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UNDERSTANDING WATER SENSITIVE URBAN DESIGN (WSUD) CONCEPT

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Abstract

Water Sensitive Urban Design (WSUD) is a multidisciplinary approach to the integration of water cycle management into urban planning and design. It is an internationally recognised concept that offers an alternative to traditional development practices of stormwater management. Water Sensitive Urban Design (WSUD) is an integrated management of stormwater. using a holistic approach to the planning and design of urban development that aims to minimize negative impacts on the natural water cycle and protect the health of aquatic ecosystems.

The WSUD objectives can be achieved by implementing the integration of various Best Planning Practices (BPPs) and Best Management Practices (BMPs). BPPs involve site analysis, land capability assessment and land use planning for enhancing the capability of stormwater management, while BMPs involve managing stormwater quantity and quality with the application of structural and non-structural measures. Non-structural BMPs include development policy, environmental consideration at project site, education programs and law enforcement, while structural BMPs are stormwater treatment measures which are used to achieved the multiple objectives of stormwater management (Lloyd et. Al., 2002).

This literature review paper presents the philosophy of Water Sensitive Urban Design (WSUD), its implementation through the integration of BPPs and BMPs. The paper also explains the application of structural and non-structural WSUD measures.

Key words : WSUD, stormwater management, urban stormwater, urban drainage system

INTRODUCTION

Background

WSUD is a philosophical approach to urban planning and design that aims to minimise the hydrological impacts of urban development on the surrounding environment (Lloyd et al. 2002). WSUD has been promoted and developed on the premise of integrating development with the principles of environmental sustainability (Gardiner & Hardy 2005). The principles of WSUD are now recognised and adopted internationally to reduce impacts of urbanisation on receiving waterways (SEQHWP 2007).

WSUD approach primarily focuses on stormwater quantity and quality management, and the main objective of WSUD techniques is to improve stormwater quality. WSUD approach offers an alternative to the traditional conveyance approach to stormwater management by minimising the extent of impervious surfaces, mitigating the changes to the natural water balance and improving stormwater quality. An integrated approach to stormwater management is the key to Water Sensitive Urban Design. This integrated approach views stormwater as a resource rather than a threat and considers all aspects of stormwater runoff within a development area, including environmental, social and cultural issues (Victorian Stormwater Committee 1999).

WSUD techniques have been implemented all over Australia. Some development areas in Australia are well known as successful WSUD large scale projects such as the Pimpama Coomera Water Futures Project and The Healthy Home in Queensland, Fig Tree Place and Kogarah Town Square in New South Wales, Lynbrook Estate in Victoria, and New Brompton Estate and Salisbury City Council ASR scheme in South Australia (McAlister & BMT WBM 2007). Some guidelines and procedures for WSUD have been provided by Local or State Governments. For example: "Water Sensitive Urban Design Technical Design Guidelines for South East Queensland" (SEQHWP 2006); "Water Sensitive Urban Design Technical Guidelines for Western Sydney" (UPRCT 2004); "WSUD Engineering Procedures: Stormwater" (Melbourne Water 2005); and "Stormwater Management Manual for

Western Australia" (DWGWA & DEGWA 2007). The "National Guidelines for Evaluating Water Sensitive Urban Design (WSUD)" which provides a framework to be used by both developers and assessors in formulating and evaluating WSUD strategies (McAlister & BMT WBM 2007).

The integrated approach of WSUD has become more popular since it has the potential to reduce development costs, minimise pollution and safeguard urban water quality. However, the adoption of this integrated approach in many cases has been constrained because it is seem to have high operation and maintenance cost, and in some cases it can reduce the size of developable land (McAlister & BMT WBM 2007). Therefore, providing knowledge on the benefits which can be gained by the application of WSUD techniques should include the capability to safeguard urban water quality as it can motivate institutions to accept and implement a holistic approach to WSUD

Current Lack of Understanding to WSUD Concept

Recently, some research studies have focused in evaluating the performance of WSUD applicable techniques. Coombes and Kuczera (2000) have studied the WSUD development site, "Tank Paddock" to compare the benefit of using WSUD approaches to the traditional approaches. The results proved that the WSUD scenario could significantly reduce stormwater peak and discharge volume, reduce the construction cost up to 53% and create other indirect benefit such as reduced potential erosion, reduced pollutant transport and safer roads during large storm events. However, other research studies such as by Foley and Daniell (n.d.), and Coombes et al. (2000) it is not clearly possible to scientifically relate the output of WSUD devices to water quality improvement.

It is well known that various WSUD measures have been widely used in Australia. There is no real doubt about their ability to reduce stormwater quantity and peak flow. The real doubts are with regards to water quality since there is no scientific information to confirm how efficient they are in removing pollutants. Also, there is no real scientific understanding of the pollutant removal processes in the various WSUD treatment devices.

IMPLEMENTATION OF WSUD CONCEPT

Water Sensitive Urban Design (WSUD) is commonly used in the planning and design of the urban environment that is 'sensitive' to the issues of environmental protection and water sustainability. According to the Victorian Stormwater Committee (1999) as presented in the Urban Stormwater: Best Practice Environmental Management Guidelines, the five key objectives of WSUD are as follows:

1) The protection and enhancement of natural water systems such as creeks, rivers and wetlands within urban catchments.
2) The integration of stormwater treatment into the landscape by incorporating multiple uses that provide a variety of benefits including water quality treatment, wildlife habitat, public open space and visual and recreational amenity for the community.
3) Protection of the quality of water draining from urban catchments.
4) Reduction of runoff volume and peak flows from urban development by using on-site detention measures and minimising impervious areas.
5) Minimisation of the drainage infrastructure development cost.

The achievement of WSUD objectives above can be gained by implementing the integration of various Best Planning Practices (BPPs) and Best Management Practices (BMPs). The incorporation of Best Planning Practices and Best Management Practices in Water Sensitive Urban Design is illustrated in Figure 1.

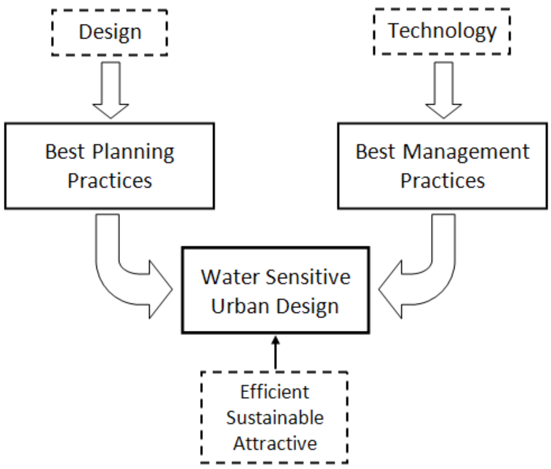

Figure 1: Incorporation of BPPs and BMPs in WSUD (Whelans et al. 1994)

Combining BPPs and BMPs in WSUD requires both structural and non-structural elements that perform the prevention, conveyance, treatment, collection, storage and reuse of urban water. Non-structural WSUD measures complement the performance of structural WSUD measