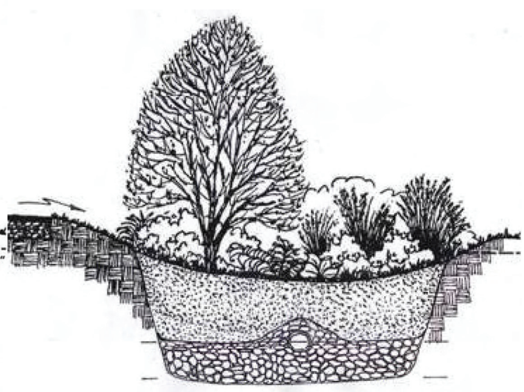

Figure 2-6: Denitrification System[33]

Specifically, full infiltration bioretention facilities are suited for nutrient runoff generating areas, such as residential and business campuses; partial infiltration

[29] TRCA & CVCA, 2010 (pg. 4-64)
[30] ESD et al., 2007 (pg. 25)
[31] ESD et al., 2007 (pg. 26)
[32] ESD et al., 2007 (pg. 28)
[33] ESD et al., 2007 (pg. 27)

bioretention facilities are suited for nutrient and metals loadings generating areas, such as parking lots, residential and business campus; no infiltration bioretention facilities are suited for hot-spots areas, such as transfer sites, gas stations, and transportation depots.[34]

In addition, *Bioretention Manual* mentions another type of bioretention system in which a fluctuating aerobic/anaerobic zone is added below the raised underdrain discharge pipe in a partial infiltration system (Figure 2-6). This type is suited for higher nutrient loadings (particularly nitrate) generating areas, such as residential communities, since nitrates can be mitigated through some natural denitrification processes achieved by the fluctuation created by infiltration and saturation into the surrounding soil.[35]

2.2.1.3 General Structure

The typical construction layers of a bioretention system from top to bottom are as follows[36]:

1. Vegetation layer, where the aboveground part of plants live;
2. Ponding area (optional), where water stays for long period;
3. Mulch layer (optional), to protect the soil;
4. Growing medium, which consists of selected soil to support the growth of plant roots;
5. Geotextile filter (optional), to separate the growing medium and the drainage layer, in the meantime playing a role in filtering polluted water;
6. Drainage layer (optional), which consists of gravel filter and drainage pipe;
7. Waterproof layer (optional), which is an impermeable liner to prevent water infiltration (in a "no infiltration system").

[34] ESD et al., 2007 (pg. 24-27)
[35] ESD et al., 2007 (pg. 26)
[36] Dunnett & Clayden, 2007 (pg. 53)

2.2.1.4 Stormwater Quantity Control

One of the main objectives of the sponge city concept is to deal with the amount of excess runoff in some targeted areas. This objective will be achieved by bioretention practices through the following processes[37]:

1. Interception –plant leaves or stems, and soils cooperate to capture rainfall or runoff, and collect or pool the water in the bioretention system;

2. Infiltration –water move downward through soils;

3. Evaporation –water evaporates back to the atmosphere from the surfaces of plants and soils;

4. Transpiration –water move upward from soils, through plants, back into the atmosphere. (Most of the water captured by plants will be transpired to the atmosphere during this process. Evaporation and transpiration are also combined together and known as evapotranspiration.)

The runoff volume reduction capacity of a bioretention system can be influenced by many factors, such as whether with underdrain, native soil infiltration rate, rainfall patterns, and sizing criteria. According to the results of some studies, the estimated runoff reduction in the bioretention systems with underdrain (including partial infiltration and no infiltration applications) is 45%, and that in the bioretention systems with no underdrain is 85%.[38]

2.2.1.5 Stormwater Quality Control

The bioretention can also solve the problem of water pollution by cleansing contaminated water through the cooperation of plants, soils and organisms. The pollutants can be divided into two groups: organic contaminants and inorganic contaminants. Organic materials include oil leakages, animal waste, etc; inorganic materials include nutrients, heavy metals, etc. The cleansing processes include[39]:

1. Settling – suspended particles and solids settle out when the water ponds in a

[37] Dunnett & Clayden, 2007 (pg. 40-41)
[38] TRCA & CVCA, 2010 (pg. 4-70)
[39] Dunnett & Clayden, 2007 (pg. 41-42)

bioretention system;

2. Filtration – particles in the runoff are filtered out when the water moves downward through the earth;

3. Assimilation – growing plants take up nutrients and contaminants (During their growth plants can absorb and store mineral nutrients in their bodies, and after their death and decay the nutrients will be released back to the nature. In addition, plants are able to take up heavy metal contaminants, which can be taken away subsequently by cutting back and removing the grown plants. The technology to use living plants to clean up contaminated soil, air and water is known as "phytoremediation");

4. Adsorption – contaminants within dissolved substances are attracted and bound onto the surfaces of plants roots, soil particles or humus, and other organic substances;

5. Degradation and decomposition – soil microorganisms break down chemicals and organic contaminants (The technology to use living microorganisms to remove environmental pollutants thereby restoring the original natural situations and preventing further pollution is known as "bioremediation"[40]).

Even though the processes of water purification are generally carried out in plant-based areas, the key operators in the water treatment are the soil and the microorganisms instead of the plants. However, the vegetation layer plays a significant role in supporting and assisting the processes of water purification. Firstly, plants can create secondary pore space inside the soil to increase its permeability; secondly, the growth of plants' shoots and roots can prevent the compaction of the soil; thirdly, the surfaces of plants' roots can provide habitats for microorganisms to live on; lastly, plants can transport oxygen from the air downward to the soil.[41] (For example, wetland plants can promote the activity of microorganisms by increasing the surface areas to attach soil microorganisms with their stems and roots, or by transporting oxygen through their tissues downward to their roots growing in saturated soil to provide oxygen-rich

[40] Sasikumar & Papinazath, 2003
[41] Kenney, 1997

conditions for microorganisms to live in[42].)

Bioretention systems have been proved by both field studies and laboratory to be one of the most effective Best Management Practices (BMPs) for removing pollutants.[43] In addition, their capacity of pollutant removal is connect with their capacity of runoff reduction. For instance, in a full infiltration system, if the bioretention cell is able to infiltrate and evaporate all the runoff from a site, then no pollutant will leave the site within surface runoff.[44]

According to some studies conducted during the first decade of the twenty-first century, the purification capacity of targeted bioretention systems to remove different types of contaminants are concluded as follows: their purification capacity to remove metals[45], total suspended solids[46], and polycyclic aromatic hydrocarbons[47] have been observed to be highest; following is that to remove metals from de-icing salt in snow melt[48]; the removal rates for nitrogen and ammonia nitrogen have been observed to be lower than those mentioned above; the lowest is that for nitrate nitrogen.[49]

However, some water after infiltration practices in bioretention systems was observed to contain more total phosphorus, inferred to leach from the growing media containing high phosphorus content.[50] Due to this, the growing media should be examined before installation and their phosphorus content should be kept from 10 to 30 ppm.[51]

2.2.1.6 Other Environmental Benefits

Bioretention practices are able to mitigate the urban heat island effect by adding vegetation areas, since vegetated surfaces absorb less solar radiation than hard-paved surfaces, and water evaporation in vegetation can also lower surrounding temperature.[52]

Besides, bioretention applications can bring other benefits such as: creating a distinctive landscape by featuring plants, providing additional habitat for wildlife, improving air

[42] Dunnett & Clayden, 2007 (pg. 42)
[43] TRCA, 2009
[44] TRCA & CVCA, 2010 (pg. 4-71)
[45] Davis et al., 2003; Hunt et al., 2006; Roseen et al., 2006; Davis, 2007; TRCA, 2008
[46] Roseen et al., 2009
[47] TRCA, 2008; Diblasi et al., 2009
[48] Muthanna et al., 2007
[49] Davis et al., 2001; Dietz & Clausen, 2005
[50] Dietz & Clausen, 2005; Hunt et al., 2006; TRCA, 2008
[51] Hunt & Lord, 2006
[52] TRCA & CVCA, 2010 (pg. 4-73)

quality and so on.[53]

2.2.1.7 Potential Contamination & Solutions

Monitoring studies have proved that underlying native soils will not be contaminated by small distributed infiltration bioretention practices, even after being operated for more than ten years.[54]

The pollutants from urban runoff will not be a great threat to the groundwater, since most of them are retained by soils and infiltration practices.[55] However, since de-icing salts are usually applied to deice roadways and parking areas in sub-freezing weather, and their constituents such as chloride and sodium are not properly attenuated in soil, thereby easily transported into shallow groundwater.[56] Moreover, infiltration of these chemical elements will promote the movement of other chemical elements like copper, cadmium and lead in soil, thus creating a threat to underlying groundwater quality by increasing the possibility of certain heavy metals concentration.[57] (Actually, by sampling groundwater below infiltration practices receiving runoff lading with de-icing salt, very few studies have found concentrations of heavy metals exceeding drinking water standards.[58])

The following management approaches can be taken to decrease the potential for groundwater contamination[59]:

1. Before infiltration of runoff, the practices of sedimentation pre-treatment should be applied first, such as grit and oil separator;

2. Infiltration of runoff from less contaminated areas such as parking areas, low traffic roads and roofs should take priority;

3. Runoff from high traffic areas (such as busy highways on which large sum of de-icing salts are used), and pollution hot spots (such as source areas which highly contaminated runoff like vehicle fuelling comes from or storage areas for

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53 ESD et al., 2007 (pg. 3)
54 TRCA, 2008
55 Pitt et al., 1999
56 TRCA & CVCA, 2010 (pg. 4-64)
57 Amrhein et al., 1992; Bauske & Goetz, 1993
58 Howard & Beck, 1993; Granato et al., 1995
59 Pitt et al., 1999; TRCA, 2009

hazardous materials or heavy industry sites) should not be received by infiltration practices.

2.2.1.8 Design Considerations

In addition to the potential contamination, some other situations must be taken into consideration when applying infiltration systems into practice, such as:

1. The infiltration rate of native soil for installing a full infiltration bioretention facility should not be less than 25 mm/hour, and the facility must be at least 750 mm deep to ensure adequate filtration[60];

2. The application locations should be more than 3 metres from buildings, in order to prevent potential structural damage[61];

3. The applications should not be located in leach field or septic tank areas[62];

4. The applications should not be located in areas where compacted soils are required to support structures, hardscape, etc[63].

2.2.2 Stormwater Treatment Train

2.2.2.1 Basic Description

The essential objectives of a bioretention system can be summarized in two steps: to reduce impervious surface areas in order to reduce stormwater runoff, and to utilise plants, soil and microorganisms to move, store and filter stormwater runoff before it leaves the site.[64] The key to practically and effectively realize these objectives is to create an integrated approach that connect a series of different stormwater management facilities such as eco-roof, impermeable pavement, stormwater planter, filter strip, bio-swale, retention pond, and rain garden with each other to form a continuous stormwater management chain, thereby taking all aspects of the runoff movements from a targeted area into consideration. This integrated approach is known as the "stormwater treatment

[60] ESD et al., 2007 (pg. 24-27)
[61] Ferguson, 2005
[62] Venhaus, 2012 (pg. 150)
[63] Venhaus, 2012 (pg. 150)
[64] Dunnett & Clayden, 2007 (pg. 45)

train", also named "stormwater chain".[65]

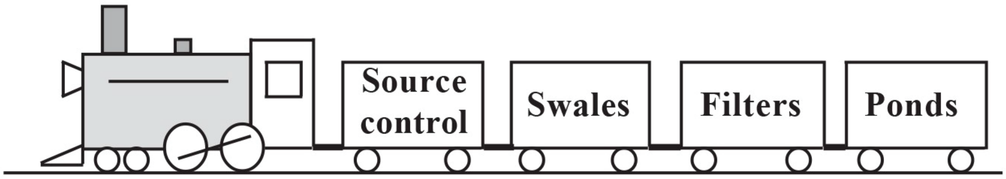

Figure 2-7: Typical Stormwater Management Train System[66]

Stormwater treatment train is essentially a series of various designed facilities cooperating to deal with stormwater in a targeted site, for the purpose of maximum rainwater treatment effectiveness. It is especially needed when pre-treatments to remove specific contaminants are required before a rainwater management practice, otherwise whose water treatment performance will be impacted.[67]

Typical stormwater treatment train system normally including three parts: the train head part (for the source control), in which green roof is a typical component; the train body part, in which a variety of facilities are applied; the train trail part (for the final control), in which rain garden or pond are often applied. (Figure 2-7)

2.2.2.2 Major Techniques

The stormwater treatment train can be applied through four techniques as follows[68]:

1. Protection techniques, which prevent rainwater from land surfaces;
2. Retention techniques, which store water until it infiltrates into the soil or evaporates back to the atmosphere;
3. Detention techniques, which store water for a short period then drain it somewhere else;
4. Conveyance techniques, which drain rainwater from the place it falls on to the place it is collected.

65 Venhaus, 2012 (pg. 149); Dunnett & Clayden, 2007 (pg. 45)
66 ARC, 2003 (pg. 4-15)
67 Melbourne Water, 2017
68 Coffman, 2002

2.2.2.3 Treatment Stages

Since different stormwater treatment applications have different treatment processes and are capable to deal with different targeted pollutants, the arrangement of their order in a stormwater treatment train is crucial for their performance of pollutant removal. In general, according to different types of targeted pollutants, the working processes of a stormwater treatment train can be divided into three treatment stages as below[69]:

1. Primary stage: targeting coarse sediment and gross pollutants, through rapid sedimentation and physical screening, sediment ponds and litter traps and grassed swales are preferable applications at this stage;

2. Secondary stage: targeting attached pollutants and fine sediment, through filtration techniques and fine particle sedimentation, bioretention systems and porous paving and infiltration trenches and swales are preferable applications at this stage;

3. Tertiary stage: targeting dissolved heavy metals and nutrients, through absorption onto sediments and biological uptake and enhanced sedimentation and filtration, bioretention or bioinfiltration systems and wetlands are preferable applications at this stage.

2.3 CONCEPTS RELATED WITH BIORETENTION

2.3.1 Phytoremediation

2.3.1.1 Basic Description

The term "phytoremediation" consists of two parts: "phyto-" means "using plants" and "remediation" means "to solve a problem". Thereby "phytoremediation" literally means "using plants to solve a problem".

Specifically, phytoremediation refers to the techniques to use plants to remove contaminants from water and soils through processes including degradation, extraction, containment, and stabilization.[70] (Figure 2-8)

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[69] Melbourne Water, 2017
[70] U.S. EPA, 2000

2.3.1.2 Working Processes

According to *Introduction to Phytoremediation*, the major processes of phytoremediation include as follows[71]:

1. Degradation: plants are able to promoting the process of degradation of organic pollutants in the rhizosphere, which refers to a soil region influenced by the plant root;
2. Extraction: contaminants can be accumulated in parts of a plant body such as leaves or shoots, and by cutting those parts of the plant can efficiently extract the contaminants from the site;
3. Containment: the roots of plant are capable to purify the soil by binding the contaminants inside;
4. Stabilization: plants are able to remove the medium by which contaminants transport.

2.3.1.3 Application Suitability

Phytoremediation is suited for soil polluted by specific contaminants staying in the upper layers with a medium level or lower.[72]

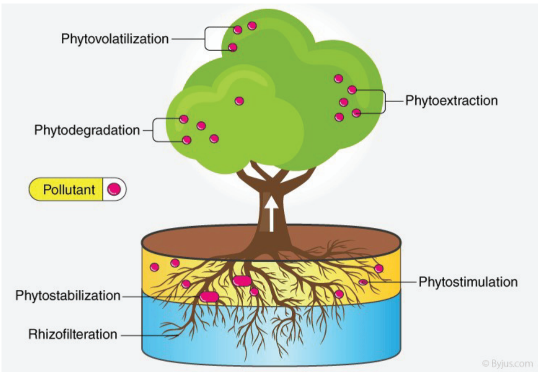

Figure 2-8: Process of Phytoremediation[73]

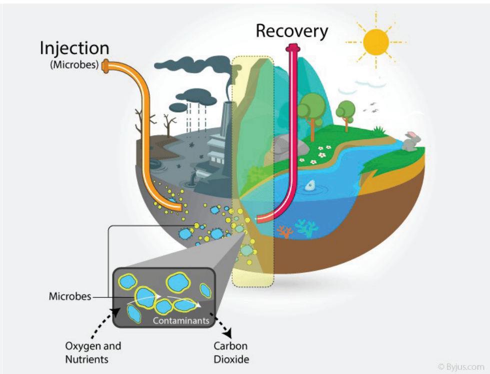

Figure 2-9: Process of Bioremediation[74]

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[71] U.S. EPA, 2000
[72] U.S. EPA, 2001b; Venhaus, 2012 (pg. 146)
[73] BYJU'S, 2019
[74] BYJU'S, 2019

2.3.2 Bioremediation

2.3.2.1 Basic Description

The term "bioremediation" consists of two parts: "bio-" means "using living organisms" and "remediation" means "to correct something wrong".so that "bioremediation" literally means "using living organisms to correct something wrong".

Specifically, bioremediation is a technology using living microorganisms to remove environmental pollutants thereby restoring the original natural situations and preventing further pollution.[75] (Figure 2-9)

Another definition for bioremediation which is more comprehensive would be: bioremediation is essentially a method of cleansing contaminants by using diverse biological metabolism to convert contaminants into harmless materials such as microbial biomass, simpler organic matter, or inorganic compound (carbon dioxide and water).[76]

2.3.2.2 Major Categories

According to the place from which contaminants are removed, bioremediation methods can be categorized into two groups[77]:

1. In situ bioremediation, which is applied to remove the pollutants from contaminated groundwater and soils. This type of bioremediation is closed to the contamination site thereby no transportation cost required, and another advantage is that it applies harmless microorganisms as bioremediants to clear up the chemical contaminations. But the disadvantage of this method is that compared to other remedial methods it is more time-consuming and it may lead to other problems.

   According to the origin of the microorganisms, in situ bioremediation can be classified as "intrinsic bioremediation" which is performed without direct microbial amendment but through improving ventilation and nutritional conditions to intermediate in local ecological conditions and to fortify natural

[75] Sasikumar & Papinazath, 2003
[76] Baggott, 1993; Mentzer & Ebere, 1996
[77] Sardrood, 2013 (pg. 7-9)

populations and to promote the metabolism of existing microfauna, and "engineered in situ bioremediation" that is carried out by introducing certain microorganisms into contamination sites.

2. Ex situ bioremediation, which deals with pollution problems out from contamination site. For this type of bioremediation the contaminated groundwater and soil need to be transported to the bioremediation site.

   According to the state of contaminants, ex situ bioremediation can be classified as "solid phase system" including soil piles and land treatment, and "slurry phase system" including solid-liquid suspension in bioreactors.

2.3.2.3 Application Suitability

Since bioremediation uses available on-site resources to eliminate contaminants, it performs in a typically more eco-friendly and cost-effective way compared to chemical treatment.[78] Stormwater management practices such as bio-swales and rain gardens that utilize the natural water-cleansing capacity of soil microbes through using vegetation and soil to treat runoff are kind of bioremediation practices. Bioremediation is commonly applied in industries extracting natural resource, such as mining and petroleum. However, bioremediation is not suited for projects with high concentrations of substances that are toxic to most microorganisms, such as cadmium, salts, or lead.[79]

2.3.3 Soil Organic Matter

2.3.3.1 Basic Description

Soil organic matter refers to the sums of all organic materials in the soil or on its surface, including both living components (such as living plant tissue as well as dead standing plant components, and organic matter associated with living soil fauna as well as cells of living soil microorganisms), and non-living components (such as particulate organic matter, dissolved organic matter, humus, and inert organic matter), but excluding aboveground living plants, irrespective of their sources.[80]

The content of organic matter in healthy topsoil from most temperate regions is between

[78] U.S. EPA, 2001a
[79] Venhaus, 2012 (pg. 143-144)
[80] Jeffrey & Paul, 2000 (pg. B-27)

3% and 5%, while the organic matter content in desert soils is less than 1%, and that in wetland soils is typically very high.[81] Moreover, due to vegetation removal and soil compaction caused by land construction and maintenance practices, the content of organic matter in urban soils is commonly lower than that in the surrounding ecosystems.[82] In addition, a soil organic matter content exceeding 3% in at least 30 cm topsoil (or comparable to similar surrounding native landscapes that can act as a reference site) is recommended by Sustainable Sites Initiative.[83]

2.3.3.2 Major Benefits

According to *Designing the Sustainable Site: Integrated Design Strategies for Small-scale Sites and Residential Landscapes*, soil organic matter has the following benefits[84]:

1. Improving the structure of soil;
2. Reducing the compaction of soil;
3. Supplying food source to microorganisms;
4. Providing nutrients needed by plants;
5. Improving air movement and water infiltration through soil;
6. Promoting the storage of water;
7. Eliminating or binding pollutants.

2.3.3.3 Maintenance Strategies

Since organic matter is continually broken down by soil organisms into beneficial substances for vegetation growth such as nutrients, and the natural source of organic matter is removed from the soil due to conventional maintenance practices such as clipping lawn and sweeping leaves, the soil must be regularly replenished. Strategies for maintaining appropriate soil organic matter levels include[85]:

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[81] Venhaus, 2012 (pg. 140)
[82] Urban, 2008
[83] Venhaus, 2012 (pg.140)
[84] Venhaus, 2012 (pg. 139)
[85] Venhaus, 2012 (pg.140)

1. Avoiding soil disturbance, such as tillage that will promote the loss of soil organic matter through speeding decomposition;

2. Leaving decaying and discarded plant material on-site, such as leaves and stems that will naturally become incorporated into the soil;

3. Increasing or maintaining vegetative cover, which can deposit organic matter within soil profile and onto soil surface;

4. Providing regular organic material inputs, such as straw, shredded leaves, and compost.

In addition, though compost is a natural product, it can leach nutrients that will cause pollution of groundwater and surface water. Due to this, when compost are applied near sensitive environmental areas or in large amounts, measures should be taken to prevent runoff and avoid contamination to receiving waters. Especially in stormwater management landscape features such as bio-roofs and bio-filtration areas, the potential for water pollution is particularly great. Therefore, the types of soil organic matter and their potential for water pollution must be taken into consideration.[86]

2.3.3.4 Restoration Approaches

It is relatively simple and cost-effective to restore appropriate soil organic matter content.[87] Two optional approaches are recommended in *Designing the Sustainable Site: Integrated Design Strategies for Small-scale Sites and Residential Landscapes* as follows[88]:

1. Continually scattering compost or mulch to over planting beds, which will gradually be moved by soil fauna like earthworms into the soil, to replenish the content of soil organic matter over time;

2. Tilling adequate (the specific quantity depends on the types, conditions, and compost content of the soil) stable and mature compost into the soil as a top layer with a depth from 15 to 45 cm.

86 Venhaus, 2012 (pg. 141)
87 Urban, 2008
88 Venhaus, 2012 (pg. 142)

2.3.3.5 Soil Microorganisms

Millions of beneficial microorganisms such as fungi and bacteria exist in one teaspoon of healthy soil.[89] The diverse and abundant microorganisms are an integral part of soil organic matter. They are supported by air, water, and soil organic matter, and in turn supporting nutrient cycling, healthy plant growth, pollutant removal, and soil structural enhancement.[90] (Figure 2-10)

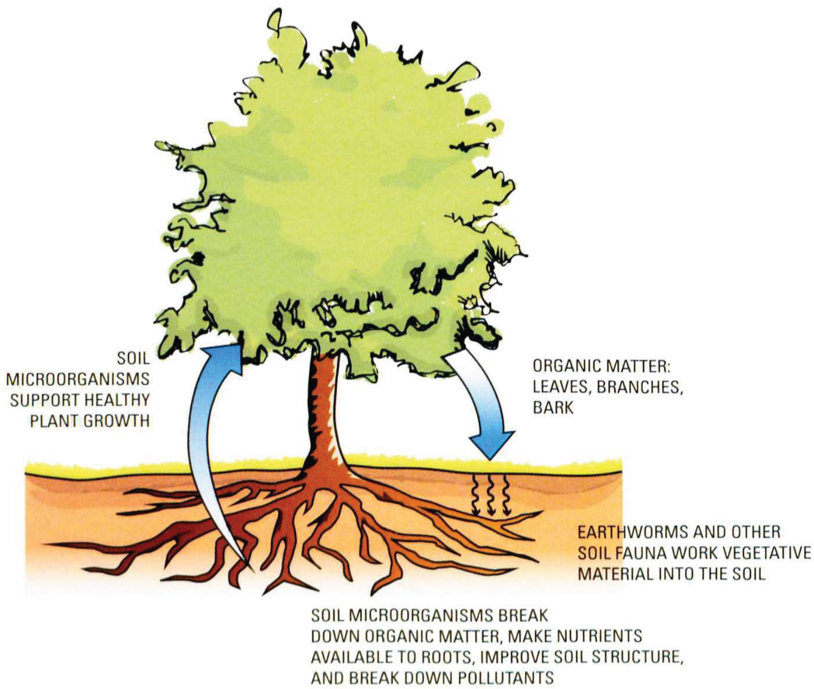

Figure 2-10: Relationship between Vegetation and Microorganisms[91]

Major strategies for encouraging and protecting soil organisms include[92]:

1. Avoiding unnecessary tillage and disturbance for soil;
2. Reducing soil compaction to promote infiltration of water and air;
3. Maintaining a suitable content of soil organic matter;
4. Avoiding pesticides that are harmful to organisms in soil;

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89 Ingham et al., 2000
90 Venhaus, 2012 (pg. 142)
91 Venhaus, 2012 (pg. 142)
92 Venhaus, 2012 (pg. 143)

5. Maintaining the diversity of plant palette to provide various food sources for soil organisms;

6. Maintaining mulch, vegetative cover, or plant materials such as leaves to avoid bare soil.

2.3.4 Soil Compaction

2.3.4.1 Basic Description

Soil particles will compact together under the pressure of weight from small repeated forces or a single intense force.[93] Soil compaction is essentially an increase in soil bulk density, defined as "the dry weight of soil divided by the total volume it occupies", and there are "maximum allowable soil bulk density" at which the soil no longer remains stable, and "growing limiting soil bulk density" at which the soil no longer supports root growth.[94]

2.3.4.2 Common Causes

Common causes of soil compaction include[95]:

1. Load from construction and maintenance equipment;
2. Load from repeated pedestrian and animal traffic;
3. Load from parking or driving at site not for vehicular traffic;
4. Rainfall on bare soils;
5. Compression or working wet soils;
6. Low levels of soil organic matter.

2.3.4.3 Impacts & Indicators

The pore space is reduced due to soil compaction, leading to the restrictions on root

[93] Venhaus, 2012 (pg. 136)
[94] Venhaus, 2012 (pg. 137)
[95] Venhaus, 2012 (pg. 137)

growth, the reduction of infiltration rates, and the decrease in biological activities.[96] If the soils are overly compacted, their capacity to absorb and cleansing water will be decreased, and as a result the runoff volume will increase, leading to the spread of contaminants.[97] (Figure 2-11)

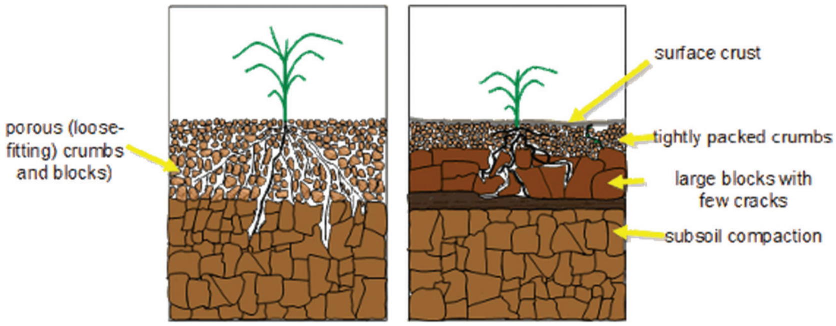

Figure 2-11: Healthy Soil (Left) & Compacted Soil (Right)[98]

Potential indicators of soil compaction include[99]:

1. Overland flow;
2. Unwanted pooling of water;
3. Bare soils without plant growth;
4. Poor growth of plants;
5. Trees root shallowly.

2.3.4.4 Protection Strategies

Preventing or minimizing soil compaction can avoid the costs of unnecessary plant replacement, erosion-control measures, and drainage issues, thereby saving time and money over the life of a project. Practicable strategies include[100]:

1. Collecting information about the conditions of the areas with degraded soils, including contamination, erosion, over-compaction;

[96] Venhaus, 2012 (pg. 136)
[97] Venhaus, 2012 (pg. 126)
[98] OSS, 2019
[99] Venhaus, 2012 (pg. 138)
[100] Venhaus, 2012 (pg. 138)

2. Locating site features of degraded soil areas requiring soil disturbance, and minimizing disturbance of healthy soils;

3. Developing a preservation plan that outlines the areas not to be disturbed and fencing them.

2.3.4.5 Restoration Steps

Over-compacted soils with limited capacity of water infiltration should be moved to the areas such as sidewalks, roads, and buildings construction sites, which require subbase layers for structural support. Other soils that are supposed to be revegetated should be restored as sustainable growing media.[101]

The steps of restoration for compacted soils include[102]:

1. Subsoiling or tilling the soils to break it apart;

2. Using compost or mineral amendments (compost is preferable since it provides many benefits for soil health) to improve the soils;

3. Avoiding the re-compaction of soils (take measure to revegetate it and limit pedestrian and vehicular traffic).

2.3.5 Structural Soil

2.3.5.1 Basic Description

Structural soil is essentially a specialized base-course medium consisting of gap-graded gravels such as crushed stone and soil with mineral and organic content, which are formulated to support different kinds of pavement while maintaining favourable conditions for root growth.[103] The soil partially fills the gaps between the gravels, and the remaining void spaces can temporarily store water, acting as a reservoir.[104] The gravels support traffic load and prevent the underlying soil from being compacted, so that the root growth can be maintained.[105] (Figure 2-11)

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[101] Venhaus, 2012 (pg. 139)
[102] Venhaus, 2012 (pg. 139)
[103] Venhaus, 2012 (pg. 130)
[104] Venhaus, 2012 (pg. 130)
[105] Fergunson, 2005

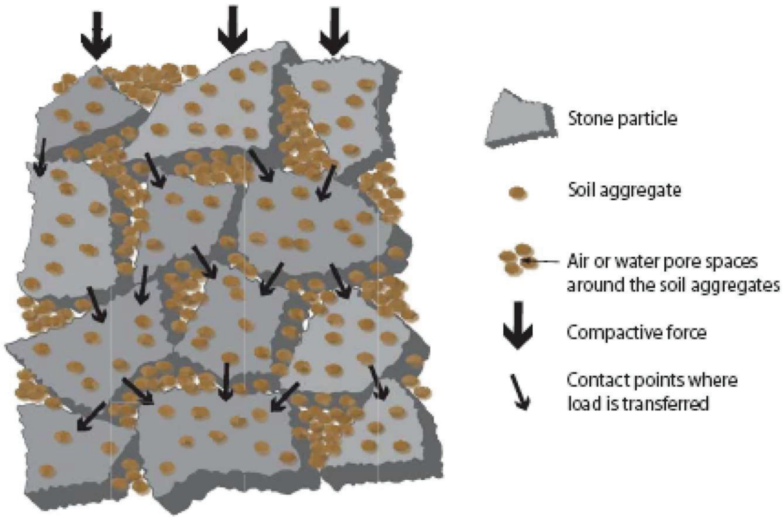

Figure 2-12: Conceptual Diagram of Structural Soils[106]

2.3.5.2 Working Processes

Structural soils play an important role in stormwater treatment practice, which is realized through bellowing processes[107]:

1. Interception, which is operated by plants that grow in structural soil;
2. Evapotranspiration, also realized with vegetation layer;
3. Infiltration, which refers to the process of water moving into the soil;
4. Storage, which refers to the process of subbase reservoir slowing and extending the release of stormwater;
5. Bioremediation, referring to the process of binding and breaking down pollutants by microorganisms, plant roots, and soil particles.

2.3.5.3 Design Considerations

The stormwater treatment capacity of structural soil system is largely dependent on the reservoir depth, the materials mix, the installation, and the maintenance practice.[108] For instance, 60 cm deep CU-Structural Soil with 26% void space is able to infiltrate more

[106] CRWA, 2009
[107] Venhaus, 2012 (pg. 130-131)
[108] Venhaus, 2012 (pg. 131)

than 15 cm of rain in 24 hours.[109] Typically, structural soils are designed to drain water within 48 hours, to protect the vegetation's health and maintain optimal function.[110]

Since the basic objective of structural soils is to support the growth of vegetation in typically unfavourable conditions, thereby providing a variety of benefits for the sites, such as mitigation of the urban heat island, the depth of the structural soil must be taken into consideration at the outset of the design.[111] For supporting the growth of large trees, the optimum depth is 60 to 90 cm.[112]

In addition, monitoring and maintenance for the structural soil systems, such as inspection for debris and trash after a large storm event, and regular cleaning for inlet and outlet pipes to prevent clogging, should be planned for their optimum performance.[113]

2.4 FACILITIES IN STORMWATER TREATMENT TRAIN

2.4.1 Green Roof

2.4.1.1 Basic Description

Green roofs are special layers with waterproofing techniques and planting media that can capture, store and remove the runoff on top of buildings, and they are designed in order to reduce the quantity of water runoff and the rate of water flow.[114]

According to the opinion mentioned in *Rain Gardens: Managing Water Sustainably in the Garden and Designed Landscape*, if irrigation cannot be supplied during a very dry summer period, the roof will not be able to stay in a "pristine fresh green" condition, and because of this reason, it is better to use the term "eco-roof" or "living roof" rather than "green roof" for preventing misunderstanding.[115] The name "rooftop garden" is also mentioned in *Low Impact Development Stormwater Management Planning and Design Guide.*[116]

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109 Haffner & Bassuk, 2007
110 Day & Dickinson, 2008
111 Venhaus, 2012 (pg. 131)
112 Haffner & Bassuk, 2007
113 Venhaus, 2012 (pg. 131)
114 STS, 2015
115 Dunnett & Clayden, 2007 (pg. 56)
116 TRCA & CVCA, 2010 (pg. 4-23)

2.4.1.2 Application History

Green roof techniques have been applied into architectural area by human beings for thousands of years since the use of roof gardens and terraces. One of the famous examples was Villa dei Misteri in Ancient Roman city Pompeii. Those roofs with planting beds can be seen as older versions of intensive roofs. In North West Europe sod roofs which can be seen as older equivalents of extensive green roofs have been used since at least the Viking era. In Germany at the end of the 19th century, a great number of green roofs with layers of sod, sand and gravel were built in numerous rental apartment blocks for the purpose of fire protection. In the period between the two world wars, Modernist architects started to bring the idea of green roofs into house designs and garden designs. The book *Cinq points de l'architecture moderne* published in 1926 by Le Corbusier considers roof gardens as a recovery of constructed areas.[117]

Figure 2-13: Green Roof in Hochschule Neubrandenburg, Germany

The techniques for green roof system have made great progresses after the Second World War. For instances, in the 1950s German researchers started to study green roofs as urban habitats; in the 1960s the use of lightweight materials as growing media for the substrate layers was investigated; in the 1970s some market-leading companies produced the commercially-available modern green roof systems.[118]

[117] Gianni Michael Vesuviano, 2014
[118] Dunnett & Kingsbury, 2004

2.4.1.3 Major Categories

According to Vesuviano's opinion, modern green roofs can be classified into two categories: extensive type and intensive type. The key differences between them are connected with the vegetation layer, substrate layer and maintenance regime. An extensive green roof is constructed with a substrate layer that is less than 150 mm deep, while the depth of an intensive green roof substrate is generally more than 150 mm. The planting options for an extensive green roof may be the tough and hardy plants which can survive in expose areas with poor soil and dry weather such as those from a mountain, cliff, coast or dry meadow area (according to Dunnett and Clayden's opinion, the best choices are Sedum family plants and mosses.[119]), while for an intensive green roof the selection of plants is much greater as the planting conditions are better. The input and maintenance regime for an extensive green roof should be low and simple, while for an intensive green roof the input may be much higher, since regular maintenance is required to remove dead and invasive plants, and irrigation may also be required when there is not enough rainfall.[120]

While according to the summary of Dunnett and Kingsbury, the types of green roof can be classified into three categories: extensive type, semi-extensive type and intensive type. The substrate depth of an extensive green roof is less than 100 mm, and the planting possibilities may be from sedum or moss communities (when the substrate depth is less than 50 mm), or grasses and alpines, low-growing drought-tolerant perennials, short wild flower meadows and small bulbs (when the substrate depth is between 50 mm and 100 mm). The semi-extensive green roof is with a substrate depth between 100 mm and 200 mm, and with a range of planting possibilities such as mixtures of bulbs, grasses, low-growing to medium-growing perennials, annuals from dry areas, wildflower meadows and hardy sub-shrubs. Intensive green roofs refer to those whose substrate layers are more than 200 mm deep, and with planting selections from edible plants, medium shrubs, turf grasses, generalist perennials and grasses (when the substrate is less than 500 mm deep), or from turf grasses, perennials, shrubs, small deciduous trees and conifers (when the substrate is more than 500 mm deep).[121]

[119] Dunnett & Clayden, 2007 (pg. 67-68)
[120] Gianni Michael Vesuviano, 2014
[121] Dunnett & Kingsbury, 2004

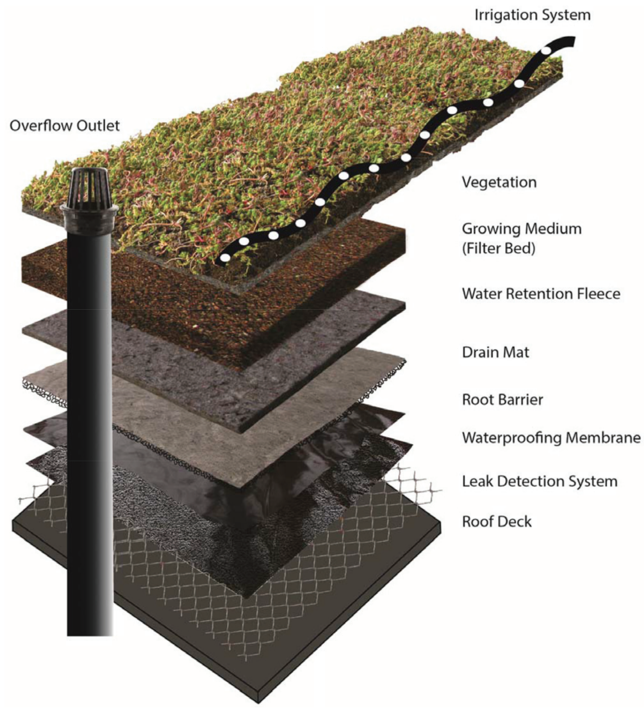

Figure 2-14: Structure of Green Roof[122]

2.4.1.4 General Structure

Figure 2-14 shows the general structure of a green roof system. According to their functions, these layers can be classified into five categories as follows:

1. Protection layer (waterproof & root barrier) – the base layer in a green roof system. This layer must meet the requirements to be both waterproof and root-proof. Essentially, it is an additional layer over and above the existing roof surface. The most important objective is to protect the roof surfaces from being damaged by the roots of the plants, especially for bitumen and asphalt roofs which are vulnerable to plant roots. The weakest parts of roof surfaces may be the joins between the roofing felt sheets since the plant roots may get inside and exploit them.[123]

   To achieve these objectives, a layer of waterproofing sheet membrane (monolithic or thermoplastic) is usually used to cover the roof surface. Otherwise, a “liquid-applied inverted roofing membrane assembly system” in

[122] TRCA, 2016 (pg. 126)
[123] Dunnett & Clayden, 2007 (pg. 57, 60)

which the waterproofing is placed between the roof structure and the insulation can also be used. Moreover, a chemical or physical root barrier is usually placed onto the membrane as an additional protective layer.[124]

2. Drainage layer – the layer standing onto the protection layer. This layer provides the function of releasing excess water collected by the green roof. Preformed plastic cellular materials are usually applied to construct a commercial drainage layer, and the form of simple lightweight aggregates can also be applied for the same effect[125]. The porosity in this layer should not be less than 25%[126].

3. Filter mat– a layer made of geotextile material above the drainage layer. It works as a filter to prevent the drainage layer from being clogged up by substrates.[127]

4. Substrate layer (growing medium) – a layer consisting of lightweight artificial soil for the plants to grow upon. Aggregate materials such as light expanded lay granules, recycled crushed bricks or tiles, perlite or vermiculite, mixed with a small portion of organic matter like green waste compost are usually used for commercial substrates.[128]

   According to *Stormwater Management Planning and Design Guide*, the materials for this layer consist of crushed brick, gravel, sand, compost or organic materials mixed with soil. In an extensive green roof, the depth of this layer ranges from 40 mm to 150 mm, and in the fully saturated situation the loading is between 80 and 170 kilogrammesa per square metre.[129] While according to *Stormwater Management Manual*, the growing medium layer cannot be less than 100 mm deep, and the compositions should include about 10% digested fibre, 20% organic materials and 70% porous materials.[130]

5. Vegetation layer – a layer consisting of plants to provide the "green elements" for the roof. The most widely used plants for this layer are sedums since they have many advantages such as hardiness and drought tolerance As succulent

[124] TRCA & CVCA, 2010 (pg. 4-31)
[125] Dunnett & Clayden, 2007 (pg. 57)
[126] PDEP, 2006
[127] Dunnett & Clayden, 2007 (pg. 57)
[128] Dunnett & Clayden, 2007 (pg. 58)
[129] TRCA & CVCA, 2010 (pg. 4-31 – 4-32)
[130] CPES, 2008 (pg. 2-38)

plants, sedums can collect much water with the tissues, and during dry seasons they can shut themselves down to conserve stored water. *Sedum album*, *Sedum reflexum* and *Sedum bispanicum* are commonly used species from Sedum genus in a green roof system.[131]

As described in *Stormwater Management Manual*, the suitable species for a green roof should be drought-tolerant, self-sustaining, able to withstand heat, low-maintenance needy, perennial or sowing, and fire-resistant. In addition, at least 90% area must be covered by drought-tolerant plants within two years. More than 50% area must be planted with evergreen species. Only 10% or less area can be covered with non-vegetated materials such as pavers, gravel ballast and so on.[132]

2.4.1.5 Design Requirements

To design an eco-roof system there are two basic requirements that should be taken into consideration: structural loading and waterproofing.[133]

For extensive green roofs, according to *Stormwater Management Manual*, if a green roof is to be added to a building structure, generally the structure must have the ability to hold a saturated weight from 75 to 150 kilogrammes per square metre area.[134] While according to *Minnesota Urban Small Sites BMP Manual*, if a green roof is heavier than 80 kilogrammes per square metre, when saturated, then it is required to consult a structural engineer.[135] *Designing the Sustainable Site: Integrated Design Strategies for Small-scale Sites and Residential Landscapes* recommends a structural loading of aound 70 to 170 per square metre, and for intensive green roofs, it should be around 290 to 970 per square metre.[136]

Moreover, only the precipitation that falls directly on the roof surface is allowed to be collected by the eco-roof, which means runoff from other areas is not allowed to be received by the eco-roof.[137]

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131 Dunnett & Clayden, 2007 (pg. 58, 68)
132 CPES, 2008 (pg. 2-38 – 2-39)
133 Dunnett & Clayden, 2007 (pg. 59)
134 CPES, 2008 (pg. 2-37)
135 Barr Engineering Company, 2003
136 Venhaus, 2012 (pg. 98)
137 TRCA & CVCA, 2010 (pg. 4-25)

In addition, there is a limit for the slope of a green roof. According to *Stormwater Management Manual*, it cannot be more than 25%.[138] While according to *Low Impact Development Stormwater Management Planning and Design Guide*, the maximum slope is only 10%, and additional erosion control measures are required for stabilizing the drainage layer on a slope roof.[139]

2.4.1.6 Major Benefits

The major benefits of green roof system include reducing runoff on a building roof from storms, filtering pollutants from the water, moderating microclimate around the building, providing a habitat for the wildlife, protecting the building roof from damages, and beautifying the appearance of the roof[140]. According to some studies, green roofs can change a post-developed peak runoff rate to a near pre-developed rate[141], and a conservative reduction rate for runoff volume is recommended to be from 45% to 55%[142]. Another study shows that a rainfall of 10 mm or less could be fully absorbed by most green roofs, and the retention rates for a rainfall of 28 mm would vary between 8% and 43%.[143] Green roofs can humidify and cool the surrounding air to mitigate the urban heat island effect. The runoff from the roof will also be cooled, which is beneficial to the aquatic life that is sensitive to temperature change.[144] Besides, green roofs are able to absorb the particulate pollutants conveyed by the air[145], to consume the carbon dioxide and oxygen production[146], to reduce noise from outer area, and so on.[147]

2.4.1.7 Potential Contamination

About the pollutant removal capacity of green roofs, a study completed in 2006 by *Toronto and Region Conservation Authority* has analysed the quality of the runoff from conventional black roofs and green roofs in Toronto. It showed the loadings of pollutants such as Nitrate, Aluminum, Zinc, Copper and total suspended solids from the eco-roof is around 70%~90% less lower than that from conventional black roof, but the

[138] CPES, 2008 (pg. 2-37)
[139] TRCA & CVCA, 2010 (pg. 4-25)
[140] STS, 2015
[141] CPES, 2008 (pg. 2-37)
[142] TRCA & CVCA, 2010 (pg. 4-26)
[143] Simmons et al., 2008
[144] TRCA & CVCA, 2010 (pg. 4-28)
[145] Johnston & Newton, 1993
[146] Getter et al., 2009
[147] Lagström, 2004

loading of total phosphorus is 248% higher than that from conventional black roof.[148]

Higher concentrations of nutrients in runoff from green roofs were also found in other studies, which may be caused by leaching from the growing medium.[149] Certain growing medium and maintenance practices such as pesticide and fertilizer application may pollute stormwater runoff.[150] Due to this, special attention should be given to components and characteristics of the growing medium and the potential for binding, retaining or leaching pollutants.[151]

Solutions like using controlled-release or coated fertilizer and using less organic matter may reduce leaching.[152] Phosphorus may be further reduced by filtering it from runoff through absorbing media.[153] Another solution is to put the green roof into a stormwater management train, using following biofiltration practices such as filter strips, swales and rain gardens for the subsequent treatment of pollutants on-site.[154]

2.4.2 Permeable Pavement

2.4.2.1 Basic Description

Permeable pavements or pervious pavements refer to the paving constructions that use materials containing pore or voids, which allow runoff from rainfall or melt snow to percolate through the surfaces. Their main objectives are to reduce runoff and to remove pollutants, so that both the quantity and quality of runoff can be under control.[155]

Permeable pavements are typically suited for low-traffic applications such as pedestrian plazas, walkways, parking lots, trails, alleys, driveways, residential streets, emergency vehicle access, and low traffic roads.[156] Vegetated pavements are typically suited for seasonally or infrequently used areas where plants are allowed to regenerate after being disturbed by human activities, and best suited to regularly rainy climates.[157]

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[148] TRCA & CVCA, 2010 (pg. 4-27)
[149] Long et al., 2007; Berndtsson et al., 2006; Hathaway et al., 2008
[150] Venhaus, 2012 (pg. 132)
[151] Köhler & Schmidt, 2003
[152] Emilsson et, al., 2007
[153] Ma & Sansalone, 2007
[154] Venhaus, 2012 (pg. 133)
[155] Dunnett & Clayden, 2007 (pg. 103)
[156] TRCA & CVCA, 2010 (pg. 4-111); Venhaus, 2012 (pg.130)
[157] Venhaus, 2012 (pg.130)

2.4.2.2 General Structure

Generally, the structure of a permeable pavement system can be divided from top to bottom into four parts: pavement surface, open graded aggregate base, open graded aggregate subbase, and subgrade.[158] (Figure 2-15)

Aggregate base and subbase must meet the requirements for both structural support and runoff storage. Clean washed stones will be suitable filling materials since any aggregate fines will migrate downwards and may clog the subgrade layer.[159]

Geotextile fabric separations should be installed both beneath the aggregate base (to prevent the base aggregates from migrating downwards to clog the void spaces of the subbase aggregate), and beneath the aggregate subbase (to prevent subbase aggregates from migrating downwards to slump into the subgrade soil).[160]

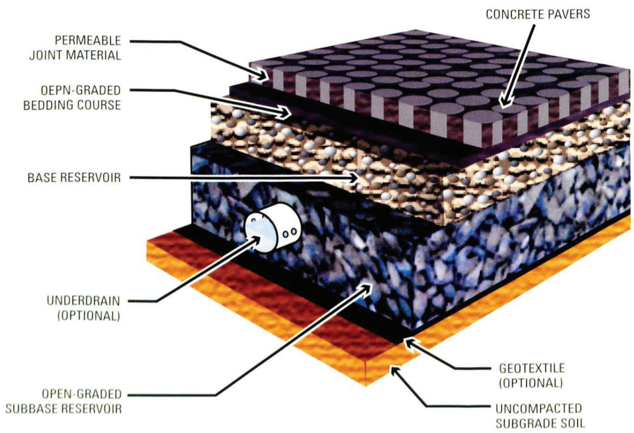

Figure 2-15: Structure of Permeable Pavement[161]

2.4.2.3 Major Categories

According to the materials used for the pavement surfaces, as described in *Stormwater Management Manual*, pervious pavements can be classified into two main groups: those poured in place such as pervious asphalt and pervious concrete, and those made of discrete units set in place such as permeable pavers.[162]

158 Hein, 2014
159 TRCA & CVCA, 2010 (pg. 4-122)
160 TRCA & CVCA, 2010 (pg. 4-122)
161 Venhaus, 2012 (pg. 128)
162 CPES, 2008 (pg. 2-40)

The classification in *Stormwater Management Planning and Design Guide* is similar, in which the materials are classified into four types: pervious concrete (Figure 2-16), porous asphalt (Figure 2-17), permeable interlocking pavers (Figure 2-18), and concrete/plastic grids (Figure 2-19).[163] Clearly, the former two can be classified into "discrete units" group and the latter two can be classified into "poured pavements" group.


Figure 2-16: Pervious Concrete[164] **Figure 2-17: Porous Asphalt[165]**


Figure 2-18: Interlocking Pavers[166] **Figure 2-19: Concrete Grids[167]**

According to the way the construction system is designed, similar to bioretention facilities, the types of permeable pavement systems also depend on the conditions of the native soils. In general there are three types of construction systems: full infiltration system (without any underdrain), partial infiltration system (with an underdrain), and no infiltration system (with an underdrain and an impermeable liner).[168] (Figure 2-20)

[163] TRCA & CVCA, 2010 (pg. 4-111)
[164] Tarmac, 2019
[165] Universal Seal, 2016
[166] PCA, 2019
[167] Rotsztain, 2013
[168] TRCA & CVCA, 2010 (pg. 4-111)

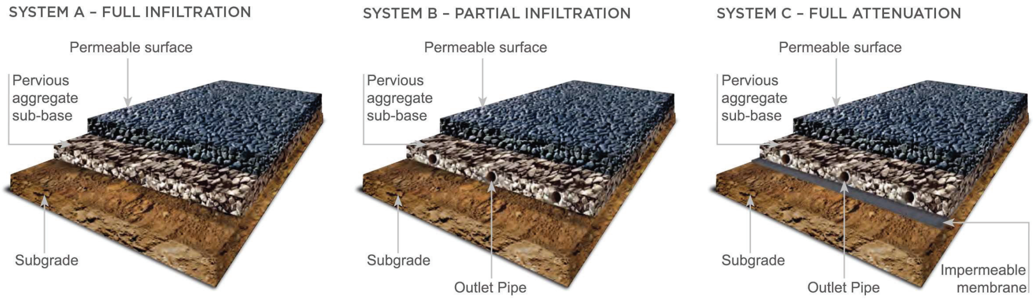

Figure 2-20: Categories of Permeable Pavement System[169]

In form and structure, pervious concrete and asphalt are similar to traditional concrete and asphalt. The main differences include that the fine materials (such as sands) have been removed from pervious concrete and asphalt structure, and their top lifts are thicker than traditional pavements for the stability requirements.[170]

Different types of permeable paver materials are provided on today's market for different usages. About the requirements for the materials, as mentioned in *Stormwater Management Manual,* restraints for paver edges need to be permanent. For commercial areas, private streets and public roadways, the width of the restrains should be at least 150 mm and the depth should not be less than 300 mm. For residential areas, the restraints can be made of plastic that is set with spikes.[171]

2.4.2.4 Working Processes

According to *Designing the Sustainable Site: Integrated Design Strategies for Small-scale Sites and Residential Landscapes*, the major processes of permeable pavements for runoff reduction include[172]:

1. Interception, operated by the vegetation growing in the pavements;
2. Evapotranspiration, also operated by the vegetation layer;
3. Infiltration, which refers to the movement of water into contact with subsoils;
4. Storage, realized by the open spaces in the pavements and the subbase, which

[169] Tarmac, 2015
[170] CPES, 2008 (pg. 2-40)
[171] CPES, 2008 (pg. 2-41)
[172] Venhaus, 2012 (pg. 129)

operate as micro-detention basins storing the water until it moves away through evaporation back to the atmosphere, percolation into subsoil, or transportation via discharge pipes;

5. Bioremediation, referring to the process of binding and breaking down pollutants by microorganisms, plant roots, and soil particles.

2.4.2.5 Design Considerations

According to *Stormwater Management Manual,* some attentions must be attached to the designing processes of pervious pavements, such as: construction of permeable pavements over underground parking, utility vaults, cisterns or other impermeable surfaces should be avoided; construction of permeable pavement over fill soils should be avoided; specific design must be established for dealing with the water retention under the pavements with slope greater than 5%, and any slope greater than 10% must be avoided; if the infiltration rate is less than 50 mm per hour, then the paving layer must cover a filter strip area.[173]

In addition, according to *Stormwater Management Planning and Design Guide*, permeable pavement systems can be designed to collect runoff from adjacent impermeable surfaces, but the ratio of "the total impermeable area releasing runoff" to "the total permeable area receiving runoff" should not exceed 6:5.[174] If there is any possibility of clogging the permeable areas, then the runoff treatment is discouraged.[175]

Moreover, for infiltration permeable pavement systems, the stone reservoir bottom should be designed to be flat to infiltrate runoff thorough the soil surface evenly. As for partial infiltration and no infiltration practices, the bottom should be design to be sloped at 1% to 5% towards the underdrain.[176] In addition, the subgrade slope should not exceed 5% in case of subbase instability caused by additional water movement.[177]

Besides, suitable restraints are required for providing edge support for paver units, in order to prevent pavers rotating under load and joints spreading afterwards. Concrete edges are the prior choices, and plastic or metal stripping can also be used in some

173 CPES, 2008 (pg. 2-41 – 2-42)
174 TRCA & CVCA, 2010 (pg. 4-120)
175 TRCA & CVCA, 2010 (pg. 4-117)
176 TRCA & CVCA, 2010 (pg. 4-122)
177 Ferguson, 2005

cases.[178]

The permeability of the pervious pavement system will decrease due to the possible clogging by contaminants such as small rocks, sediment and other debris. Due to this, permeable pavements should not receive runoff from unpaved areas[179], and maintenance like vacuum sweeping is required for this issue.[180] Even the pavement surface are 90% clogged, the permeable system should still be able to infiltrate water under design rainfall rates. The limiting infiltration rate is the subgrade soil.[181] The recommended rate for the design surface infiltration is 75 mm per hour for a 20-year-term use.[182]

2.4.2.6 Major Benefits

As an infiltration practice, the ability of permeable pavement to reduce runoff has been examined by research studies classified into two categories: full infiltration permeable paver applications, and partial or no infiltration permeable paver applications. Estimates have been made according to the results: partial and no infiltration pavement systems performed a runoff reduction capacity at 45%, while that for full infiltration pavement systems is 85%.[183]

Another test on the infiltration rates of three paving materials – pervious concrete and permeable interlocking concrete pavers and concrete grid pavers – in similar locations was done in 2006. The results showed that previous concrete performed the best infiltration rate that is 640 to 6600 cm/hour, and permeable interlocking concrete pavers performed about 100 to 4000 cm/hour, while the infiltration rate of concrete grid pavers is only 0.99 to 18.8 cm/hour.[184]

During the infiltration of runoff, permeable pavements also perform effective removal capacity to pollutants including nutrient, oils, bacteria, and deposited particulates.[185] This treatment is accomplished by catching those pollutants and putting them in to

178 TRCA & CVCA, 2010 (pg. 4-123)
179 Venhaus, 2012 (pg.130)
180 Hein, 2014
181 TRCA & CVCA, 2010 (pg. 4-125)
182 Smith, 2006
183 TRCA & CVCA, 2010 (pg. 4-115 – 4-116)
184 Hunt & Bean, 2006
185 Ferguson, 2005

contact with microorganisms and vegetation.[186]

Similar to other infiltration practices, the potential of permeable pavements to remove runoff pollutants depends on their capacity to infiltrate runoff. Full infiltration designs perform the greatest cleansing potential since they can collect most pollutants from the impermeable surfaces and release little as surface runoff.[187]

Other benefits can also be brought by permeable pavements, such as: they can mitigate the urban heat island effect, since the thermal capacity and thermal conductivity of porous materials are less than that of traditional impervious pavement[188]; they can reduce puddling or flooding during rainy seasons and can promote de-icing process during snowy seasons[189]; they can reduce surrounding noise, since porous surfaces are able to absorb sound energy and reduce air pressure between vehicle tires and the ground surfaces[190].

2.4.3 Planter

2.4.3.1 Basic Description

A planter (or "stormwater planter") is a structural vegetated container made of a durable material such as concrete, brick or stone. Its main purposes are to collect and to treat runoff, in the meantime to settle and to filter out pollutants and sediment within.[191]

Stormwater planters originated in Portland, Oregon, United Stated of America. According to the description, a stormwater planter can be seen as a "rain garden in a box[192]" or an "above-ground planting container[193]", and in *Stormwater Management Manual* it is described as a "structural landscaped reservoir[194]".

2.4.3.2 Major Categories

Similar to other bioretention facilities, stormwater planters can be classified into two

[186] Venhaus, 2012 (pg. 129)
[187] TRCA & CVCA, 2010 (pg. 4-116)
[188] Ferguson, 2005
[189] TRCA & CVCA, 2010 (pg. 4-117)
[190] Ferguson, 2005
[191] Cahill et al., 2011
[192] Cahill et al., 2011
[193] Dunnett & Clayden, 2007 (pg. 94)
[194] CPES, 2008 (pg. 2-53)

categories: infiltration planters and filtration planters (also named "flow-through planters").[195]

An infiltration planter allows water to seep into the groundwater system (the runoff can flow through the top mulch as well as the planting soil layer, and eventually infiltrate into the native soil), while a filtration planter does not allow infiltrating process and it only aims to cleanse runoff (the runoff is also allowed to flow through the top mulch as well as the inside soil layer, but it is prevented from infiltrating into the native soil and collected by drainage pipes then directed to approved disposal points). Due to this, the size of a filtration planter can be smaller than an infiltration one since its main purpose is to control the quality of runoff rather than the quantity.[196]

2.4.3.3 General Structure

As shown in Figure 2-21, the general structure of an infiltration planter consists of four layers, which from top to bottom include: a vegetation layer, a planting soil layer, a separation layer (filter fabric or fine aggregate), and a drainage layer (beneath which is the subgrade).

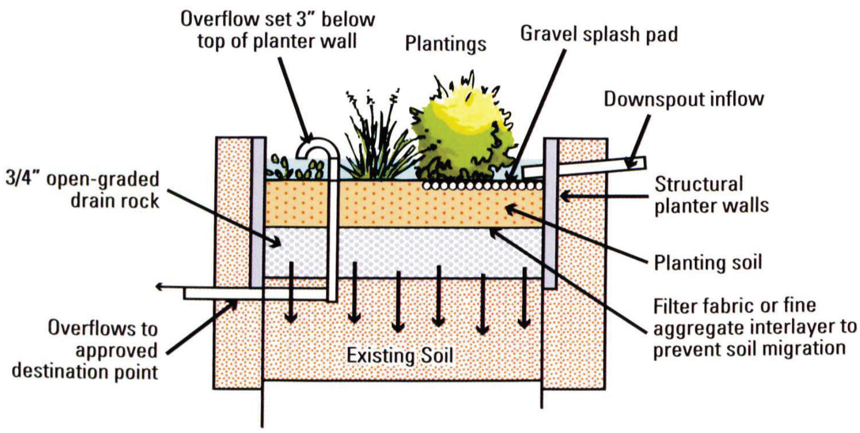

Figure 2-21: Structure of Infiltration Planter[197]

As shown in Figure 2-22, compared with an infiltration planter, the main differences of a filtration planter include: an impermeable liner is added beneath the drainage layer to prevent water infiltration into the native soil, and a perforated under drain system is

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[195] Cahill et al., 2011
[196] Cahill et al., 2011
[197] Venhaus, 2012 (pg. 156)

added within the drainage layer to discharge the excess water.

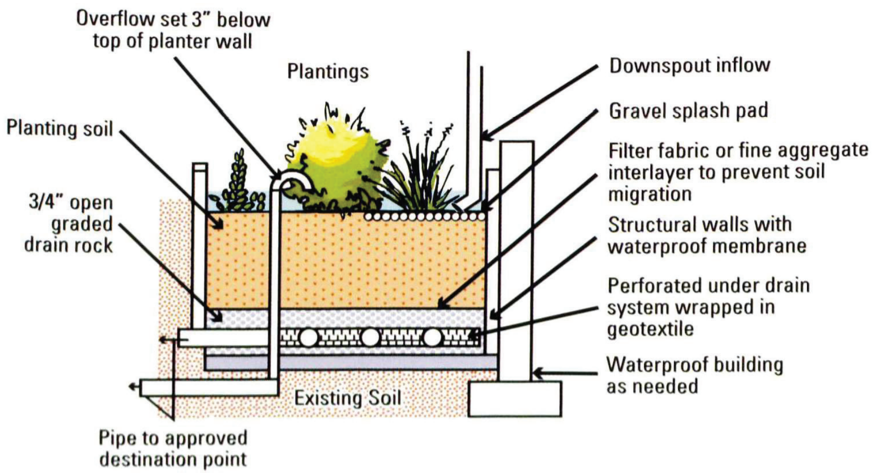

Figure 2-22: Structure of Filtration Planter[198]

2.4.3.4 Application Suitability

In the following cases filtration planters should be used instead of infiltration planters[199]:

1. When the infiltration rates of the native soil is too less to drain the water in time for the safety of the plants;
2. When the groundwater or native soils can be contaminated;
3. When the location is less than 30 metres from a well;
4. When the area is landslide or with a slope exceeding 10%;
5. When the location is in an area of new fill (less than 5 years);
6. When the location is in a possible spill area;
7. When the location is less than 3 metres from a building or a wall footing. (According to *Stormwater Management Manual*, the distance is 1.5 metres from property line and 3 metres from building foundation.[200])

[198] Venhaus, 2012 (pg. 156)
[199] Cahill et al., 2011
[200] CPES, 2008 (pg. 2-54)

2.4.3.5 Design Details

The width (measured from the area inside the planter walls) of an infiltration planter must be at least 760 mm, and of a filtration planter the width must be more than 460 mm. The minimum storage depth (from growing medium top to overflow inlet elevation) is 300 mm. A stormwater planter must be designed flat, and in any direction no slope more than 0.5% is allowed.[201] In addition, for the bottom of a infiltration planter, the distance from the bedrock should be more than 600 mm, and from the groundwater should be more than 900 mm.[202]

2.4.3.6 Subgrade Requirements

The infiltration rates of both the substrate (planting soil) and the subgrade (native soil) should be neither too high nor too low. If the rates are too high, the "retention time" for treating the water will not be enough; if the rates are too low, it will not be good for the safety of the plants.[203]

According to *Stormwater Management Manual*, the subgrade infiltration rate should be tested before the construction of a stormwater planter. If the result is higher than a certain value, then infiltration system should be applied; if the infiltration rate is lower than that, then filtration system should be applied.[204]

2.4.3.7 Plant Selection

The selection of plants for a stormwater planter can be in a wide range including different species of arbors, bushes, herbs and ground cover vegetation. It is better to apply dense vegetation for the effectiveness of water treatment and weed control. In addition, the flood-tolerant plants or drought-enduring plants should be the first choice to reduce the cost of maintenance. Moreover, ornamental plants such as colourful grasses, shrubs and perennial flowers should be taken in to consideration for aesthetic appeal of the landscape. Generally native plants should take priority, not only because exotic species may have a great impact for local habitat and hydrology, but also because

[201] CPES, 2008 (pg. 2-54)
[202] Venhaus, 2012 (pg. 156)
[203] Cahill et al., 2011
[204] CPES, 2008 (pg. 2-54)

native vegetation can provide better resource for local ecosystem.[205] Besides, for the safety of local environmental and downstream areas, the desirable species should not require additional pesticides or fertilizers and noxious species should be avoided.[206]

2.4.3.8 Major Benefits

As mentioned above, infiltration planters are able to reduce the flow rates and volumes of storm water, and filtration planters are effective at removing the pollutants and sediment from runoff. According to the estimation from *the Center for Watershed Protection*, the runoff reduction ability of stormwater planters will be from 40% until 80%, while their removal rate for phosphorus will be from 25% to 50% and for nitrogen will be between 40% and 60%.[207]

A stormwater planter can be designed to be placed in almost any type of landscape area. With the flexibility of its design and location, a stormwater planter can enhance aesthetic appeal to its surrounding area, and be able to attract wildlife.[208] Besides, compared to normal rain gardens, stormwater planters have the ability to store more water due to their different structures.[209]

2.4.4 Filter Strip

2.4.4.1 Basic Description

A filter strip is essentially a gently sloping vegetated area receiving overland sheet flow (shallow and widespread water) from adjacent impermeable surfaces, in the meantime breaking and slowing the flow, thereby reducing the total runoff and trapping the sediment and pollutants inside.[210] (Figure 2-23)

2.4.4.2 Working Processes

A filter strip acts as a stormwater treatment train component in several processes. First, it can slow down the sheet flow it received from adjacent areas during rainfall events; secondly, when the runoff flows through the vegetated surfaces of the filter strip, the

[205] Cahill et al., 2011
[206] Venhaus, 2012 (pg. 157)
[207] CWP & CSN, 2008
[208] LCREP, 2006
[209] Cahill et al., 2011
[210] Dunnett & Clayden, 2007 (pg. 118)

water will infiltrate into the soil, and in the meantime the contaminants carried by the runoff will be trapped by the vegetation and the soil, so the next runoff receiver will not be contaminated; thirdly, when rainstorms happen the vegetated layer can stabilize the soil surface, and thus prevent the soil from being eroded by the runoff.[211]

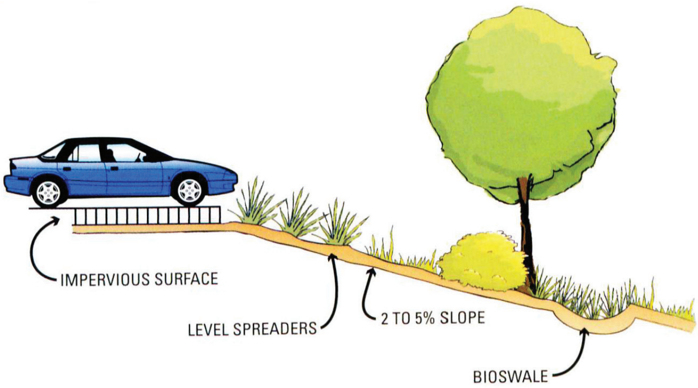

Figure 2-23: Typical Application of Filter Strip[212]

2.4.4.3 Design Considerations

The entire area of the filter strip must be covered with native vegetation such as grasses, wildflower blends, ground covers or any other combination.[213] Level spreaders, in the form of trenches filled with sand, pea gravel, bunchgrass, or crushed rock, can be installed along the front edge of the filter strips to distribute the runoff flow evenly.[214] The top of the level spreaders must be flat and with a suitable height to guide sheet flow into the soil directly, without scour.[215]

Crushed limestone may be utilised to fill the filter strips installed in commercial areas where the surface runoff may be contaminated by heavy metals.[216] In addition, the installation of filter strips must be more than 1.5 metres away from the property line, 3 metres away from buildings, and 15 metres away from creeks, streams, rivers, and wetlands.[217]

[211] Duzent, 2008
[212] Venhaus, 2012 (pg. 151)
[213] CPES, 2008 (pg. 2-62)
[214] Dunnett & Clayden, 2007 (pg. 118)
[215] CPES, 2008 (pg. 2-62)
[216] Dunnett & Clayden, 2007 (pg. 118)
[217] CPES, 2008 (pg. 2-61)

2.4.4.4 Design Details

According to *Stormwater Management Manual*, ,the width (measured in the flow direction) of a filter strip should not be less than 1.5 metres, and the slope should between 0.5% and 6%[218] (according to *Designing the Sustainable Site: Integrated Design Strategies for Small-scale Sites and Residential Landscapes*, the slope should not exceed 5%[219]). In addition, the adjacent pavement areas, which drain water to the filter strip, should not slope more than 6%.[220] Dense stands of vegetation is required, and fertilizer or other practises that may cause contamination should be avoided in the strip areas[221] About the selection of plants, both flood-tolerant and drought-tolerant, and also both tall and deep-rooted species can be considered, for the survival ability and runoff management capacity.[222]

2.4.4.5 Major Benefits

A filter strip can provide mane benefits to the site, including reducing the damages from flood, reducing water pollution thereby creating better aquatic ecosystem, reducing soil erosion thereby providing habitat for wildlife, creating attractive landscape thereby improving aesthetic value of the site.[223]

2.4.5 Swale

2.4.5.1 Basic Description

A swale is a long depression with shallow depth and narrow width, for the purposes of temporarily collecting and conveying runoff, thereby reducing total runoff rate and removing some pollutants within the water.[224]

As shown in Figure 2-24, swales are quite suitable for managing runoff from linear areas such walkways, driveways, highways and other roads, since they are essentially long and narrow depressions. Besides, for conveying and treating runoff from roofs, parking lots and other landscaped areas such as yards and parks, wales are also suited.

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218 CPES, 2008 (pg. 2-61)
219 Venhaus, 2012 (pg. 151)
220 CPES, 2008 (pg. 2-61)
221 Venhaus, 2012 (pg. 151)
222 Smith, 2000
223 Duzent, 2008
224 Dunnett & Clayden, 2007 (pg. 106)

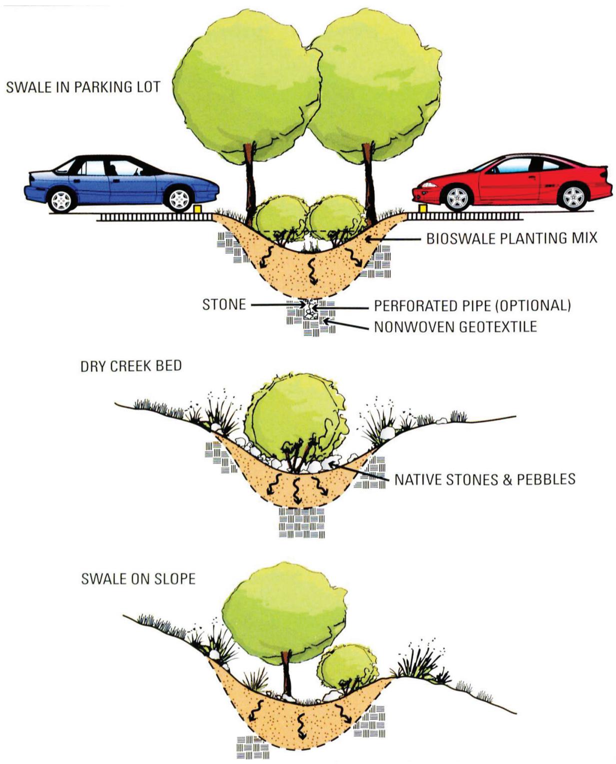

Figure 2-24: Typical Application of Swale[225]

2.4.5.2 Major Categories

According to different structures, swales can be classified into two major categories: "enhanced vegetated swales" (also named "enhanced grass swales") and "bio-swales" (also named "infiltration swales" or "dry swales"). Enhanced vegetated swales are essentially vegetated open channels for conveying, treating and attenuating stormwater runoff; bio-swales can be regarded as "enhanced vegetated swales incorporating engineered soil (such as growing media or filter media) bed, perforated pipe underdrains (optional), and bioretention cells (which are configured as linear open channels)". Due to these differences, bio-swales are better at water quantity and quality control than enhanced vegetated swales.[226]

According to the way the shallow zone is vegetated, the swales can also be classified into two groups: "grassy swales" and "vegetated swales". Grassy swales are usually vegetated with short turf grasses, and they are more suitable for the sites where water

[225] Venhaus, 2012 (pg. 152)
[226] TRCA & CVCA, 2010 (pg. 4-137, 4-149)

flow is encouraged. Vegetated swales are those where multi-level plantings (trees, shrubs, and groundcover plants) are applied, and their primary function is to promote infiltration.[227]

Swales can also be classified into "dry swales" and "wet swales". A dry swale acts as a bioretention facility temporarily storing, filtering and infiltrating strormwater runoff, which should remain dry during no-rainfall periods; while a wet swale functions in water quality treatment similarly as a wetland, since it typically stays wet due to the low bottom level below the water table.[228]

2.4.5.3 Design Considerations

Along the length of swales, check dams should be installed periodically to promote infiltration and to slow down the flows. If the installation site sloping, check dams are able to break the slope and to prevent erosion which is caused by excess flow.[229] The materials should be non-toxic and durable such as concrete, brick, rock or soil. The width and depth of the check dams depend on that of the swale.[230]

Similar to other bioretention facilities, the infiltration rates of native soils will determine the type of the swales. During a test taken before the construction, if the infiltration rate is higher than a certain value, then the swale should be built as an "infiltration system"; if the infiltration rate is lower than that, then the swale should be built as a "partial infiltration system" or "flow-through system".[231] In addition, if it is an infiltration swale, the distance between the construction location must be more than 1.5 metres from a property line and 3 metres from a building foundation, and for a flow-through swale there is such no requirement.[232]

2.4.5.4 Design Details

According to *Stormwater Management Manual,* on private property the swale should be built more than 1.5 metres wide and on street it should be more than 2.4 metres. The bottom should be flat and at least 0.6 metres wide. The side slope cannot be more than

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227 Dunnett & Clayden, 2007 (pg. 108)
228 Sample & Doumar, 2013
229 Dunnett & Clayden, 2007 (pg. 106)
230 CPES, 2008 (pg. 2-49)
231 CPES, 2008 (pg. 2-48 – 2-49)
232 CPES, 2008 (pg. 2-49)

1:3, and in a pedestrian-adjacent area it cannot be more than 1:4. The longitudinal slope must be less than 6%.[233]

According to *Stormwater Management Planning and Design Guide*, the bottom of a swale should be from 0.75 to 3.0 metres wide. The maximum side slope for enhanced vegetated swales is 1:2.5, and for bio-swales it is 1:3. The longitudinal slope should be from 0.5% to 4%.[234] Besides, if with check dams then the longitudinal slope should be more than 3%.[235]

According to *Designing the Sustainable Site: Integrated Design Strategies for Small-scale Sites and Residential Landscapes*, the typical slope is between 1% and 6%, and the optimal rate is from 1% to 2%.[236] For the selection of plant species, it is better to plant in multi-layers such as a combination of trees and shrubs and groundcover plants, and similar to filter strip, both flood-tolerant and drought-tolerant, and also both tall and deep-rooted species would be a good choice, for its capacity of survival and runoff management.[237] But, the plants restricting too much runoff will not be the optimum choice for the capacity of water transportation.[238]

The total area of a swale including the side slopes and the bottom must be planted with vegetation, and the depth of the growing medium shall be around 450 mm. Below the growing medium may be a layer of drain rock, and between the two layers a separating layer (which can be made of filter fabric) must be set.[239]

If overflow is predicted to occur, then in the swale must be connected to the main drainage network through a drainage pipe.[240] In private property areas, the material of the pipes should be cast iron (PVC SCH40 or ABS SCH40). In addition, 75 mm pipes are required if the total impervious area to be drained is less than 140 m²; 100 mm pipes are required if the total area is more than 140 m². In street areas, 150 mm or 200 mm ASTM 3034 SDR 35 PVC pipe and perforated pipe are required.[241]

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233 CPES, 2008 (pg. 2-49)
234 TRCA & CVCA, 2010 (pg. 4-143, 4-155)
235 PDEP, 2006
236 Jurries, 2003
237 Venhaus, 2012 (pg. 152)
238 Jurries, 2003
239 CPES, 2008 (pg. 2-49)
240 Dunnett & Clayden, 2007 (pg. 110)
241 CPES, 2008 (pg. 2-50)

According to *Pennsylvania Stormwater BMP Manual*, the temporal storage as well as infiltration for 25 mm storm and the conveyance for ten-year storm event should be provided by vegetated swales. For this purpose, an average ponding depth of 300 mm throughout and a 450 mm maximum depth at the end point of the channel should be maintained by swales. The ponding time should be more than 30 minutes and less than 48 hours, from which a 24-hour ponding time is desirable. According to some studies, when the depth of water flow is less than 150 mm, the swales show the maximum filtering ability. Higher flow velocities will reduce filtering rates and the vegetation will be caused to bend over if they are submerged by the water, which will reduce the roughness of the swales.[242]

2.4.5.5 Runoff Quantity Control

Instead of storing water permanently, swales take part in water management only during rainfall events, by allowing runoff to infiltrate into the soil and in the meantime filtering out pollutants, accumulating and holding the water for a few hours or days until directing the water into following stormwater treatment facilities, such as rain gardens or ponds.[243]

The ability of retaining runoff in native-looking swales was proved by some tests to be better than that in manicured swales. According to the results of the tests, 41% of the runoff was retained by the meadow-like swales mixed with flowering plants and native grasses, while only 27% was retained by the swales covered with short turf grasses.[244]

2.4.5.6 Runoff Quality Control

For bio-swales, their runoff removal capacity and pollutant removal capacity are similar with other bioretention facilities.[245] For enhanced vegetated swales, the pollutant removal operation is generally realised by infiltration, rather than filtration, since vegetation or check dam is only able to trap pollutants on the swale surface temporarily. The pollutant removal rates of swales depend on influent pollutant concentrations, and for most pollutants their cleansing capacity is moderate.[246]

[242] PCSL et al., 2006 (pg. 87)
[243] Dunnett & Clayden, 2007 (pg. 106)
[244] France, 2002
[245] TRCA & CVCA, 2010 (pg. 4-153 – 4-154)
[246] Bäckström et al., 2006

According to the results of some studies, the removal rate of enhanced vegetated swales for total nitrogen is 50%, for total phosphorus is 55%, for total suspended solids is 76%,[247] and for total copper and zinc is 60%.[248] The removal rates are also affected by site specific factors like swale length, vegetation cover, infiltration rate, soil type, and slope.[249]

2.4.6 Rain Garden

2.4.6.1 Basic Description

Rain gardens are essentially shallow planted depressions (usually with a depth of between 100 and 200 mm) that receive, soak up and filter runoff from other areas such as roofs, patios, driveways or other hard surfaces.[250]

They are designed not to transport water but to collect and absorb runoff, which is 30% more than that infiltrated by a conventional lawn, and to make the pollutants carried by the water settle and filter out during the periods when the runoff flows through the vegetation and infiltrates into the soil.[251]

With the practices of vegetation and infiltration, rain gardens are similar to other stormwater treatment facilities, such as stormwater planters, infiltration swales, and detention ponds, but these facilities differ from rain gardens in size, or shape, or water treatment. Rain gardens are relatively larger areas and playing a role as a “full stop” or a “substantial comma in the stormwater chain” to absorb as much storm water as possible.[252]

2.4.6.2 Application History

The designs of rain gardens originated in the late 1980s. The idea came from Prince George’s County, Maryland, United States of America (as the concept of “bioretention”, which aims to use vegetated areas to absorb contaminated runoff and make it infiltrate back into the ground, was carried out by Maryland Environmental Protective Department at the first time in public landscape schemes). The first case was applied in

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[247] Deletic & Fletcher, 2006
[248] Barrett, 2008
[249] TRCA & CVCA, 2010 (pg. 4-141)
[250] Hinman, 2013 (pg. 3); Venhau, 2012 (pg . 153)
[251] Dunnett & Clayden, 2007 (pg. 139)
[252] Dunnett & Clayden, 2007 (pg. 141)

a parking area, from which a natural practice using vegetation and soil was approved to be more cost-effective, compared to a standard engineering system. The performance data of the rain garden applications has been delivered by a collaboration with the University of Maryland to support the environmental and economic case. With the development of rain garden technology, this new idea has often been applied in private gardens.[253]

2.4.6.3 General Structure

As shown in Figure 2-25, the basic structure of a rain garden includes four layers: vegetation layer, mulch layer, soil mix layer, and existing soil layer. The recommended depth of the soil mix is from 300 mm to 600 mm; the typical ponding depth (from the lowest mulch level to the overflow level) is from 150 mm to 300 mm; and the maximum side slope of on the mulch layer is 2 horizontal to 1 vertical.[254]

To increase the capacity of water drainage, highly porous soil (amended with sand or compost) should be applied underlying the garden. In some cases, a gravel reservoir and perforated sub-drainage are also required to encourage quick drainage.[255]

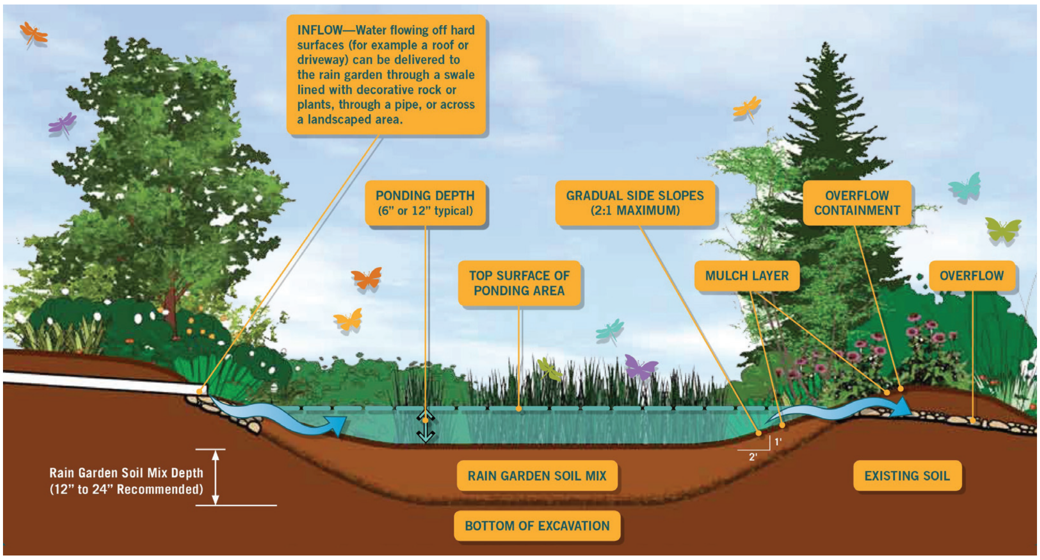

Figure 2-25: General Structure of Rain Garden[256]

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[253] Dunnett & Clayden, 2007 (pg. 141)
[254] Hinman, 2013 (pg. 30)
[255] Venhaus, 2012 (153)
[256] Hinman, 2013 (pg. 30)

2.4.6.4 Application Suitability

Rain gardens can be regarded as small type of sustainable stormwater management component, and would be the most popularly applied component in all kinds of areas such as public, residential and commercial areas.[257] Rain gardens are always seen as effective components to deal with environmental problems such as rainwater flood or pollution, but they will not work sustainably if they cannot bring enjoyment to the owners. It is essential to make a rain garden into a multifunctional place, rather than focusing on a single issue, and it is of great importance to place people-centred benefits on the same level with environmental benefits.[258]

According to *Rain Garden: A How-to Manual for Home Gardens* from the University of Wisconsin, there are some concerns that should be taken into consideration for designing a rain garden[259]:

1. The minimum distance between the rain garden and the house is 3 metres, in order that infiltrating water will not seep into the foundation;

2. The rain garden should not be placed directly over any septic system;

3. The rain garden should not be built in a shady area without any sunshine;

4. The rain garden should not be placed in an area where water ponds, since wet patches indicate slow infiltration;

5. Flatter areas are more suited for building a rain garden, since digging will be easier.

2.4.6.5 Design Considerations

To realize its maximum capacity of collecting runoff, a rain garden should face upslope by its longer side, whose length should be twice as its shorter side (which is recommended to be at least 3 m wide).[260]

A rain garden should be placed along a gentle slope that is less than 12%, and excessive

[257] Steiner & Domm, 2012
[258] Dunnett & Clayden, 2007 (pg. 15)
[259] University of Wisconsin, 2003 (pg. 4)
[260] Dunnett & Clayden, 2007 (pg. 144)

soil digging will be required if the slope is greater than 12%.[261]

In a rain garden at least 1 m deep growing media or infiltratable soil should be placed until reaching impervious bedrock, and 0.3m deep topsoil should be set as the top layer.[262]

The plant species suited for rain gardens should be able to tolerate both temporary inundation and dry conditions, since the flooding is not continuous but periodic.[263]

The infiltration rate of the native soil must meet the requirement of "when the rain garden is full of runoff, the water will infiltrate into soil within 24 to 48 hours", so that the plants will not stand in water for too long.[264]

2.4.6.6 Major Benefits

According to *Rain Garden: A How-to Manual for Home Gardens*, the main benefits of building rain gardens include[265]:

1. They can filter the pollutants carried by runoff, such as pesticides and fertilizer for lawn, fluid leakages from vehicles like oil, and other harmful substances from roofs or pavements, thereby protecting the receiving waters from pollution;

2. They can provide valuable habitat for wildlife, such as butterflies, birds, and beneficial insects;

3. They can recharge the aquifers through promoting infiltration of runoff into the ground;

4. They can reduce the negative effects of flooding caused by storms;

5. They can enhance the aesthetic level of sites;

6. Since the water is supposed to drain within 24 to 48 hours, and mosquitoes need longer time (normally 7 to 12 days) for laying and hatching eggs, rain garden will not cause the problem of raising mosquitoes;

[261] Franti & Rodie, 2013 (pg. 14, 17)
[262] Dunnett & Clayden, 2007 (pg. 139)
[263] Dunnett & Clayden, 2007 (pg. 140)
[264] Franti & Rodie, 2013 (pg. 4, 7)
[265] University of Wisconsin, 2003 (pg. 2-3)

7. Normally a rain garden will not be expensive to build and it does not require much maintenance afterwards.

2.4.6.7 Pollutant Purification Capacity

According to the results of some studies on simulated runoff events, the created biphasic rain gardens are capable to effectively remove nutrient pollutants and herbicide contaminants under high pollution loading levels. The removing rate is 91% for removing nitrate, 99% for removing phosphate, 90% for removing atrazine, 92 for removing dicamba, 99% for removing glyphosate, and 90% for removing 2,4-dichlorophenoxy.[266]

Other studies has also shown that the total reduced load of NH_4^+-N, TP and TN from targeted rain garden were more than 50%, but the reduction value was decreasing with the monitoring time increasing.[267]

The pollutant purification capacity of rain garden mainly depends on the cooperation of planting absorption, microbial degradation, and modified media filtration. In general, the lifetime of a rain garden can be divided into three periods[268]:

1. During the first 1-3 years, the rain garden is in its "growing age" with small vegetation layers and few microbial communities, whose pollutant absorption and degradation rate is lower than the filter media;

2. During the next 5-8 years, the rain garden can be seen as a "middle-aged rain garden", with the grown plants and expanded microbial communities, whose assimilation and degradation of pollutants will reach a dynamic balance with the filter medium adsorption;

3. During the last 10-15 years, the rain garden moves into its "elder age", due to the saturation of the pollutant absorption capacity of the filter medium, and the purification work mainly depends on the vegetation and microorganism.

[266] Yang et al., 2013
[267] Guo et al., 2018
[268] Guo et al., 2018

2.4.7 Pond

2.4.7.1 Basic Description

There are generally three types of ponds applied in a stormwater treatment train: wet pond, extended wet pond, and dry pond.[269]

Wet pond (also named “retention pond” or “retention basin”) refers to “impermeable basin that retains water permanently”. It acts as one of the final elements to collect runoff in a stormwater treatment train, and provides a final container where the water stays.[270]

Dry pond (also named “dry detention pond” or “detention basin”), in contrast, refers to “basin that dries out during low rainfall periods and only fills with water during rainfall events, while the collected water will be released in hours”.[271] (Figure 2-26)

Extended wet pond, in the form of combining those two types, has both permanent pool filled with water and additional storage that only fills with water (which will be released in hours) during storm events.[272]

Figure 2-26: Dry Pond Before Rainfall, China

Figure 2-27: Dry Pond After Rainfall, China

2.4.7.2 Water Treatment

Sedimentation may be an available solution to reduce the water pollution since many pollutants in urban runoff are in a state of suspended solids. “To convert the detention

[269] CPES, 2008 (pg. 2-68)
[270] Dunnett & Clayden, 2007 (pg. 121)
[271] Dunnett & Clayden, 2007 (pg. 121)
[272] CPES, 2008 (pg. 2-68)

basins (which already exist in some areas) into multifunctional basins to remove and store particulate pollutants" will be a feasible, economical and effective approach to runoff quality control.[273] This idea was inherent in the programs of the Soil Conservation Service, and firstly introduced into urbanizing areas by some studies (which begin in the year 1975) on nonpoint source pollution.[274]

As the main objective of this detention basin application is to fulfil the capacity of water quality control, and since the average pollutant load is usually contained in the relatively smaller discharges occurring after smaller floods that happen several times each year, the effectiveness of water quantity control in the detention basin will not be targeted.[275] Actually, in order to realize enough effectiveness of particulates settlement, the capacity of water quantity control will be sacrificed in some way, due to the reduction of some flood control outlets, for prolonging the runoff retention.[276]

2.4.7.3 Biodiversity Benefits

The water level in wet ponds is not stable, rising during heavy rain and falling after a period of time. This can create a wet area of draw-down zone that can provide a habitat potential for biological diversity. Besides, the biological diversity can be promoted by geographical diversity such as mixtures of shallows and hummocks.[277] Small wet ponds play a quite important role in protecting and promoting biodiversity. For instance, more than two-thirds of wetland animals and plants are supported by wet ponds in Britain.[278]

For most wetland wildlife, one of the most important things is that sufficient stability in the wet pond is provided. That means, the extent of dramatic changes of water level (which happen when great amount of runoff flows into the pond during stormwater periods, and drains away afterwards) should be minimized. Besides, the wet pond and its sediments will be disturbed (which will further lead to clouding as well as algal growth) by surging water caused by rapid inflow. To avoid these, direct inflow from main stormwater sources into the wet pond (such as downspouts water) should be avoided (which means that the wet pond should set in a position after other stormwater

273 William et al., 1983 (pg. 69)
274 William et al., 1983 (pg. 151)
275 William et al., 1983 (pg. 151)
276 William et al., 1983 (pg. 153-154)
277 Dunnett & Clayden, 2007 (pg. 121, 125)
278 William et al., 1997

treatment practices).[279]

2.4.7.4 Application Suitability

Since dry detention ponds are potentially not as attractive as wet ponds, especially lacking the aesthetic feature of their banks, they are not well suited for smaller-scale private gardens (unless the dry ponds can be used as smooth lawed basins for multiple servings during dry seasons).[280]

As for the cost of the detention basins, some issues must be considered, such as the size and number of the basins, proper maintenance of the basins, and the presence of insect vectors (such as mosquitoes). On one hand, the relatively larger basins are more economic according to most analysts' opinions; on the other hand, small basins still have some advantages, such as the flexible location of building basins, the convenience of assigning maintenance responsibilities, and the financial savings from public planning and construction.[281]

2.4.7.5 Design Details

For safety reasons, the depth and slopes of a pond should be designed as mild as possible. The depth around the perimeter of the pond should be distributed evenly, and not exceeding 0.6 metres. The slopes in the pond should not be more than 1 vertical to 3 horizontal. The structure of a detention basin should be divided into as least two cells, from which the forebay cell should share around 10% of the design surface area. Besides, in the forebay cell of a dry detention pond, a minimum of 150 mm dead storage should be provided for sediment accumulation.[282]

The edge of the water surface should be at least 6 metres away from property lines and structures. The distance between the toe of the pond berm embankment and the neatest property line should be 50% of the berm height, and the minimum distance is 1.5 metres. The edge of the water surface should be at least 30 metres away from a well, distribution box, septic tank, or septic tank drain field. The maximum rate of the surrounding slope is 10%. The edge of water surface should be at least 60 metres away

[279] Dunnett & Clayden, 2007 (pg. 122)
[280] Dunnett & Clayden, 2007 (pg. 121-122)
[281] William et al., 1983 (pg. 160-161)
[282] CPES, 2008 (pg. 2-69 – 2-70)

from the top of a slope whose rate is more than 15%.[283]

2.4.7.6 Potential Contamination

As a runoff collector in the stormwater chain, a wet pond is very easy to get polluted with contaminants within runoff, such as soluble pollutants, organic compounds and heavy metals. The wildlife will get harmed by potentially toxic elements, in the meantime algae will grow since the nutrient levels will increase in the water (which will also get green and murky). Due to these, it is necessary to set the wet pond in a position after other stormwater treatment practices (such as small reed beds, infiltration strips, and swales), which can pre-treat the runoff and act as buffer zones between the runoff contributors and the receiver. In addition, it is also important to prevent the wet pond from receiving drainage water from potential contamination sources such as heavily fertilized lawns or roads.[284]

It is also important to avoid too much solar exposure of open water areas, since high levels of light will increase the heat gain in the water body, thereby promoting the growth of algal and the development of anaerobic conditions.[285] One solution for light level control is to shade the water surface with planting materials (algal blooms will be cut down if half the water surface is shaded).[286]

2.5 SUMMARY

"Sponge City" is a concept for solving water-related problems in cities. The main objective of this concept is to create an ecological and economic way of development under conditions of conservations for natural water resources and remediation for contaminated water bodies. The practice processes of the sponge city concept include infiltration, detention, retention, purification, utilization, and discharge of rainwater. The key approaches to realise the sponge city concept include applying bioretention systems and creating stormwater treatment trains.

A bioretention system is a practice to deal with issues related to water quality and quantity, through plants, microorganisms and soil in a targeted area. The basic concepts related with a bioretention system include phytoremediation that refers to using plants

[283] CPES, 2008 (pg. 2-69)
[284] Dunnett & Clayden, 2007 (pg. 122)
[285] CPES, 2008 (pg. 2-75)
[286] Dunnett & Clayden, 2007 (pg. 134)

to purify contaminated water, bioremediation that refers to using living microorganisms to remove pollutants and to restore natural environment, soil organic matter that concerns all the organic materials (excluding aboveground living plants) related with soil, soil compaction and structural soil both of which concern the issues about soil conditions and the influences to plant growth.

A stormwater treatment train is an integrated approach that connect a series of water treatment facilities with each other to form a continuous stormwater management chain, in order to concern all aspects of runoff movements in a targeted area. The major facilities include green roof, permeable pavement, planter, filter strip, swale, rain garden, and pond.

CHAPTER 3 APPLICATIONS IN LEINEFELDE-WORBIS

3.1 BACKGROUND

The German town of Leinefelde-Worbis is located in the district of Eichsfeld in northwestern Thuringia, close to the border with Niedersachsen (Figure 3-1). With a height of 365 metres above sea level, an area of 96.55 km², and a total population of nearly 20 thousand, it is by area as well as by population the largest municipality in the district Eichsfeld and the functional centre for the eastern part of the district.[287]

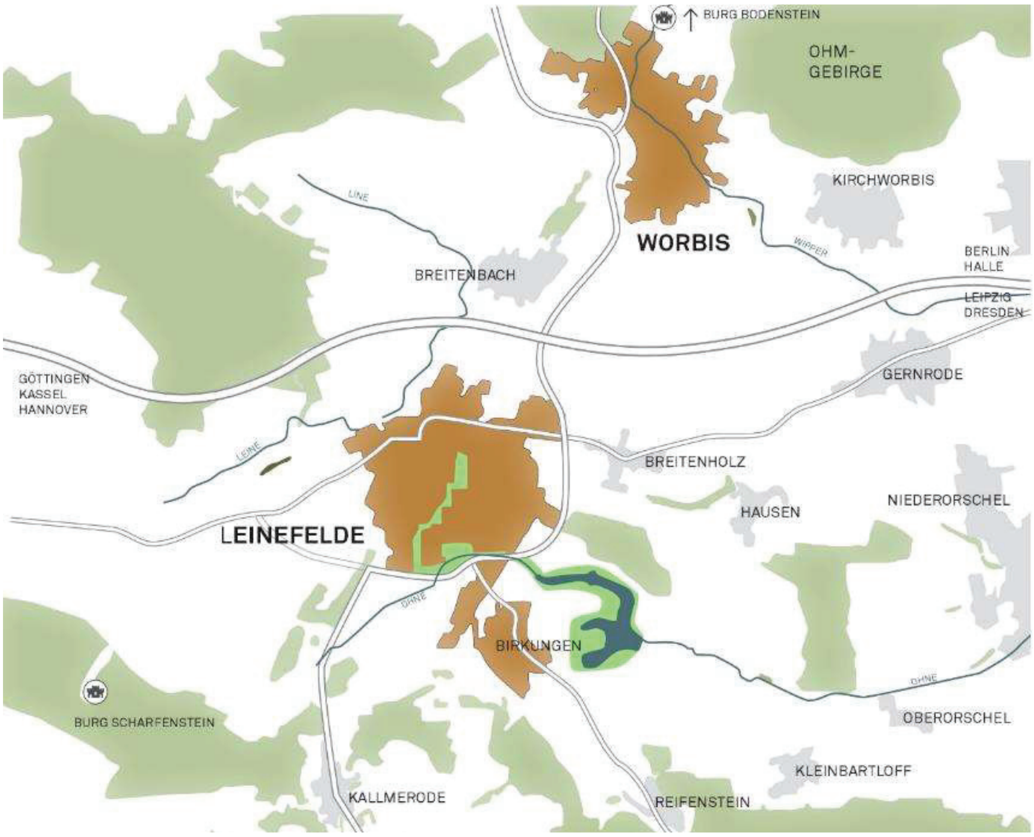

Figure 3-1: Location of the site[288]

In the year 2024, the Landesgartenschau (State Garden Exhibition) is going to be held in Leinefelde-Worbis City, whose motto is "Reconciliation between City and Landscape" (in German "Aussöhnung zwischen Stadt und Landschaft"). The objective is to develop a sustainable, functional and creative high-quality interface between settlement and landscape space through the integration of the urban planning, construction and

[287] Leinefelde-Worbis, 2019
[288] Bewerbungsunterlagen SINAI, 2017

landscape planning concepts.[289]

With the Landesgartenschau 2024, the city of Leinefelde-Worbis faces a major challenge after the successful urban redevelopment in Leinefelde. The area to be planned will be connected with the existing "Green Axis" (in German "Grünen Achse", marked as "4" in Figure 3-2), which runs from north to south through Leinefelde. The southern outskirt of Leinefelde, which is the core of the new entire area, is to be planned as a "Garden City" (in German "Gartenstadt", marked as "1" in Figure 3-2). The garden city will be partially built until the Landesgartenschau 2024 and will be completed later. Further to the south, the course of the Ohne River will be transformed in a natural way, cooperating with natural plants, wetland biotopes and orchards to create a walk path (marked as "2" and "5" in Figure 3-2). The walk path can then be continued without long detours to the Birkunger reservoir, where the tourists can experience the "Green Loop" (in German "Grüne Schleife", marked as "3" in Figure 3-2),) in the form of a campsite, with restaurants, a boat landing stage and a bathing area on the north shore. For this purpose, necessary measures must be taken to control the water quality of the Birkunger reservoir as well as the Ohne river.[290]

Figure 3-2: Landesgartenschau core area with "Green Axis" and "Green Loop"[291]

[289] Stadt Leinedelde-Worbis, 2019
[290] Landesgartenschau, 2019
[291] Bewerbungsunterlagen SINAI, 2017

The main objective of the project for the study is to provide a sustainable development plan for the entire garden city area (providing spaces for the private properties, streets, and other necessary components including public green spaces and playground), in the consideration of low impacts on the water quality in the Ohne river. This newly planned "Garden City" is to derive its special qualities from the idea of sustainability and the interrelation between the urban area to the north and the natural landscape to the south[292]. (Figure 3-3)

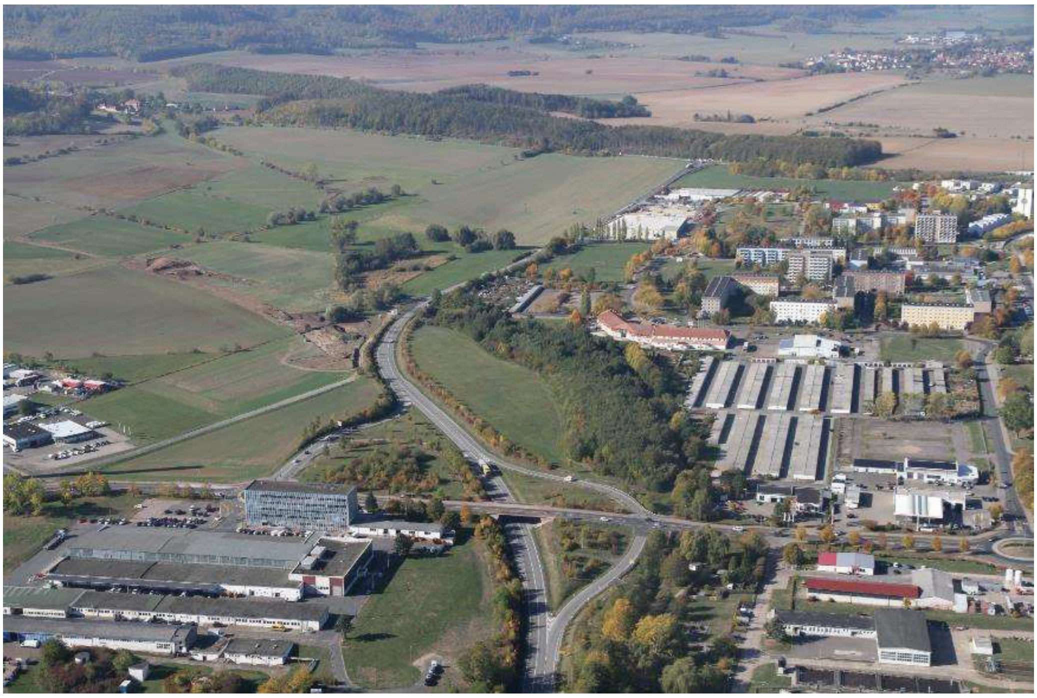

Figure 3-3: Bird's eye view of the project site area[293]

3.2 SITE ANALYSIS

3.2.1 Location Information

The project site is a transition zone between the residential area in the south city and the landscape area in the suburban space. Its main boundary is formed by the Lisztstraße on the north, the Beethovenstraße on the west, the Ohne river on the south, the Birkungerstraße and the paving area surrounding the Autohaus on the east. The size of this area is approximately 6.30 ha. (Figure 3-4)

[292] Stadt Leinedelde-Worbis, 2019
[293] Stadt Leinefelde-Worbis, Darstellung GRAS, 2019

Figure 3-4: Current situation in this area[294]

3.2.2 Elevation Data

This area is almost flat, with a 1% - 2% slope from north to south, with the highest point located in the northwest, and the lowest point located in the southeast. (Figure 3-5)

3.2.3 Building Situation

The commercial building in the bend of the Beethovenstraße must be considered as an existing framework condition. This also applies to the fast food restaurant and the car dealership on Liztstraße. The Autohaus is to be considered as an existing framework condition including the surrounding paving area. These buildings are excluded into the planning area in this project.[295]

The garage court by the Ohne river with its 850 garages represents an urban development malady and should be demolished by 2020. Clearance and the construction of replacement garage near the apartment have been initiated. The area is therefore in full perspective for the development of the future "Garden City" available. The building marked as "Gaststätte Biereck" in Figure 3-4 will be demolished in perspective and the

[294] Google Map, 2019
[295] Stadt Leinedelde-Worbis, 2019

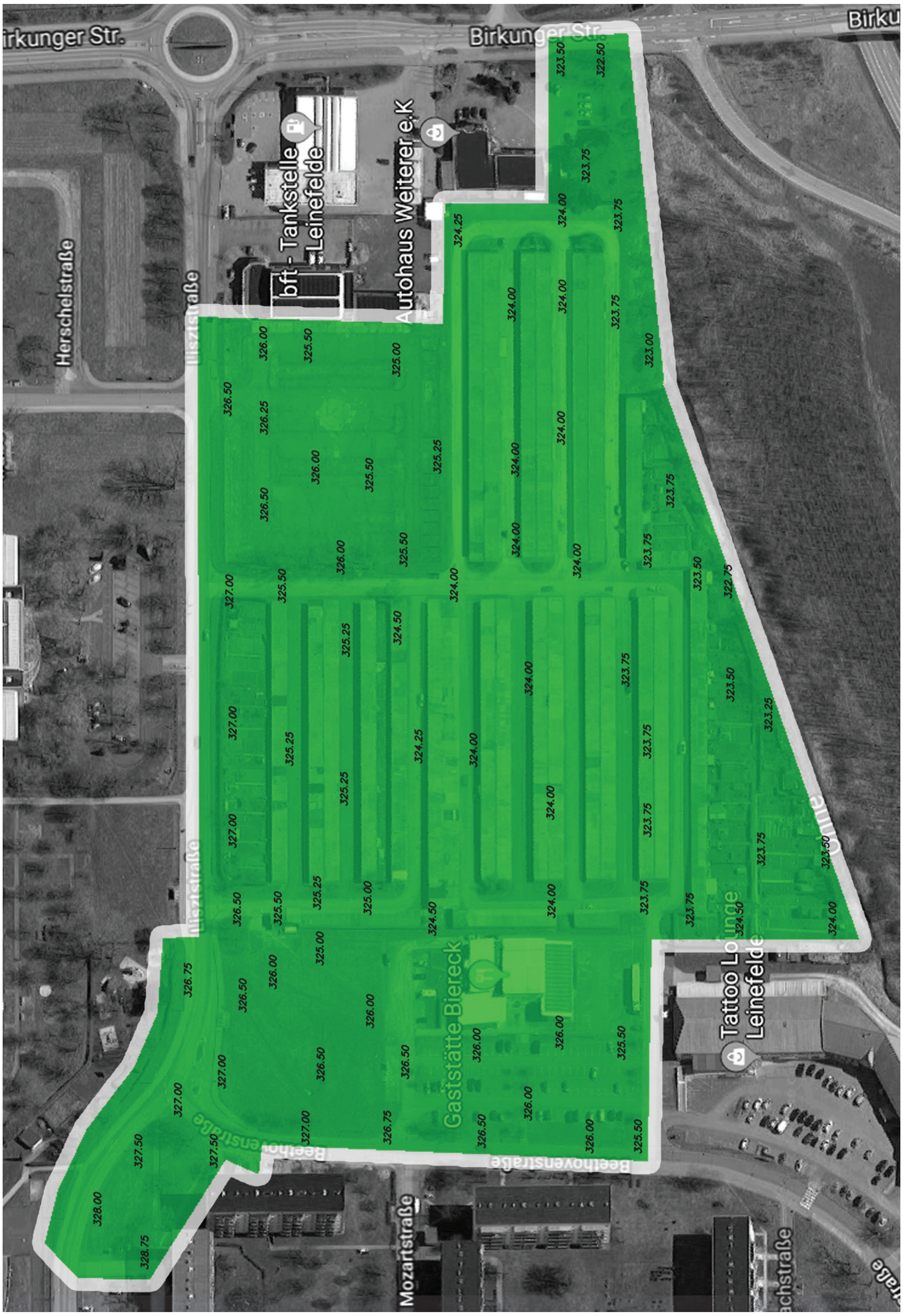

Figure 3-5: Current Elevation Map[296]

[296] LGS2024 KG mMedien & Profile, 2019

area will be included in the area to be planned. The parking lot to the west is also to be included in the area to be covered. Spare parking spaces for the west adjoining housing development must be proven a suitable form.[297]

3.2.4 Subsoil Conditions

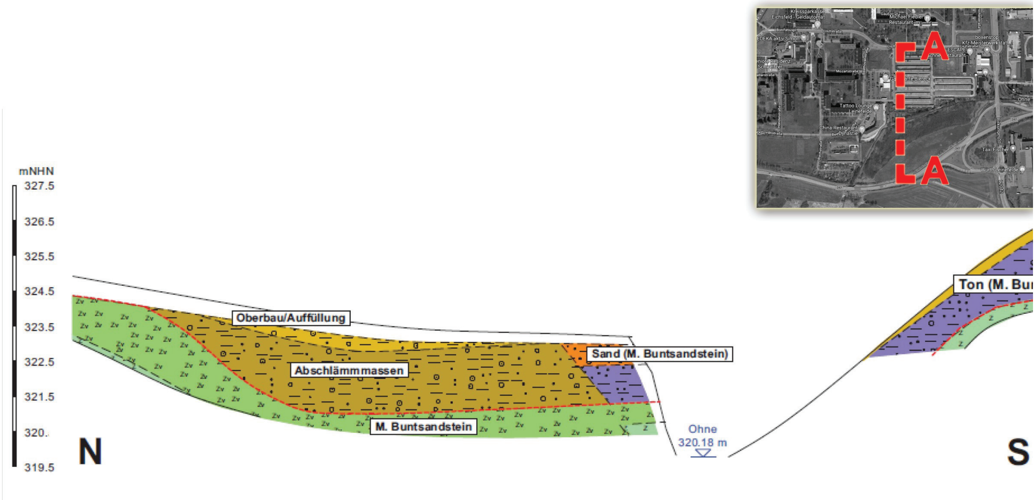

Figure 3-6: Section A-A of the subsoil layer structure[298]

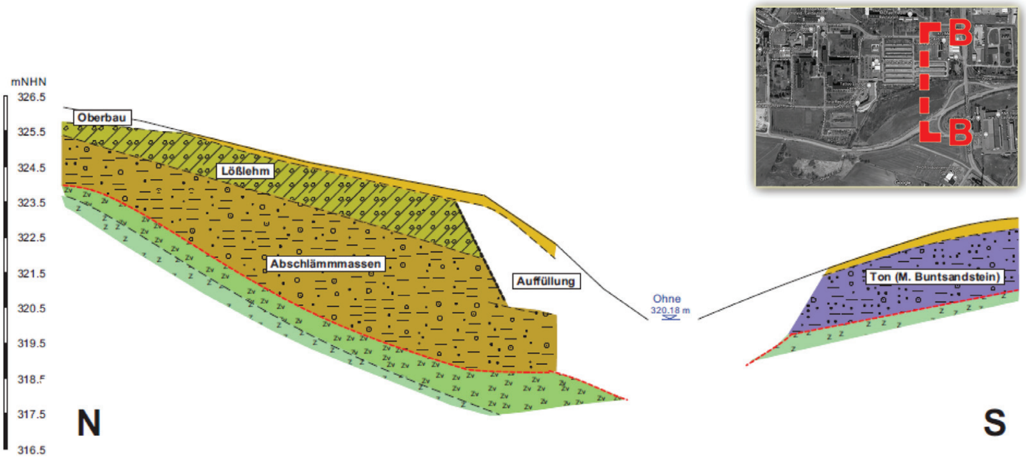

Figure 3-7: Section B-B of the subsoil layer structure[299]

297 Stadt Leinedelde-Worbis, 2019
298 IBBB mbH, 2018
299 IBBB mbH, 2018

According to the results of the foundation inspections work, the subsoil layer structure in this project site area mainly consists of five layers: top structure (Oberbau), filling material (Auffüllung), loess loam (lößlehm), silt mass (abschlämmmassen), and mixed sandstone (Buntsandstein). (Figure 3-6 and Figure 3-7)

Accoding to the results of the test for the infiltration of the soil, the permeability of the unconsolidated rock (Lockergestein) varies from 3×10^{-6} m/s to 3×10^{-8}m/s (proved), and the permeability of the solid rock (Festgestein) varies from 1×10^{-5} m/s to 1×10^{-7}m/s (assumed). Substrate predominantly low permeable. The subsoil is tested to perform a low average permeability which is not higher than 1×10^{-6}m/s.[300]

3.2.5 Air Pollution

The area of the project site may be affected by road traffic noise from the southeast as the Bundesstraße 247 runs as a bypass.[301] The expected traffic and noise pollution area shown in Figure 3-8 and Figure 3-9.

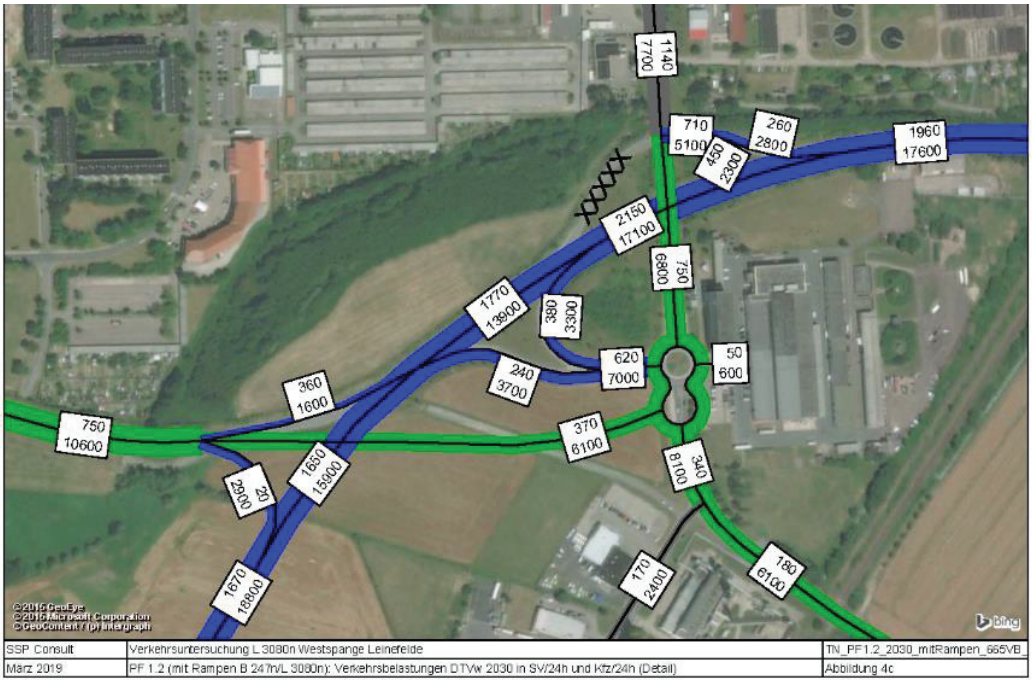

Figure 3-8: Expected traffic loads in the surrounding area[302]

300 IBBB mbH, 2018
301 Stadt Leinedelde-Worbis, 2019
302 TLBV, 2019

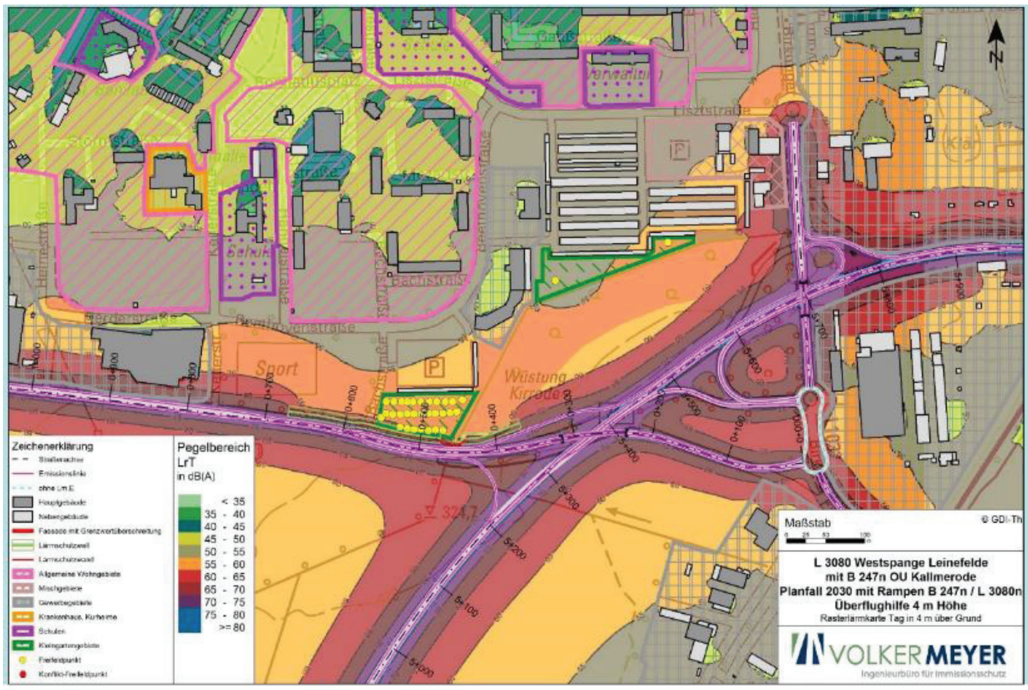

Figure 3-9: Noise protection calculation results (fly-over 4 metre height)[303]

3.2.6 Water Environment

By the south boundary of the garden city flows the Ohne river, which is a water body of about 14 km in length. It rises in the village named Kallmerode (not far from the garden city) from the southwest, and emerges into the Birkungen reservoir.[304] (Figure 3-10)

There are several rainwater sewer pipes going diagonally through the garden city with 45 degrees in the flow direction of the Ohne river, without pre-treatment. The outlet structures are located at the bottom of the existing river profile.[305] (Figure 3-11)

With a small catchment area, the Ohne river currently represents as a narrow, barely perceptible ditch with a small amount of water. Water from the surrounding areas need to be introduced into the Ohne river, thereby supporting the water balance due to the current low outflow.[306]

303 TLBV, 2019
304 Stadt Leinedelde-Worbis, 2019
305 Stadt Leinedelde-Worbis, 2019
306 Stadt Leinedelde-Worbis, 2019

In this case, the rainwater management system in this area must be re-planned in such a way that the water of the river and the artificial reservoir can be quantitatively and qualitatively improved.

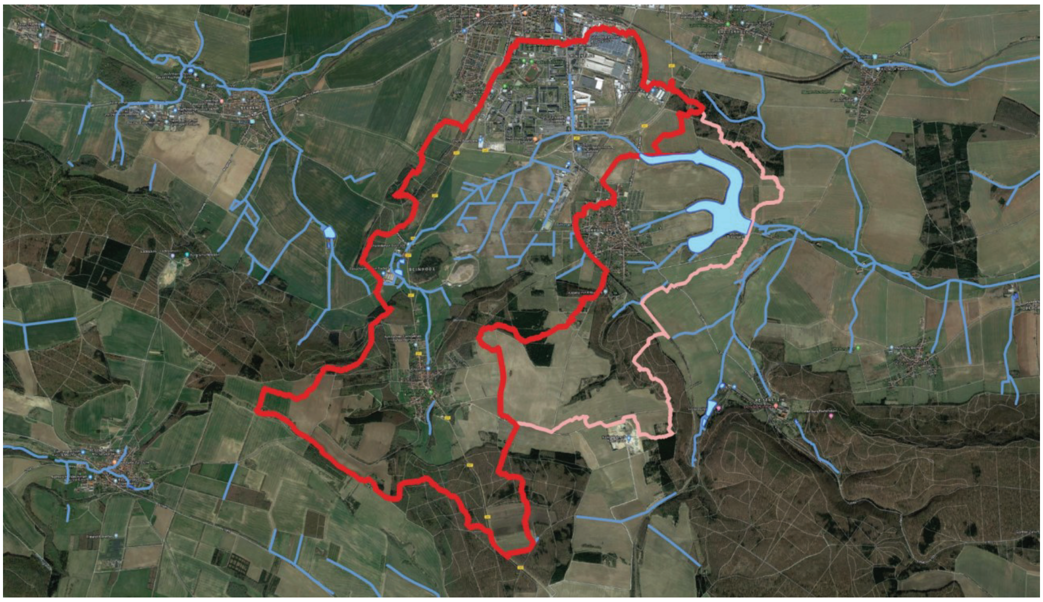

Figure 3-10: Catchment area of the Ohne river[307]

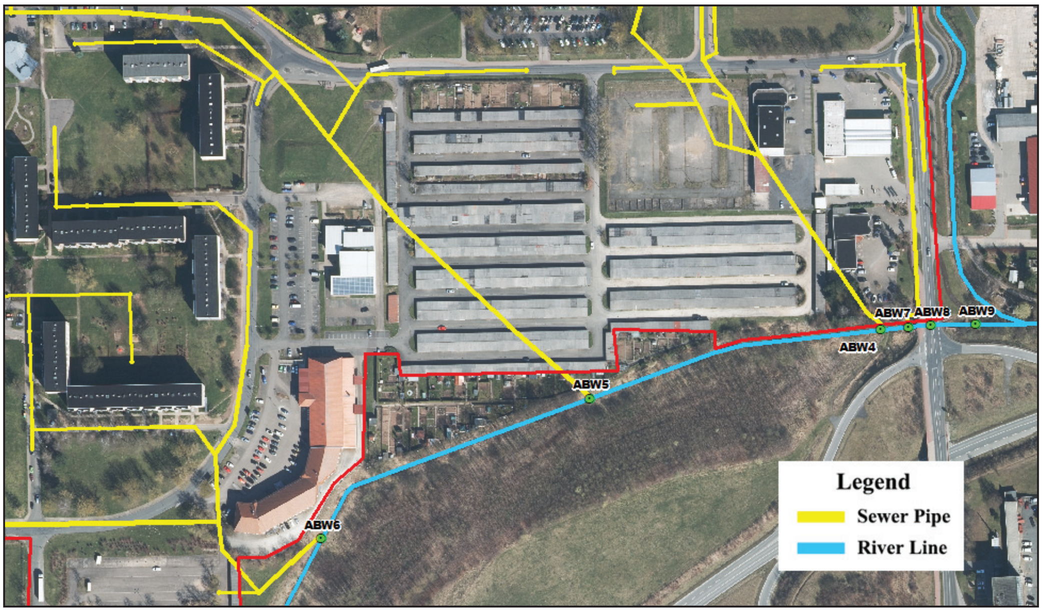

Figure 3-11: Current outlet rainwater sewer system in this area[308]

[307] Sieker et al., 2019
[308] Sieker et al., 2019

3.3 WATER ISSUES AT THE SITE

As mentioned above, the Ohne river is located by the south boundary of the garden city. It flows from the west to the east and finally into the Birkunger reservoir. During stormwater events, the river receives runoff without pre-treatment from the northern urban areas, thereby creating a great threat to the water quality of the river and the reservoir, and this is the main issue to be deal with at this site. Due to this, the main objective of this project is to find an effective solution to prevent the potential water pollution, caused by stormwater runoff without necessary treatment from the garden city area.

3.3.1 Causes of Water Problems

Water pollution is usually related with flooding, and both of them can be caused by three leading factors: development of floodplains, impervious surfaces, and combined sewer overflows.[309]

3.3.1.1 Development of Floodplains

Floodplants are relatively flat and low areas that are adjacent to water bodies and subject to flooding. They can be recognized as extension of water system, and act as conveyances and storages of overflowing water during flooding seasons. Major benefits that can be provided by floodplains include: reduction of flooding severities, removal of water pollutants, erosion control and channel stability, groundwater recharge, wildlife habitat, stream baseflow and so on. The development or alteration of floodplain will great reduce these valuable benefits mentioned above.[310]

3.3.1.2 Impervious Surfaces

Impervious surfaces decrease vegetated areas that are able to infiltrate and filter runoff and thus reduce the water volume remove the pollutants carried by it. They are regarded as the primary cause of problematic runoff in urban areas. According to the study from *Federal Interagency Stream Restoration Working Group*: when the impervious site surface is less than 10%, only 10% of stormwater will become surface runoff; when the impervious site surface is 10%-20%, 20% of stormwater will become surface runoff;

[309] Venhaus, 2012 (pg. 120)
[310] Venhaus, 2012 (pg. 121)

when the surface is 35-50% impervious, 30% of stormwater will become surface runoff; when the surface is more than 75% impervious, 55% of stormwater will become surface runoff.[311] (Figure 3-12)

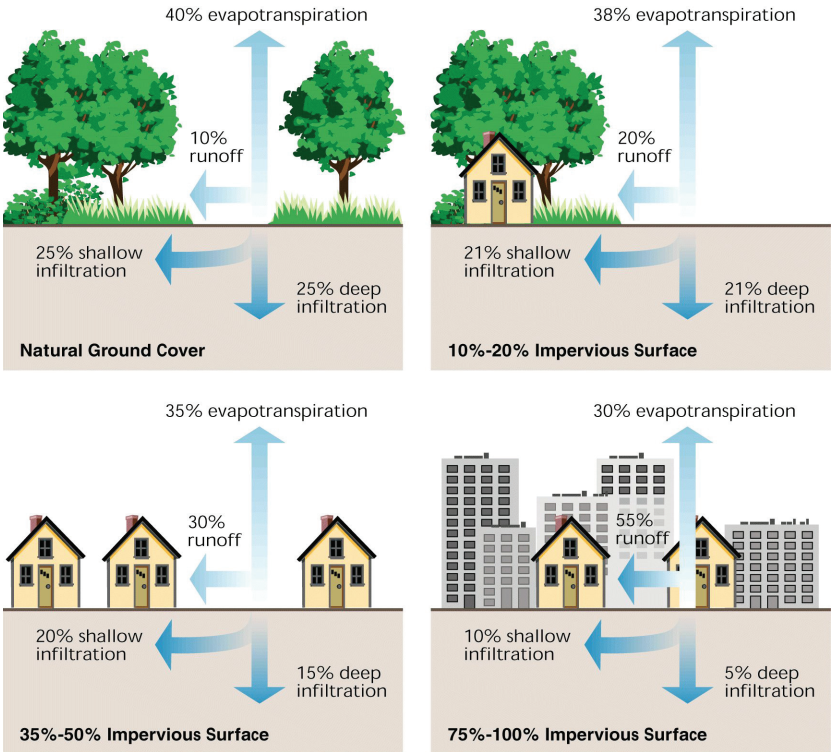

Figure 3-12: Relationship between Impervious Cover and Surface Runoff[312]

3.3.1.3 Combined Sewer Overflows

The traditional way of dealing with the storm water by piping them into another water body such as a lake or a river, is becoming more and more difficult to cope with the increasing rainwater runoff and the pollution brought by them on the earth surface, and will not be able to take the chance to use the stormwater as a valuable resource.[313]

Moreover, the older drainage systems, known as combined sewer systems, take not only excess stormwater from nature but also wastewater from humans (such as industrial waste and sewage), and convey the polluted water into a treatment plant. When intense rainfall events happen, stormwater runoff volume excesses the capacity of combined

[311] Dunnett & Clayden, 2007 (pg. 34)
[312] FISRWG, 1998 (pg. 3-23)
[313] Kenway & Lant, 2012

sewer systems, and the wastewater overflows into nearby receiving waters. This can result in pollution problems for natural water bodies since the sewage will be discharged into streams and rivers.[314] (Figure 3-13)

In addition, the excess stormwater may carry a large amount of pollutants when running off the sealed surfaces, such as discharges from automobiles, excrements from animals, bacteria, dust and dirt, sediment, heavy metals and so on. This can be a heavy pollution when the runoff drains into the natural water bodies such as ponds, streams or rivers. Some toxic elements inside may be harmful to the aquatic life, and some nutrients such as nitrogen or phosphorus can lead to the growth of algae, lack of oxygen and murkiness in the water bodies. This will largely diminish the quality of the natural water bodies, and create a great threat to the health of humans and wildlife.[315]

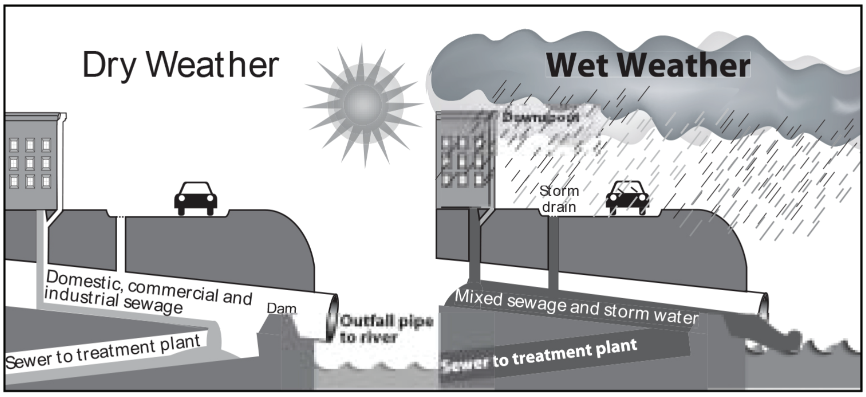

Figure 3-13: Typical Combined Sewer Overflow Structure[316]

3.3.2 Categories of Water Pollutants

According to *Stormwater Management in Urbanizing Areas*, the pollutants carried in urban stormwater runoff include both organic and inorganic components, as well as both soluble and insoluble materials. General stormwater pollutant categories include: suspended sediment, heavy metals, nutrients (nitrogen, phosphorus), bacteria and viruses, toxic organics (pesticides, PCBs), acids, oxygen-demanding substances, petroleum-based substances or hydrocarbons, and humic substances (precursors for trihalomethanes).[317]

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[314] Dunnett & Clayden, 2007 (pg. 35); Venhaus, 2012 (pg. 123-124)
[315] Dunnett & Clayden, 2007 (pg. 36)
[316] EPA, 2001 (pg. 1-2)
[317] William et al., 1983 (pg. 58-60)

According to *Designing the Sustainable Site: Integrated Design Strategies for Small-scale Sites and Residential Landscapes*, another classification of the major pollutant types include: sediments from improperly managed landscapes, vehicle wastes (fluids, exhaust, brake linings, tires and engine wears), animal wastes, fertilizer, pesticides, insecticides, road salts, coal tar-based sealants from paved roads, roofing materials, and debris.[318]

Compared with those two categories, the major categories of stormwater pollutants can be summarised as below:

1. Sediments;
2. Metals;
3. Chloride;
4. Nutrients;
5. Bacteria and viruses;
6. Other pollutants, such as acid, toxic organic, humus, hydrocarbons, etc.

3.3.3 Sources of Water Pollution

There are two kinds of water pollution sources: point source and nonpoint source. Point source refers to the pollution discharged into water bodies from specific, confined and discernible locations like sewers, ditches and pipes, while nonpoint source refers to the pollution which is discharged dispersedly across broad geographic areas and cannot be attributed to discrete points, such as polluted runoff from parking lots, roads, and other impermeable pavements. Because of the diverse original locations, compared with point source pollution, nonpoint source pollution is typically more difficult to trace, monitor and control. In this case, more efforts need to be put into the treatment of nonpoint source water pollution.[319]

From those mentioned above the suspended sediment may present in the largest amount. The possible reasons that would cause this problem may be concluded as: denuded and

[318] Venhaus, 2012 (pg. 122)
[319] Venhaus, 2012 (pg. 120)

loose soil, intense rainfall, moist soil that is saturated before, steep slope by the receiving water, and so on. According to some studies, the particulate form would be the most common form for the most important pollutants in runoff in an urban area.[320]

One of the major sources of suspended sediment pollution is soil erosion. In the urban areas, wind and cars could also be the transportations for particles, which would stay on the surface of impervious materials, or permeable ones. Then, those pollutants may be washed off from the surfaces into a receiving waters by some stormwater.[321] However, in the urban area, since most of the land has been developed into impervious surfaces, the washoff of the deposited particles becomes the most influential elements instead of soil erosion.[322]

Abrasion of automobile tires may also be one source of particle pollution. According to a study, more than 1 billion pounds of tires are worn off in the U.S.A. and 94% of this pollution stays in a form of large particles. In addition to the particle pollution, there are also pollutants such as zinc, oil and some oxygen-demanding organic polymers.[323]

Discharge of automobiles is also an important source of many pollutants in urban runoff. Some of the pollution originate from oil, which contains some chemical elements such as zinc and phosphorus. Some of the pollution originate from worn structures such as copper, chromium, and lead, which would stay on the surfaces. Some of the pollution originate from exhaust emissions such as nitrous oxides, hydrocarbons, and phosphorus. When there is a rainfall, all these various forms will be washed out from the atmosphere and become part of rainwater runoff pollution.[324]

Some pollutants may be transferred from particulate phase into dissolved phase or take the contrary transfer during the period when they flow into runoff. This fact will influence the way the potential control strategies to be designed. For example, the solids separation will fail to remove the pollutants remaining in soluble state, while on the contrast, the streamflow will not be able to carry the pollutants attached to sediment in a receiving water system. Most materials can be transferred between particulate and dissolve phases, except a few materials such as nitrate which stay in the dissolved phase

320 William et al., 1983 (pg. 60)
321 William et al., 1983 (pg. 60-61)
322 William et al., 1983 (pg. 63)
323 William et al., 1983 (pg. 61)
324 William et al., 1983 (pg. 61)

mostly.[325]

According to *Designing the Sustainable Site: Integrated Design Strategies for Small-scale Sites and Residential Landscapes*, the main stormwater pollutant sources can be summarized as below[326]:

1. Sediments, from bare or disturbed soil;

2. Metals, from fuel, pesticides, vehicles, asphalt paving, and roofing materials;

3. Chloride, from de-icing salts;

4. Nutrients, from failing septic systems, animal waste, and fertilizers;

5. Bacteria and viruses, from failing septic systems, animal waste, and combined sewer overflows;

6. Other pollutants, from herbicides, vehichles, etc.

3.3.4 Impacts of Water Pollution

According to *Stormwater Management in Urbanizing Areas*, the potential impacts caused by water pollution include the depletion of oxygen budget of the water body, the accumulation of toxic materials in water body, the stimulation of the growth of plants and microorganisms such as rooted aquatics and algae.[327]

According to *Designing the Sustainable Site: Integrated Design Strategies for Small-scale Sites and Residential Landscapes*, the impacts caused by the major stormwater pollutants can be summarized as below[328]:

1. Sediments, which reduce water quality, degrades aquatic habitat, and transport other pollutants such as metals or nutrients;

2. Metals, which harm the health of wildlife and humans, even at low levels;

3. Chloride, which can pollute water & soil, and harm plants & aquatic wildlife;

[325] William et al., 1983 (pg. 67)
[326] Venhaus, 2012 (pg. 123)
[327] William et al., 1983 (pg. 58)
[328] Venhaus, 2012 (pg. 123)

4. Nutrients, which stimulate algal blooms, lower dissolved oxygen levels, and reduce water clarity;

5. Bacteria and viruses, which harm the health of wildlife and humans;

6. Other pollutants, which harm the health of wildlife and humans, etc.

3.4 SITE STRATEGIES FOR THE ISSUES

Water pollution problems can be solved, in a large extent, by using both man-made facilities such as green roofs and permeable pavements, and natural components such as vegetation and soil to replace the impermeable land surfaces, in order to transform the sites into “sponges” to absorb, store and clean the stormwater runoff.[329] Vegetation, soil, and the microorganisms living in the soil are able to bind and break down a lot of water pollutants. The natural cleansing mechanisms can be applied in stormwater treatment strategies such as biofiltration facilities that catch runoff with vegetation and filter the water into soil.[330] Several components such as green roofs, bio-swales, rain gardens, and retention basins have already been used in urban sustainable stormwater management system during the last twenty years to release the adverse effects brought by urbanization.[331] This can not only improve the situation of hydrological cycle, but also bring some ecological benefits such as biodiversity conservation, pollution treatment and climate regulation.[332]

According to the above points, the overall strategies can be summarized as follows**:**

1. Naturalising the riverfront area;

2. Reducing impermeable surfaces;

3. Increasing plant coverage;

4. Improving soil health;

5. Separating rainwater from sewers;

6. Creating stormwater treatment train.

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329 Davis, 2005
330 Venhaus, 2012 (pg. 125)
331 Brown & Farrelly, 2009
332 Gill et al., 2007

3.4.1 Naturalising the Riverfront Area

The southern area of the garden city (which is adjacent to the Ohne river) should be developed as a natural landscape area rather than a hard paving land, to prevent potential pollution directly to the river body. In the meantime, bioretention practices such as filter strip and rain garden can be applied in this area, to act as a buffer zone (runoff purifier) between the residential area (runoff contributor) and the river body (runoff receiver), for the adequate treatment of polluted runoff.

3.4.2 Reducing Impermeable Surfaces

A large proportion of the land surfaces in urban areas are impervious, which is a major cause of water pollution. Reducing the volume and speed of runoff can decrease the possibility of the pollution of groundwater and other receiving waters. Automobile leakages, airborne pollutants, and other contaminants accumulate on impermeable land surfaces, all of which are liable to be carried away by runoff.[333]

There is a phenomenon named “first flush effect”, which means that on an impervious surface often exist large quantities of pollutants that will easily be transported into the initial surface runoff during a rainfall. This phenomenon should be taken into consideration within the stormwater pollution measurement and management.[334] Collecting and infiltrating the first flush is an effective way to treat pollutants at the source, which will prevent the spread of pollutants.[335]

Effective site strategies to reduce impermeable surfaces include[336]:

1. Designing natural surfaces instead of pavements
2. Selecting permeable materials for pavements
3. Using structural soils
4. Applying green roof

333 Venhaus, 2012 (pg. 126)
334 William et al., 1983 (pg. 68-69)
335 Venhaus, 2012 (pg. 126)
336 Venhaus, 2012 (pg. 127)

3.4.2.1 Designing natural surfaces instead of pavements

One of the negative effects of urbanization is the over-paving in urban areas, which results in several adverse impacts on the environment and humans. Recommended strategies for this include: redeveloping some outdated sites like grey-field lands and urban infill properties; reducing the size of some areas like parking spaces, driveways, or roadways; removing the pavements in turnaround centre; integrating green space in parking areas, driveways, and roadways.[337]

3.4.2.2 Selecting permeable materials for pavements

Permeable pavement is one of the stormwater treatment practices, which is discussed in detail in Subsection 2.4.2.

3.4.2.3 Using structural soils

Structural soil is one concept applied in stormwater management, which is discussed in detail in Subsection 2.3.5.

3.4.2.4 Applying eco-roof

Eco-roof is one of the stormwater management facilities, which is discussed in detail in Subsection 2.4.1.

3.4.3 Increasing Plant Coverage

Plants can play a mediating role between the rainstorm and the earth. The leaf surfaces will intercepts the rainfall when a stormwater event happens, and the intercepted water will afterwards evaporate back to the atmosphere or indirectly fall downwards to the ground. Due to this, the threat from heavy rainfall events will be largely alleviated by the vegetation layers. Some of the water can be absorbed by the plants through their roots, transported by their stems, and released back to the air by their leaves during the process of transpiration.[338] Besides, the roots of plants can expand into the soil and increase the ability of soil to infiltrate and absorb water, thereby promoting the processes of bioretention.

[337] Venhaus, 2012 (pg. 128)
[338] Dunnett & Clayden, 2007 (pg. 34-35)

By holding rainwater on their surfaces and assisting bioretention, plants are able to take a source control of rainwater runoff quality.[339] The factors determining the percentage of rainfall intercepted by plants include rainfall patterns, plant species, sizes and foliation periods.[340] The broadleaf evergreen trees perform the greatest capacity to hold rainwater, and the following are that of broadleaf deciduous and conifer trees.[341] According to an estimate, about 3.4 million kiloliter of rainwater is caught by street trees each year, and thereby saving 35.6 million U.S. Dollar due to a decrease in the expenditure of treatment for water pollution and infrastructure.[342]

Vegetation layer is also able to catch the pollutants transported with sediment or other suspended particles in stormwater runoff through dividing the sediment out of suspension, and retain the pollutants some of which are eventually broken down by plants or plant-associated soil organic matter. Moreover, vegetation plays an important role in blocking the transportation of pollutants by slow down wind and other natural factors.[343]

In addition, the more diverse plants have been placed, the greater benefit our environment can get. Low monoculture vegetation such as simple mown turf areas will not be as effective as mixed naturalistic plantings in soaking-up and trapping excess runoff, or in purifying water by removing the pollutants and contaminants inside. Moreover, compared to intensively managed grass areas, multi-level plantings will result in increasing the wildlife and habitat value and supporting greater biodiversity.[344]

3.4.4 Improving Soil Health

In bioretention practices, soil as a natural component plays a key role in solving water pollution problems. The benefits for a sustainable site provided by healthy soil include[345]:

1. Supporting plant growth;
2. Infiltrating, detaining and retaining runoff;

[339] Venhaus, 2012 (pg. 144)
[340] Xiao et al., 2000
[341] Xiao & McPherson, 2002
[342] Peter et al., 2007
[343] Venhaus, 2012 (pg. 145-146)
[344] Dunnett & Clayden, 2007 (pg.15)
[345] Venhaus, 2012 (pg. 136)

3. Treating and filtering contaminants from runoff;
4. Sequestering carbon from the atmosphere;
5. Providing habitat for various animals and plants.

Soil health and its capacity for absorbing, retaining and cleansing runoff are majorly influenced by two factors: soil compaction and soil organic matter, both of which are discussed in detail in Section 2.3.

3.4.5 Separating Rainwater from Sewers

As mentioned in Subsection 3.2.6, there are several rainwater sewer pipes going through the garden city into the Ohne river, without pre-treatment, and the outlet structures are located at the bottom of the existing river profile. This can cause potential problems since stormwater runoff volume may excess the capacity of the sewer system, and the water can overflow into the Ohne river, with pollutants from the sewerage and land surfaces. Due to this, a sustainable urban drainage system must be created to solve these problems.

3.4.6 Creating Stormwater Treatment Train

Several stormwater treatment facilities such as green roof, permeable pavement, stormwater planter, swale, filter strip, rain garden, and pond are often applied to deal with the water problems at targeted sites. However, the application of a single stormwater management practice may not be sufficient to deal with runoff in many cases, one of the effective approaches to these situations is to combine a series of stormwater management practices such as green roofs, swales, filter strip and rain garden into an integrated system, to build a stormwater treatment train.[346] This integrated approach is discussed in detail in Subsection 2.2.2.

3.5 SUMMARY

The site of the practical project for the study is located in the southern area of Leinefelde-Wobis, a small town in northwestern Thuringia, Germany. The area is almost flat with a 1%-2% slope from north to south. All the buildings inside the area to be planned should be removed. The subsoil performs a low permeability. There is

[346] Venhaus, 2012 (pg. 149)

expected traffic noise from the surrounding roads. The site is to be planned into a garden city, by the southern boundary of which is the Ohne river, flowing from west to east into the Birkunger reservoir.

The main objective of this project is to find an approach to remove the threat of water pollution from the garden city area to the Ohne river. By analysing various aspects of water pollution (including the main causes, the categories, the sources, and the impacts), four major strategies (including naturalising the riverfront area, reducing impermeable surfaces, increasing plant coverage, improving soil health, separating rainwater from sewers, and creating stormwater treatment train) are proposed for the following planning and design practice.

CHAPTER 4 PLANNING AND DESIGN

4.1 OVERALL PLANNING

4.1.1 Planning Concept

As mentioned above, the entire area of this project site is to be planned as a garden city. By the south of the garden city flows the Ohne river, which runs from the west to the east and finally merges into the Birkunger reservoir. Adjacent to the other boundaries of the garden city is the urban area of Leinefelde.

During stormwater events, polluted water from the urban area is discharged into the Ohne river through the current sewer system, creating a great threat to the water quality of the Birkunger reservoir. This is the main problem needed to be solved in this project.

The main objective of this project is to apply the concept of sponge city by creating a stormwater treatment train in this garden city, in order to solve the water issues at the site, in the meantime planning an organic residential area with sixty private properties as well as necessary urban infrastructure and creating a sustainable living environment for the residents in the garden city. (Figure 4-1)

4.1.2 Overall Structure

As shown in Figure 4-2, the entire garden city (the total planned area is 63 000 m²) is planned into three parts: the residential area (which is 54 110 m²), the south green park (which is 7172.8 m²), and the east rain garden (which is 1717.2 m²).

The residential area is mainly planned as a living environment for the residents in the garden city. It consists of sixty private properties (the area of each is 500 m²), two through streets (the width of each is 16.55 m) to connect the main entrances and the green park or the rain garden, several local streets (the width of each is 9.7m) to connect the private properties with the through streets or the streets surrounding the garden city, and multiple public open green spaces.

The south green park is planned as a public space for local residents to enjoy recreation and activities, in the meantime playing a key role in the stormwater management plan as a bioretention system to collect and purify polluted runoff from the residential area before discharging the water into the Ohne river. It mainly consists of the meadow (the area of which is 3882.4 m²), the bioretention (the planned area is 2190.4 m²), and the playground (the area of which is 500 m²).

Figure 4-1: Master Plan

The east rain garden is placed in the eastern corner. Its main role is to collect potential runoff from the Birkungerstraße and the paving area around the Autohaus. It consists of both hard surfaced area including the parking lots and pedestrian paths to the east, and green space area including the grassland and the biofilter hollow.

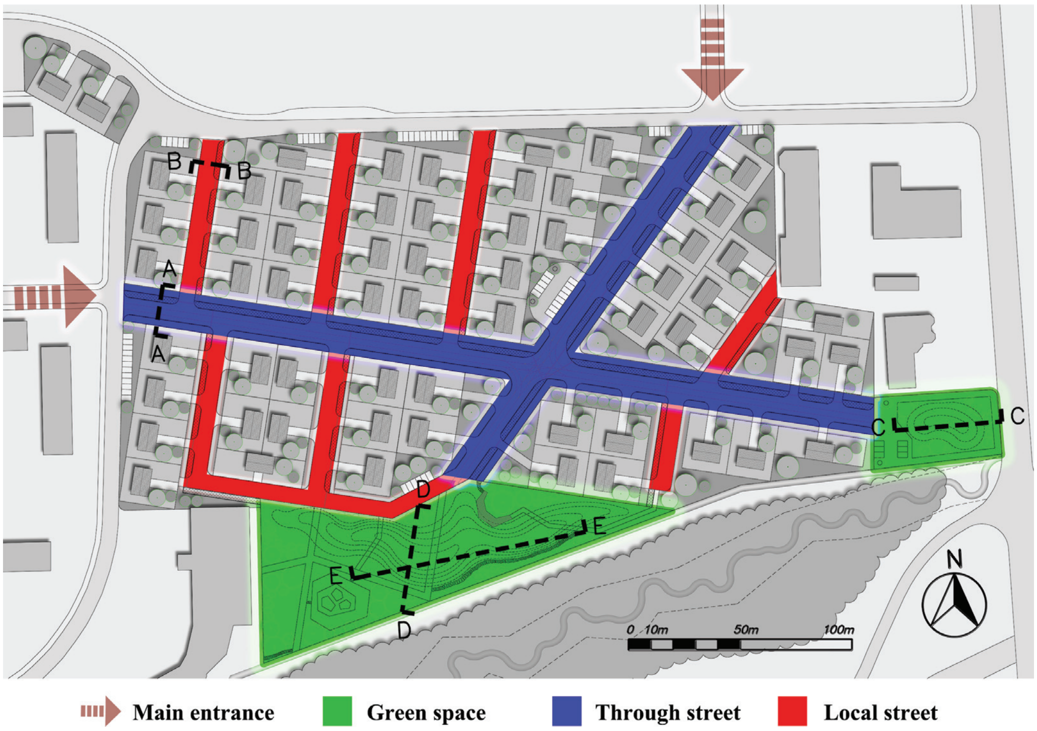

Figure 4-2: Structural Analysis Plan

4.1.3 Facility Analysis

From the major stormwater management practices (including green roof, permeable pavement, planter, filter trip, swale, rain garden and pond) discussed in Section 2.4, five of them are selected as the rainwater treatment facilities at this site based on the following considerations: green roofs are selected for the source control in the private properties; permeable pavements are selected into the paving areas to improve infiltration; the suited facilities for the stormwater treatment in the streets can be swales or planters, from which swales are more suited due to their conveyance capacity; filter strip is suited for the pre-treatment before the final purification; and the final stormwater treatment can be carried out by rain garden or pond, from which rain garden is a better choice due to the water environment (all the excess rainwater will be discharged into the Ohne river and eventually directed into the Birkunger reservoir, so there is no need to keep the water in the garden city for long periods of time).

According to the analysis above, The application places and the characteristics of the five selected facilities for runoff prevention, detention, retention, filtration, and conveyance are summarised in Table 4-1 (active factors are marked with "✓").

Candidate Facility	**Green roof**	**Permeable pavement**	**Swale**	**Filter strip & Rain garden**
Application place	Planted roof surfaces	Hard paving surfaces	By streets and by properties	Planted rainwater collection area
Prevention	✓	✓		✓
Detention	✓		✓	
Retention	✓	✓	✓	✓
Filtration			✓	✓
Conveyance			✓	

Table 4-1: Characteristics of Selected Facilities[347]

4.1.4 Drainage Plan

As shown in Figure 4-3, the new level plan is based on the current topography described in Section 3.2.2. The area is almost flat with 1% - 2% slope from north to south. During stormwater events, excess rainwater from the private properties is directed into the nearest swales in the streets, through surface runoff or underground pipes (connected to the swales). No rainwater is allowed to be directed through the existing rainwater sewer pipes (as mentioned in Subsection 3.2.6.) into the Ohne river. All the swales are connected one by one with underground pipes to drain the water, and their longitudinal slopes are inclined to the south green park. Potential contaminated runoff from the Birkungerstraße as well as the paving area around the Autohaus will be collected by the east rain garden, thereby posing no threat to other areas in the garden city. (Figure 4-4)

The bioretention system in the south green park is designed to take all the potential runoff according to predicted precipitation from the entire garden city. The details are discussed in Section 4.4. The collected rainwater will be filtered by the selected plants (phytoremediation), the soil as well as its organic matter (bioremediation), and the

[347] Dunnett & Clayden, 2007 (pg.48)

engineered filter media. After all these filtration processes, the purified water will be discharged into the underground pipes and directed to the Ohne river.

Figure 4-3: Level Plan

Due to the low permeability of the native subsoil (mentioned in Subsection 3.2.4), all the bioretention practices at the site are designed as "partial infiltration systems" (except the east rain garden, which is designed as a "biofilter system" to prevent potential groundwater contamination).

Figure 4-4: Drainage Plan

Figure 4-5: Perspective from the Southeast

Figure 4-6: Perspective from the Southwest

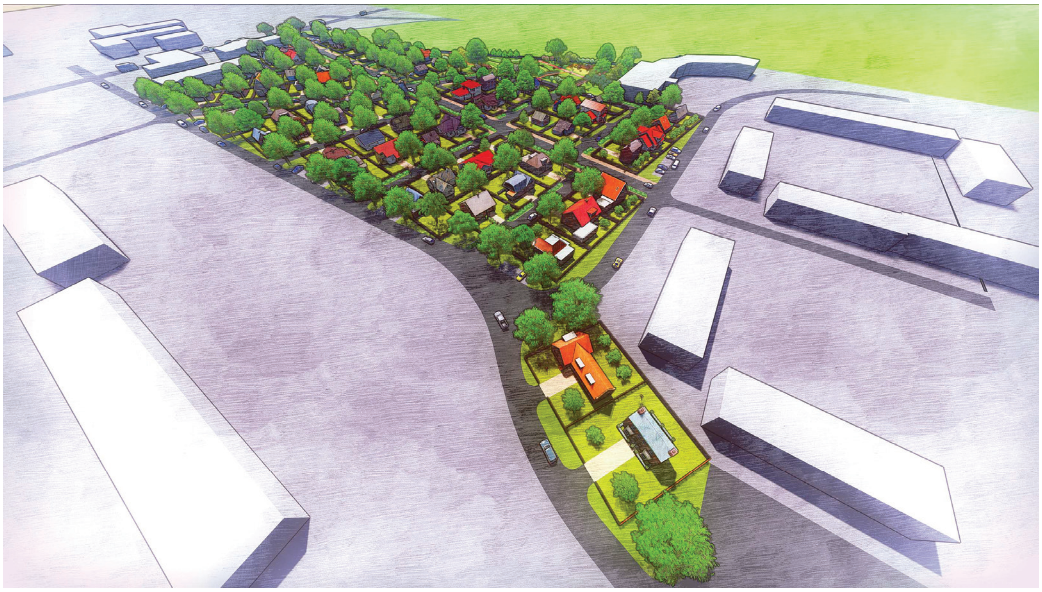

Figure 4-7: Perspective from the Northeast

4.2 DETAILED DESIGN

4.2.1 Through Street

The two through streets connect the two main entrances on the north and west, to the two green space areas on the south and east, at the same time playing a key role in directing the rainwater from adjacent private properties and connected local streets, through the swale lines to the bioretention system.

Figure 4-8: Perspective from the Northwest

Figure 4-9: Perspective from the Eastern Main Entrance

The total width of each through street is 16.55 metres. It can be divided into four parts from the cross section, including two pedestrian areas (each is 3 metres in width) on both sides, a motorway (7.4 metres wide) in the middle, and a swale (2.7 metres wide) between the motorway and one of the pedestrian areas. There are three paving bandings (each is 0.15 metres in width) between the pedestrian area, swale area and motorway. (Figure 4-11)

Figure 4-10: Perspective from the Northern Main Entrance

The swales are designed as "enhanced vegetated swales", which are essential channels whose surfaces are vegetated with selected plants, providing water treatments in purification and conveyance during rainfall events. According to the discussion in Subsection 2.4.5, the swale should be at least 2.4 metres on street area. The bottom should be flat and at least 0.6 metres wide. The side slope cannot be more than 1:3. The longitudinal slope must be less than 6%.[348] For the swales in the through streets, the width of the bottoms is 0.9 metres, and the horizontal width of the side slopes is also 0.9 metres, while the depth of the side slopes is 0.3 metres. In this case, the total width of the swale is 2.7 metres, and the rate of the side slope is 1:3.

The paving materials of the pedestrian areas and the motorway should be selected from permeable pavement materials. For the motorway the porous asphalt is recommended, while for the pedestrian areas both the pervious concrete and interlocking pavers are suited.

4.2.2 Local Street

The local streets connect the private properties with the through streets and the surrounding streets, also during stormwater events converging into a drainage network collecting rainwater from adjacent private properties to the through streets or directly to the bioretention system, through the swale net.

[348] CPES, 2008 (pg. 2-49)

The total width of each local street is 9.7 metres. It can be divided into two parts from the cross section: the swale area and the paving area. The paving area is 7 metres wide, and it is accessible for both pedestrians and vehicles. There are two paving bandings (each is 0.15 metres in width) on the both sides of the swale area (Figure 4-12).

Figure 4-11: Section A-A for the Through Street

Figure 4-12: Section B-B for the Local Street

Figure 4-13: Perspective of the Swale Underground Pipe

Figure 4-14: Perspective from the Intersection of the Two Through Streets

For the swales (also designed as “enhanced vegetated swales”) in the local streets, the width of the bottoms is 0.6 metres, and the horizontal width of the side slopes is also 0.9 metres, while the depth of the side slopes is 0.3 metres. In this case, the total width of the swale is 2.4 metres, and the rate of the side slope is 1:3. Each two adjacent swales are connected by a groundwater pipe at both ends, for the water circulation in the drainage system (Figure 4-13). The paving materials of the paving areas should also be selected from permeable pavement materials. The pervious concrete or the pervious concrete is recommended.

4.2.3 East Rain Garden

The east rain garden is placed in the southeast corner of the garden city, whose main role is to collect potential runoff from the Birkungerstraße and the paving area around the Autohaus, in order to prevent contaminated runoff from flowing into other areas of the garden city, and in the meantime separating the garden city from noise pollution from the Birkungerstraße.

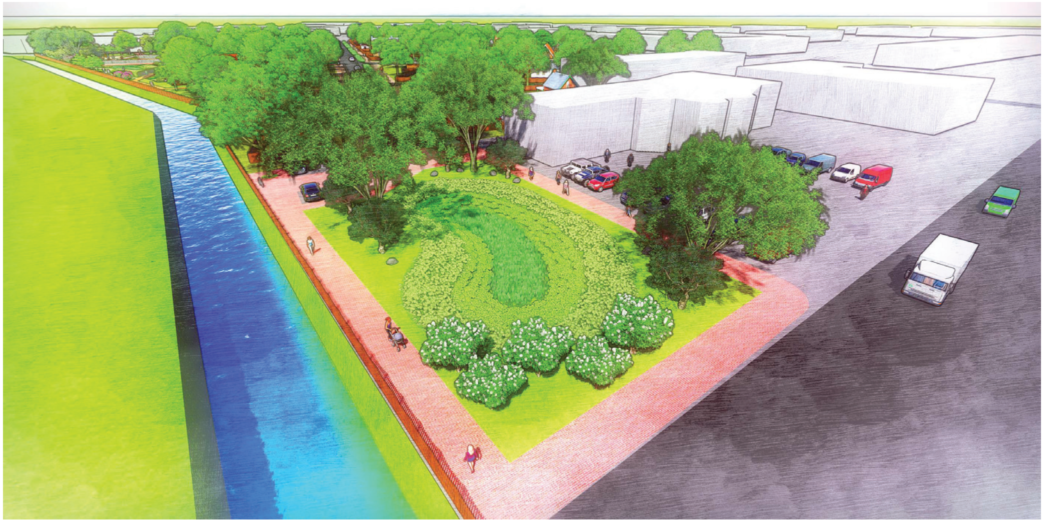

Figure 4-15: Perspective of the East Rain Garden

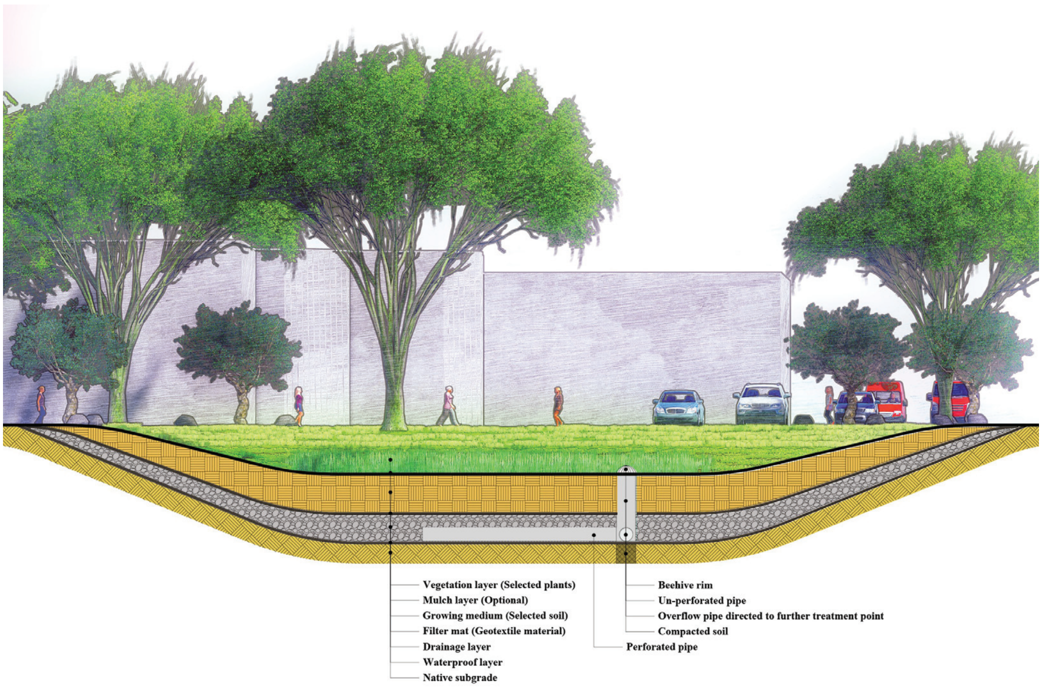

Figure 4-16: Section C-C for the East Rain Garden

The total area of the east rain garden is 1717.2 m². It consists of the green space area (960 m²) including the meadow and the biofilter hollow, and the hard surfaced area (757.2 m²) including the parking lots and the pedestrian paths connected to the east.

In the middle of the green space area is a vegetated hollow, surrounded by a flat meadow. The planted hollow is essential a biofilter system, whose total area is 548.5 m² and the bottom is 1 metre deep. The structure of the biofilter system consists of six layers, which from top to bottom are the vegetation layer, the mulch layer (optional), the growing medium, the filter mat, the drainage layer, and the waterproof layer. Under the waterproof layer lies the native subgrade soil. (Figure 4-16)

When the runoff flows into the biofilter system, it will infiltrate into the growing medium and be filtrated by the filter mat, before entering the penetrating into the drainage layer. The waterproof layer separates the drainage layer from the native subgrade layer, in order to prevent contaminated water from threatening groundwater system. So the system is designed as a “no infiltration bioretention system” (also named “biofilter system”). A drainage pipe is designed within the biofilter system to collect and direct the overflow water from the drainage layer to further treatment point.

4.2.4 South Green Park

The south green park is located at the lowest point of the garden city, adjacent to the Ohne river. It is planned as a public space for local residents to enjoy recreation and activities, in the meantime playing a key role in the planned rainwater management train as a bioretention system to collect and purify the runoff from the residential area before draining it into the Ohne river. The green park mainly consists of three parts: the meadow, the playground, and the bioretention area.

The meadow is a flat grassy land surrounding the bioretention area. Its total area is 3882.4 m². Its surface is decorated with different types of selected plants (with consideration of their growth habit, growing and grown size, season-to-season appearance and so on) as well as some hard landscaping elements (such as pedestrian paths, sitting stones and wooden decks). The playground is located in the southwest of the green park. The total area is 500 m². It is a place for the residents to enjoy various entertainment activities, especially for children. Several recreational equipment are placed inside the playground, such as slide, swingset, chin-up bars, etc. (Figure 4-25)

Several paths are places through the whole green park area, connecting different parts for the circulation of pedestrians. The paths are connected with the pedestrian bridges crossing over the rain garden depression (Figure 4-24). A wooden deck is placed on the meadow in the northern part of the green park. The residents can lie on the deck and enjoy the beautiful scenery in front of them (Figure 4-23).

The bioretention area lies in the heart of the green park. The total area is 2190.4 m^2, and the hollow is 2 metres deep. According to the surface planting types, the bioretention system can be divided into two parts from the horizontal line 1 metre below the meadow level: the upper part can be considered as a “filter strip” that is a grassy slope with some stones on the surface, and the lower part can be considered as a “rain garden” that is a depression whose surface is vegetated with selected plants (Figure 4-17, 4-18). With the level changes in the hollow, the biretention area will present different features in different precipitation situations (Figure 4-19, 4-20, 4-21).

As shown in Figure 4-17 and 4-18, the rain garden structure consists of seven layers as follows (from top to bottom):

1. Vegetation layer, consisting of selected plants;
2. Mulch layer (optional), for soil protection;
3. Growing medium, filled with selected soil with suitable water permeability;
4. Upper separator layer, filled with coarse sand for filtration;
5. Lower separator layer, filled with crushed gravel for further filtration;
6. Filter mat, made of geotextile material for the final filtration.
7. Drainage layer, filled with uniformly graded storage rocks, between which lies several overflow pipes directed to the Ohne river.

Since the inflow water is systematically purified through the previous series of purification processes, and due to the low water permeability of the native soil (as mentioned in Subsection 3.2.2, the subsoil is tested to perform a low average permeability which is not higher than 1×10^{-6} m/s), the bioretention system in the green park is designed as a “partial infiltration system”. In this case, beneath the drainage layer is directly the native subgrade soil, which allows a certain rate of water infiltration.

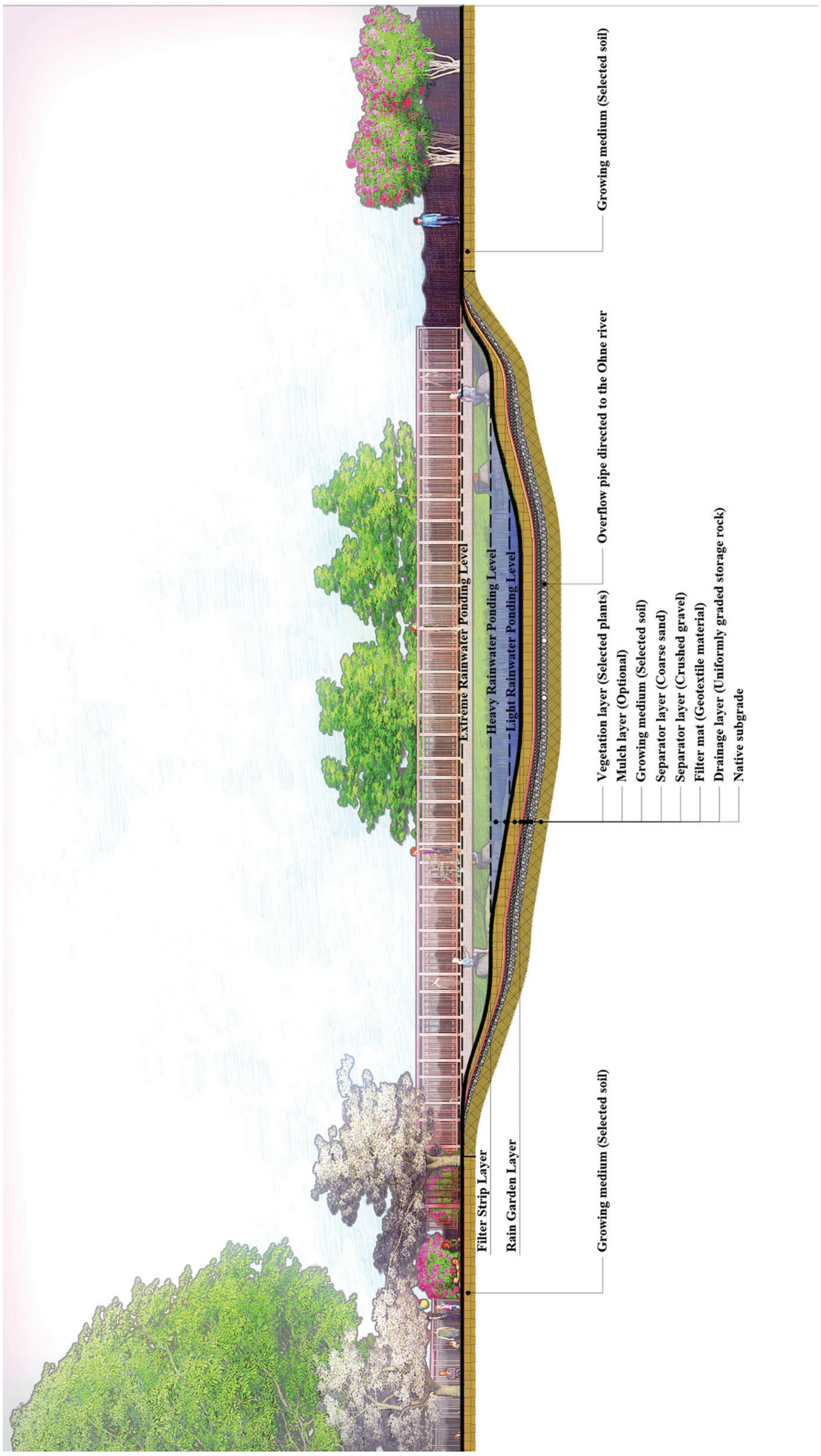

Figure 4-17: Section D-D for the South Green Park

Figure 4-18: Section E-E for the South Green Park

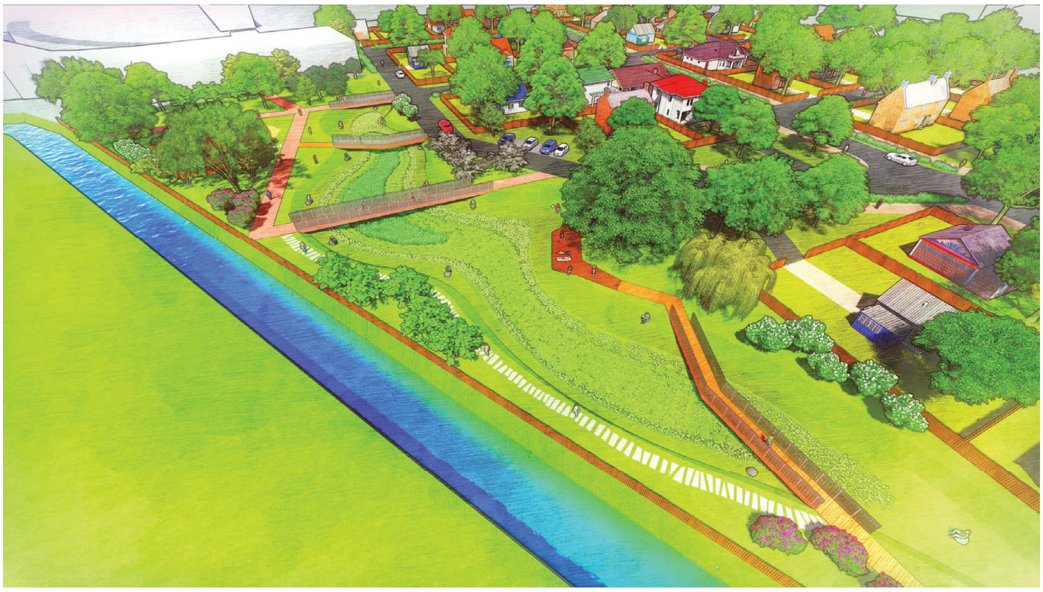

Figure 4-19: Perspective of the South Green Park (During Rainless Seasons)

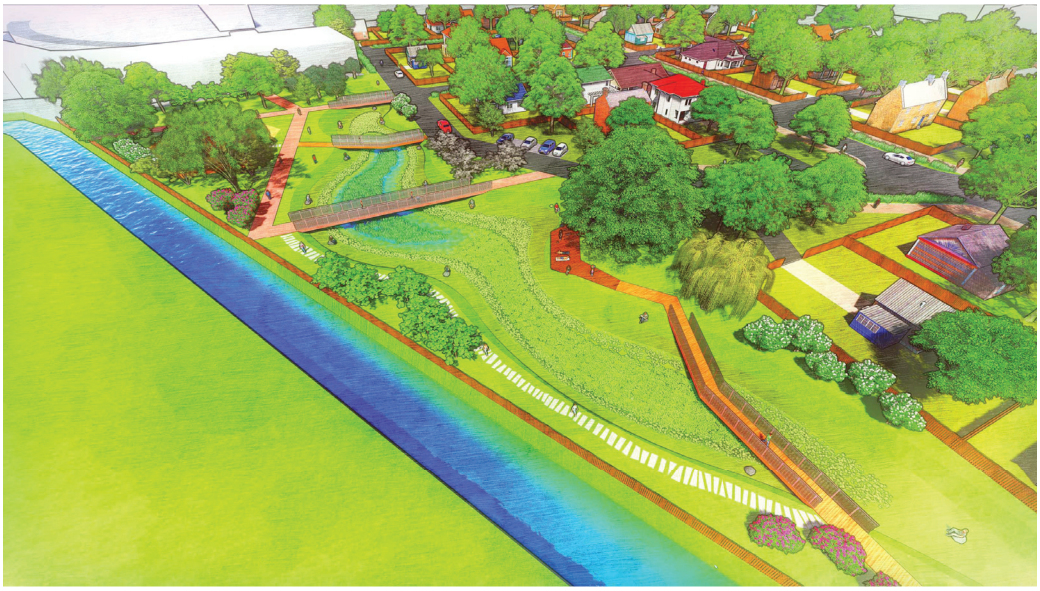

Figure 4-20: Perspective of the South Green Park (After Moderate Rainfall Events)

4.2.5 Parking Lot & Open Green Space

There are 60 public parking lots planned in the public space of the residential area (the quantity of which can be changed according to the actual needs). The length of each lot is 4.5 metres and the width is 2.5 metres. All the parking lots should be made of permeable pavements, for which concrete grids are recommended (pervious concrete, permeable interlocking pavers can also be selected in some cases). (Figure 4-22)

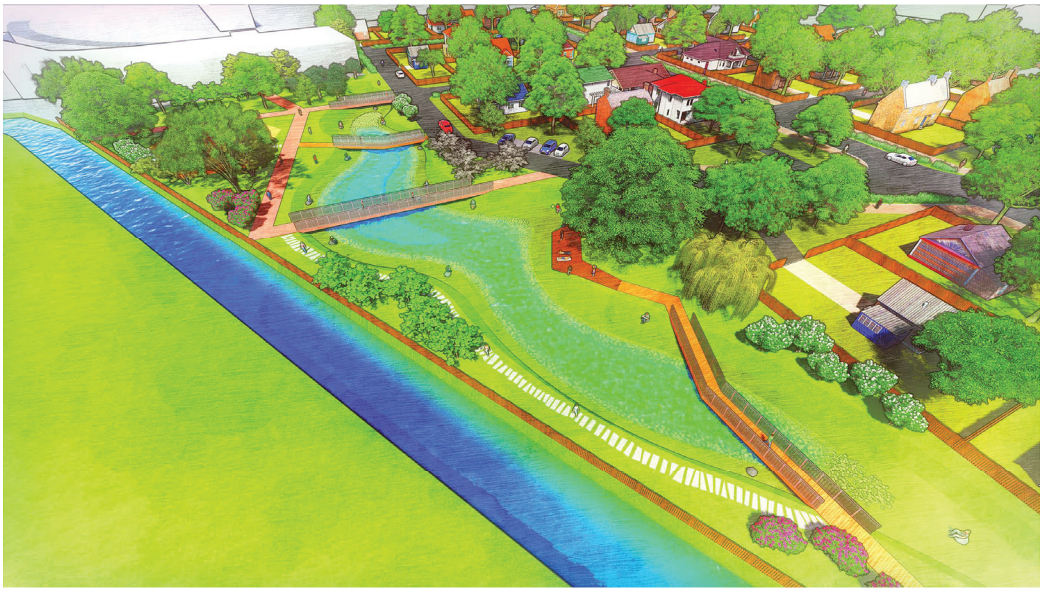

Figure 4-21: Perspective of the South Green Park (After Violent Rainfall Events)

Figure 4-22: Parking Lots and Open Green Space

The open green space refers to the multiple pieces of planted land adjacent to the private properties and the streets. They are scattered throughout the public spaces of the garden city. All of the green space is covered with grasses or planted with trees and shrubs, increasing the plant coverage in the whole garden city area and improving the infiltration capacity of the garden city. The open green space also plays a significant role in creating a sponge city system. (Figure 4-22)

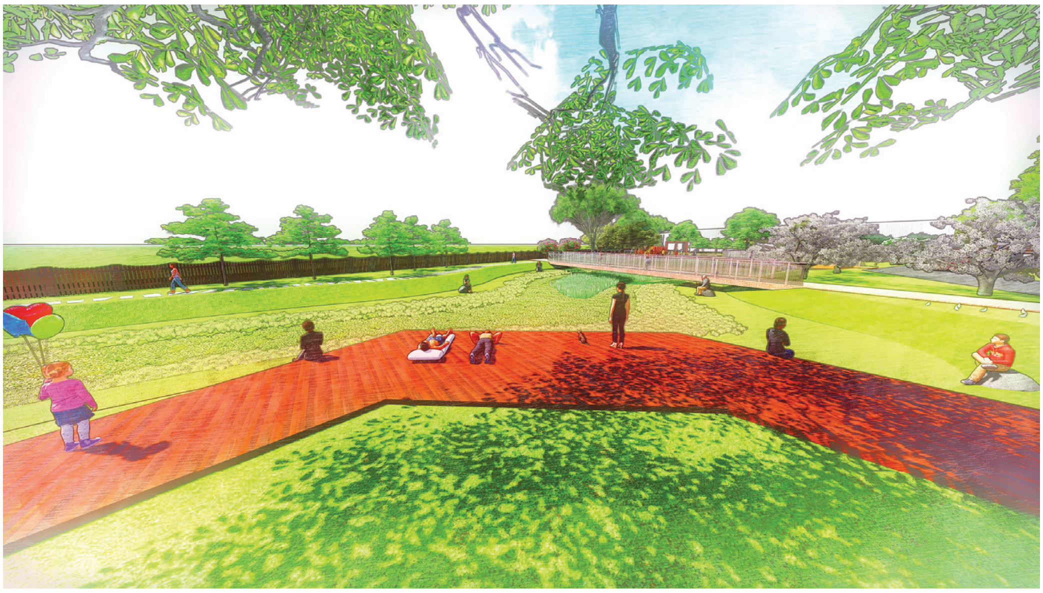

Figure 4-23: Wooden Deck on the Meadow

Figure 4-24: Path & Bridge

4.3 PROPOSALS FOR THE PRIVATE PROPERTY DESIGN

There are 60 private properties in the garden city, and each area is 500 m^2. In this case, the private properties account for almost half of the total garden city area. The stormwater management applied in the private properties has a great impact on the overall stormwater treatment result.

All the stormwater management facilities are recommended for the designs of buildings and yards inside the private properties. Among those stormwater treatment elements, green roof is one of the most suited and effective practices, due to the limited space in the properties. Besides, for the private yard the recommend facilities include permeable paving, filter trip, rain garden and pond, which can function as intermedia treating and directing the rainwater from the houses and yards to the swales in the streets through surface runoff or underground pipes.

Figure 4-25: Playground

Figure 4-26: Bioretention Area

4.4 CALCULATIONS OF THE BIORETENTION SYSTEM CAPACITY

According to the drainage plan (Subsection 4.1.4, Figure 4-10), all the runoff from potential precipitation events will be directed into the south green park, for the final purification in the bioretention system before being drained into the Ohne river. So it is necessary to calculate the potential maximum runoff volume in this area as well as the total capacity of the bioretention system (which is essentially the total volume of its hollow), to make sure that the system is capable to take the maximum runoff.

4.4.1 Site Area Values

According to the plan, from total area of the garden city (6.3 ha), the area of the east rain garden at the southeastern corner is 1 717.2 m², which will not drain any water into the bioretention system in the south green park.

The total area of the private properties (60 in total, each one is 500 m² big) is 30 000 m². According to the rules, the maximum rate of the hard surface area in a private property is 80%[349]. To calculate the extreme cases, the total impermeable surface area is counted as 24 000 m², and the total green space area is counted as 6 000 m².

The total area of the south green park is 7 172.8 m², from which the total area to place different facilities (including the playground, pedestrian paths, and the wooden platform) is 1407.8 m², and the total area of green space is 5 765 m².

The total area of the street pavement is 13 832.4 m², including the pedestrian areas, the motorway areas, and the paving areas for mixed use.

The total area of the swales is 2 078.6 m².

The total area of the parking lots (60 in total, each one is 11.25 m² big) is 675 m².

The total area of the open green space in the residential area is 7 524 m².

So the total area of the hard surfaces considered for the rainwater inflow can be calculated as: A_1 = 24 000 + 13 832.4 + 675 + 1407.8 = 39 915.2 m²

And the total area of the green space considered for the rainwater inflow can be

[349] Baunutzungsverordnung – BauNVO, 2019

calculated as: $A_2 = 6\ 000 + 7\ 524 + 2\ 078.6 + 5\ 765 = 21\ 367.6\ m^2$

4.4.2 Calculation of Runoff Volume

According to *Neue Wege für das Regenwasser*, the following formulas are given for the calculation of rainwater volume[350]:

$Q_r = r_{T;n} \cdot \Psi_m \cdot A_{ges}$

From the above formula:

$r_{T;n}$ in $l/(s \cdot ha)$ is a rate from which T refers to "time" and n refers to "frequency".

Ψ_m refers to "runoff coefficient of catchment area".

A_{ges} in m² refers to "area of catchment with runoff into bioretention system".

Runoff coefficients for various surface covers can be classified in the following table:

Surfaces or Construction	Runoff Coefficients
Wooden element, flat roofs	$\Psi_m = 0.50$ to 0.70
Asphalt roads and footpaths	$\Psi_m = 0.85$ to 0.90
Plaster	$\Psi_m = 0.75$ to 0.85
Row patches (open)	$\Psi_m = 0.25$ to 0.60
Gravel roads and small paving	$\Psi_m = 0.25$ to 0.60
Gravel paths	$\Psi_m = 0.15$ to 0.30
Unpaved areas, railway stations	$\Psi_m = 0.10$ to 0.20
Park and garden areas	$\Psi_m = 0.05$ to 0.10

Table 4-2: Runoff Coefficients for Various Surface Covers[351]

Taking into account extreme conditions, Ψ_m is considered as 0.90 for total hard surface area which is 39 915.2 m² according to the previous calculations, and considered as 0.1 for the total green space area which is 21 367.6 m² according to the previous calculations.

The selective heavy precipitation heights (in mm) in this area for different rainfall

[350] Geiger & Dreiseitl, 2001 (pg. 47-51)
[351] Geiger & Dreiseitl, 2001 (pg. 48)

duration (unit: minute) and return intervals (unit: year) from 1951 to 2010 is shown in the following table:

	T = 1a	T = 5a	T = 20a	T = 100a
5 min	5.8 mm	8.5 mm	10.8 mm	13.5 mm
15 min	9.7 mm	15.7 mm	20.9 mm	26.9 mm
30 min	12.2 mm	20.2 mm	27.2 mm	35.3 mm
60 min	14.6 mm	24.8 mm	33.6 mm	43.7 mm
120 min	18.0 mm	29.5 mm	39.4 mm	50.8 mm

Table 4-3: Precipitation Heights in the Area[352]

From the data the most serious situation (120min, T=100a) is taken.

So $r_{T;n} = [\ (50.8/1\ 000)\cdot 10\ 000\cdot 1\ 000\ ]/(120\cdot 60) = 70.6$ l / (s·ha).

So for the impermeable surface catchment:

$Q_r = r_{T;n} \cdot \Psi_m \cdot A_{ges} = 70.6 \cdot 10^{-6} \cdot 0.9 \cdot 39\ 915.2 \cdot 10^2 = 253.62$ l/s

Then the volume of runoff can be calculated as:

$V_1 = Q_r \cdot T = 253.62 \cdot 10^{-3} \cdot 120 \cdot 60 = 1\ 826.1\ m^3$

And for the green space catchment:

$Q_r = r_{T;n} \cdot \Psi_m \cdot A_{ges} = 70.6 \cdot 10^{-6} \cdot 0.1 \cdot 21\ 367.6 \cdot 10^2 = 15.1$ l/s

Then the volume of runoff can be calculated as:

$V_2 = Q_r \cdot T = 15 \cdot 10^{-3} \cdot 120 \cdot 60 = 108.7\ m^3$

So the total volume of the runoff from the potential heaviest rainfall for 120 min in 100 years can be calculated as:

$V = V_1 + V_2 = 1\ 826.1 + 108.7 = 1\ 934.8\ m^3$

From above V refers to “the runoff volume”, and T refers to “the rainfall duration”.

352 Malitz, 2014

4.4.3 Extended Calculation of Runoff Volume

Another more precise method of calculation is given by *Planung, Bau und Betrieb von Anlagen zur Versickerung von Niederschlagswasser* as following[353]:

The required storage volume (in m³) $V_M = (Q_{zu} - Q_S) \cdot D \cdot 60 \cdot f_Z \cdot f_A$

From which $Q_{zu} = 10^{-7} \cdot r_{d(n)} \cdot A_u$

and $A_u = \Psi_m \cdot A_E$

So $V_M = 10^{-7} \cdot r_{d(n)} \cdot \Psi_m \cdot A_E \cdot D \cdot 60 \cdot f_Z \cdot f_A$

From the above formulas:

A_E in m² refers to "total area of catchment with runoff into bioretention system".

A_u in m² refers to "calculation value of impermeable area".

D in minutes refers to "period of rainfall".

Q_{zu} in m³/s refers to "inflow to during the rainfall period D".

Q_S in m³/s refers to "infiltration rate during the rainfall period D", which will be considered as 0 under extreme conditions without any infiltration.

$R_{d(n)}$ in l/(s·ha) is a rate from which d refers to "time" and n refers to "frequency", which is similar to the $r_{T;n}$ before.

The additional factor f_Z prevents a possible underestimation leading to a lower calculated volume. Depending on the risk measure according to *DWA-A 117*, the additional factor f_Z between 1.1 and 1.2 is recommended.[354] For the worst situation, in the following calculations f_Z will be taken as 1.2 in the calculation.

Through the processes of stormwater concentration, due to possible detained, retained and overflowed water during transport, the water inflow may be reduced to the stormwater retention area, This affects the required volume and is taken into account by the reduction factor f_A. However, the reduction in the required volumes should not be

353 DWA, 2005 (pg.22)
354 DWA, 2005 (pg.22)

considered if the time of water transport is too short and or the rates of soil infiltration is too low, and in these situations the reduction factor can be taken into account as $f_A \approx 1$.[355] Taking into account extreme conditions, in the following calculations f_A will be taken as 1 in the calculation.

Ψ_m refers to “runoff coefficient of catchment area”. It is recommended as the table below:

Area Type	Type of Attachment	Ψ_m
Slanted roof	Metal, glass, slate, fibre cement brick, paperboard	0.9 – 1.0 0.8 – 1.0
Flat roof (inclination up to 3 ° or approx. 5%)	Metal, glass, fibre cement roof paperboard gravel	0.9 – 1.0 0.9 0.7
Green roof (inclination up to 15 ° or approx. 25%)	Humus <10 cm construction humus ≥ 10 cm construction	0.5 0.3
Roads, paths and square (flat)	Asphalt, seamless concrete paving with tight joints solid gravel plaster with open joints loose gravel, gravel grass composite stones with joints, permeable stones lawn grid stones	0.9 0.75 0.6 0.5 0.3 0.25 0.15
Embankments, banquets and trenches with runoff into the drainage system	Clay soil loamy sandy soil gravel and sand soil	0.5 0.4 0.3
Gardens, meadows and cultivated land with possible rainwater runoff into the drainage system	Flat terrain steep terrain	0.0 – 0.1 0.1 – 0.3

Table 4-4: Recommended Runoff Coefficients from DWA-A 138[356]

355 DWA, 2005 (pg.22)
356 DWA, 2005 (pg.21)

Taking into account extreme conditions, Ψ_m is calculated as 1.0 for the impermeable surfaces area and calculated as 0.3 for the green space area.

So for the impermeable surface catchment:

$V_{M1} = 10^{-7} \cdot r_{d(n)} \cdot \Psi_m \cdot A_E \cdot D \cdot 60 \cdot f_Z \cdot f_A$

$= 10^{-7} \cdot 70.6 \cdot 1 \cdot 39\,915.2 \cdot 120 \cdot 60 \cdot 1.2 \cdot 1 = 2\,434.8\ m^3$

And for the green space catchment:

$V_{M2} = 10^{-7} \cdot r_{d(n)} \cdot \Psi_m \cdot A_E \cdot D \cdot 60 \cdot f_Z \cdot f_A$

$= 10^{-7} \cdot 70.6 \cdot 0.3 \cdot 21\,367.6 \cdot 120 \cdot 60 \cdot 1.2 \cdot 1 = 390.9\ m^3$

Then the total volume of the runoff from the potential heaviest rainfall for 120 minutes in 100 years can be calculated as:

$V_M = V_{M1} + V_{M2} = 2434.8 + 390.9 = 2825.7\ m^3$

4.4.4 Bioretention System Capacity Calculation

For the hollow in the bioretention system: at the level of 323.5 m the horizontal area is 2 790.4 m^2; at the level of 323.0 m the horizontal area is 2 033.0 m^2; at the level of 322.5 m the horizontal area is 1 351.7 m^2; at the level of 322.0 m the horizontal area is 832.0 m^2; at the level of 321.5 m the horizontal area is 233.0 m^2.

So the total volume of the hollow in the bioretention system can be calculated as:

$V = [(2\,790.4+2\,033.0)/2] \cdot 0.5 + [(2\,033.0+1\,351.7)/2] \cdot 0.5 + [(1\,351.7+832)/2] \cdot 0.5 + [(832+233)/2] \cdot 0.5 = 2\,864.2\ m^3 > 2\,825.7\ m^3 > 1\,934.8\ m^3$

As calculated above, the total volume of the potential heaviest rainfall for 120 min in 100 years can be taken by the bioretention system.

4.5 ANALYSIS OF THE POLLUTANT PURIFICATION

4.5.1 Potential Pollutants

According to the summary in Subsection 3.3.4, the major stormwater contaminants include: sediment from bare or disturbed soil, metals from fuel or pesticides or vehicles or asphalt paving or roofing materials, chloride from de-icing salts, nutrients from failing septic systems or animal waste or fertilizers, bacteria and viruses from failing septic systems or animal waste or combined sewer overflows, and other pollutants such acid, toxic organic, humus, hydrocarbons, etc[357].

As discussed in Subsection 4.2.3, the east rain garden will collect all the potential runoff from the Birkungerstraße and the paving area around the Autohaus, both of which can be the main sources of chloride and sodium from de-icing salts applied to deice high traffic in sub-freezing weather, and other car pollutants. In this case, the highly contaminated runoff will not be received by other areas of the garden city.

4.5.2 Purification Procedures

According to the discussion about the treatment stages of stormwater treatment train in Subsection 2.2.2, the purification procedures are summarised in the following table:

Stage	Location	Facilities	Processes	Pollutants
Primary stage	Private properties	Green roof, etc	Rapid sedimentation, physical screening, etc	Gross pollutants, coarse sediment
Secondary stage	Public space in the Residential area	Swale, permeable pavement	Fine particle sedimentation, filtration techniques	Fine sediment, attached pollutants
Tertiary stage	Green park	Filter strip, rain garden	Enhanced sedimentation and filtration, biological uptake, etc	Nutrients, dissolved heavy metals

Table 4-5: Procedures of Purification[358]

4.5.3 Primary Purification Stage

As mentioned in Section 4.3, green roof and other stormwater treatment facilities are recommended in the private properties.

According to the analysis in Subsection 2.4.1, the loadings of pollutants such as Nitrate,

357 Venhaus, 2012 (pg. 123)
358 Melbourne Water, 2017

Aluminum, Zinc, Copper and total suspended solids from the eco-roof is around 70%~90% less lower than that from conventional black roof.[359]

4.5.4 Secondary Purification Stage

As mentioned in Subsection 4.2.1 and Subsection 4.2.2, permeable pavement and swale are applied in the stormwater treatment in the public areas including the streets, parking lots and open green spaces.

According to the analysis in Subsection 2.4.2, permeable pavements perform effective removal capacity to pollutants including nutrient, oils, bacteria, and deposited particulates, during the infiltration of runoff through the pervious material[360]. This treatment is accomplished by catching those pollutants and putting them in to contact with microorganisms and vegetation[361].

According to the analysis from Subsection 2.4.5, the removal rate of swales for total nitrogen is 50%, for total phosphorus is 55%, for total suspended solids is 76%,[362] and for total copper and zinc is 60%.[363] The removal rates are also affected by site specific factors like swale length, vegetation cover, infiltration rate, soil type, and slope.[364]

4.5.5 Tertiary Purification Stage

The bioretention system for stormwater treatment in the green park is essentially a combination of a filter strip and a rain garden. The runoff from the streets firstly flows through the filter strip area, which operates the first step of purification in the system. Then the water is directed into the rain garden area for further purification.

As mentioned in Subsection 2.4.4, when the runoff flows through the vegetated surfaces of the filter strips, the water will infiltrate into the soil, and in the meantime the contaminants carried by the runoff will be trapped by the vegetation and the soil.[365]

As mentioned in Subsection 2.4.6, biphasic rain gardens are capable to effectively remove nutrient pollutants and herbicide contaminants under high pollution loading

359 TRCA & CVCA, 2010 (pg. 4-27)
360 Ferguson, 2005
361 Venhaus, 2012 (pg. 129)
362 Deletic & Fletcher, 2006
363 Barrett, 2008
364 TRCA & CVCA, 2010 (pg. 4-141)
365 Duzent, 2008

levels. The removing rate is 91% for removing nitrate, 99% for removing phosphate, 90% for removing atrazine, 92 for removing dicamba, 99% for removing glyphosate, and 90% for removing 2,4-dichlorophenoxy.[366]

4.5.6 Purification Effectiveness

According to the analysis above, the effectiveness of water purification is summarised in the following table:

Pollutant Type	Main Sources	Purification Stages	Purification Processes	Purification Facilities
Sediment	Bare or disturbed soil	Primary & secondary stage	Physical screening, sedimentation and filtration	Green roof, permeable pavement, swale
Metal	Roof, fuel vehicles, asphalt, etc	Primary & secondary stage	Filtration, biological uptake	Green roof, swale
Bacterium & Virus	Animal waste, etc	Secondary stage	Filtration and infiltration	Permeable pavement
Nutrient	Animal waste, etc	Secondary & tertiary stage	Filtration and infiltration, biological uptake	Permeable pavement, rain garden, swale
Other pollutants	Herbicides vehicles, etc	Tertiary stage	Sedimentation and filtration, biological uptake	Rain garden

Table 4-6: Summary of Purification Effectiveness[367]

4.6 CONSIDERATIONS FOR THE PLANT SELECTION

The most important stormwater management facilities in this project are the swales which treat rainwater runoff during the conveyance, and the bioretention system (including the filter strip and the rain garden) which ultimately treats all the rainwater inflow. Among those the rain garden plays a key role, since it is the final station for the rainwater in the entire stormwater treatment train system.

366 Yang et al., 2013
367 Melbourne Water, 2017; Venhaus, 2012 (pg. 123)

4.6.1 Environmental Suitability

In most temperature climates a bioretention cell will not dry out completely during extended periods of time, even in long drought periods there will be some moist soil existing. In the meantime, the plants in a bioretention cell hardly suffer prolonged periods of submergence under water, since a typical bioretention cell is designed to drain away excess water within 24 to 48 hours, rather than contain the water as a pond. So a bioretention cell cannot be considered just as a wet or dry system, but swings periodically between both. In this case, suited plants for a bioretention cell should be both flood- and drought- tolerant species, which are supposed to live in situations around water bodies, or in areas with soil moisture, or from habitats with significant amount of precipitation during part of each year.[368]

On the other hand, plants from regularly moist conditions are often able to cope with drier soils in areas where aggressive weeds can be controlled by suitable maintenance, on condition that the soil is reasonably fertile. However, plants from dry habitats tend to have trouble in surviving in flooding or waterlogged soils. In addition, the bioretention cell consists of a gradient of moisture levels, the margins of which will hardly get flooded or wet in most cases. So drought tolerant plants should also be taken into consideration.[369]

4.6.2 Geographical Origin

About the selection between native and exotic plant species, different opinions have been raised. Native species are usually regarded more ecological than exotic ones, unless detailed issues, like which regions they come from, are taken into consideration.[370] Compared to native plants, exotic species are seen to be less suited to local environmental conditions and need more maintenance input, while at the same time some of them are considered to be too suited for the areas to invade the community of local plants, but actually these issues are essentially related to their biological traits like dispersal effectiveness, seed production, and palatability to herbivores, not with their geographical origins.[371]

[368] Dunnett & Clayden, 2007 (pg. 169)
[369] Dunnett & Clayden, 2007 (pg. 169-170)
[370] Hitchmough, 2003
[371] Dunnett & Clayden, 2007 (pg. 146)

Some arguments support that compared to exotic species, native plants are able to provide better conditions for local wildlife such as invertebrates. In general, local insects and other invertebrates are more associated with the plants established longer in a region, especially with the trees.[372] However, some arguments support that many introduced trees behave better than local species, and more importantly, exotic species are able to fill the gap of food source during the flowerless seasons for native species.[373] The analysis from the Biodiversity in Urban Gardens in Sheffield project has indicated that invertebrate biodiversity does not essentially depend on the composition of the vegetation in the garden, but on the structure of planting layers – if the plants are arranged into diverse layers, such as in tree-shrub-groundcover combination.[374] Moreover, if without designated nature conservation value, limiting planting options to native species has a negative impact on multi-culture society.[375]

4.6.3 Recommended Species

For the swales, the filter strip, and the rain garden in this plan, herbaceous perennials and grasses would be the most suited choices. According to their appearance features (height, colour and bloom period), their moisture tolerance (shown in four categories: wet, moist, mesic and dry), and their preference to light (sun or shade), some recommended species that would be suited for this area are listed in Table 4-7.

The explanation of moisture tolerance factors in Table 4-7 are as follows[376]:

1. Wet: from areas where water continuously stands on site surface for long periods to cause constantly waterlogging;
2. Moist: from areas where soil is constantly moist;
3. Mesic: from areas where soil is neither excessively dry nor excessively wet;
4. Dry: from areas with extended dry periods.

In this case, a variety of plant species with different moisture tolerance can be selected for the different moisture levels in the rain garden gradient as mentioned above.

[372] Kennedy & Southwood, 1984
[373] Dunnett & Clayden, 2007 (pg. 148)
[374] Smith et al., 2005
[375] Wilkinson, 2001
[376] Dunnett & Clayden, 2007 (pg. 171)

Name	Height	Colour	Bloom	Wet	Moist	Mesic	Dry	Light
Aruncus diocus	150 cm	White	Jun-Aug		✓	✓		Sun/ shade
Caltha palustris	30 cm	Yellow	Apr-May	✓	✓			Sun/ shade
Cardamine armara	40 cm	White	Apr-Jun		✓	✓		Sun
Cadamine pratenisis	30 cm	Lilac	Apr-May		✓	✓		Sun
Deschampsia cespitosa	100 cm		Jun-Jul		✓	✓		Sun/ shade
Equisetum heymale	60 cm				✓	✓		Sun/ Partial shade
Eupatorium cannabinum	100 cm	Pink	Jul-Aug		✓	✓		
Filipendula ulmaria	100 cm	White	Jul-Aug		✓	✓		Sun
Fritillaria meleagris	20 cm	Pink	Apr-May		✓			Sun
Geum rivale	30 cm	Pink	May-Jun		✓			
Gladiolus palustris	50 cm	Pink	Jul-Aug		✓	✓		Sun
Glyceria maxima	100 cm		Jul	✓	✓			Sun
Iris pseudarorus	100 cm	Yellow	Jun-Jul	✓	✓	✓		
Juncus effusus	60 cm		Jun-Aug	✓	✓			Sun
Juncus inflexus	60 cm		Jun-Aug	✓	✓			Sun

Name	Height	Colour	Bloom	Wet	Moist	Mesic	Dry	Light
Leucojum aestivum	50 cm	White	May-Jun		✓			
Lychnis flos-cuculi	40 cm	Pink	May-Jun		✓	✓		Sun
Lysimachia nummlaria	5 cm	Yellow	Jun-Jul		✓	✓		Partial shade
Lysimachia punctata	90 cm	Yellow	Jun-Jul		✓	✓		
Lythrum virgatum	100 cm	Purple	Jul-Aug		✓	✓		
Matteuccia struthiopteris	70 cm				✓	✓		Partial shade
Menthe aquatica	50 cm	Purple	Jun-Jul	✓	✓			Sun
Molinia caerulea	60 cm				✓	✓		Sun
Myosotis palustris	40 cm	Blue	May-Jul	✓	✓			Sun/ Partial shade
Osmunda regalis	150 cm			✓	✓			
Persicaria bistorta	80 cm	Pink	May-Jun		✓	✓	✓	Sun/ Partial shade
Petasites hybridus	50 cm	Pink	Mar-Apr		✓	✓		Sun/ Partial shade
Primula vulgaris	10 cm	Yellow	Mar-Apr		✓	✓		Shade
Symphytum caucasicum	90 cm	Blue	May-Jun		✓	✓		Sun/ shade

Name	Height	Colour	Bloom	Wet	Moist	Mesic	Dry	Light
Telekia speciosa	200 cm	Yellow	Jul-Sep		✓	✓		
Thalictrum aquilegifolium	90 cm	Cream	May-Jul		✓	✓		Sun/ Partial shade
Trollies europaeus	40 cm	Yellow	May-Jun		✓	✓		Sun/ Partial shade
Veronica beccabunga	30 cm	Blue	Jun-Jul	✓	✓			Sun
Veronica longifolia	100 cm	Blue	Jul-Aug	✓	✓	✓		Sun

Table 4-7: Recommended Plant Species[377]

4.7 SUMMARY

The overall plan is made according to the concept of applying the idea of the bioretention system to create a stormwater treatment train in this garden city to solve the problem of potential water pollution to the Ohne river, in the meantime placing the 60 private properties in this area and creating a suitable living environment for the residents in the garden city. Four facilities are selected to form the stormwater treatment train in the public area, including permeable pavement, swale, filter strip and rain garden, while green roof and other facilities are recommended to be applied in the private properties.

The garden city is to be planned into three parts (the “residential area”, the “south green park”, and the “east rain garden”), all of which are connected by two types of streets (the “through street” and the “local street”) throughout the garden city. The drainage plan starts from the private properties, through the swales in the streets, and finally reaches the bioretention system in the green park. Potential contaminated runoff from the Birkungerstraße as well as the paving area around the Autohaus will be collected by the east rain garden, thereby posing no threat to other areas in the garden city.

[377] Dunnett & Clayden, 2007 (pg. 172-179)

In order to ensure the bioretention system in the green park is capable to take all the potential runoff from the entire garden city, both the volume of potential maximum precipitation in this area and the volume of the design hollow in the biretention system are calculated through scientific methods. In this project, most of the potential water pollutants are removed through three stages, according to the purification analysis, based on the theoretical study in the previous chapters. A variety of plant species with different moisture tolerance are recommended for the different moisture levels in the bioretention system.

CHAPTER 5 CONCLUSION

Through systematically analysing the theories of the sponge city concept by reviewing and analysing related literatures, and developing an effective approach to pollution problems in receiving waters nearby residential areas by proposing a new landscape plan for the “garden city” area in Leinefelde-Worbis, the scientific principle of stormwater management can be concluded as “applying a series of suited bioretention practices to create a stormwater treatment train in targeted areas”.

The idea of bioretenion is essentially water treatment practice based on the cooperation of plants, soils and microbes at site. To improve the sustainability and effectiveness of selected bioretention facilities, soil health and plant selection must be taken into considerations for site strategies as well as following planning and design. Soil compaction and organic matter are the major factors that influence soil heath and its water treatment capacity. The suited plants for general bioretention practices should be both flood- and drought- tolerant species, due to the environmental conditions in typical bioretention facilities.

All the components to form the stormwater treatment train should be selected in the consideration of their characteristics (suitable location, water treatment capacities, etc) and the conditions of local environment (soil permeability, surrounding receiving waters, and so on). The selection of the bioretention facility types (full infiltration, partial infiltration, and no infiltration) also depends on the practical needs and environmental conditions.

The capacity of the stormwater treatment train should be predicted in advance through scientific analysis or calculation, in order to ensure the effectiveness of both rainwater quantity and quality control.

Due to the limitation of the study depth, some detailed technologies including further treatment for the pollutants such as chloride, sodium, and others that cannot be completely removed by bioretention practices, have not been further elaborated. Future research work can continue on these details.

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Figure 2-3: Full Infiltration System	**ENVIRONMENTAL SERVICES DIVISION, DEPARTMENT OF ENVIRONMENTAL RESOURCES, THE PRINCE GEORGE'S COUNTY, MARYLAND.** (2007) *Bioretention Manual.* Environmental Services Division, Department of Environmental Resources, the Prince George's County, Maryland.
Figure 2-4: Partial Infiltration System	**ENVIRONMENTAL SERVICES DIVISION, DEPARTMENT OF ENVIRONMENTAL RESOURCES, THE PRINCE GEORGE'S COUNTY, MARYLAND.** (2007) *Bioretention Manual.* Environmental Services Division, Department of Environmental Resources, the Prince George's County, Maryland.
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Figure 2-7: Typical Stormwater Management Train System	**ARC.** (2003) *Technical publication 10: Stormwater management devices - Design guidelines manual.* Auckland Regional Council, Auckland.
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DECLARATION OF ACADEMIC INTEGRITY

Hereby, I declare that I have composed the presented thesis independently on my own and without any other resources than the ones indicated. All thoughts taken directly or indirectly from external sources are properly denoted as such.

This thesis has neither been previously submitted to another authority nor has it been published yet.

Neubrandenburg, 23th September 2019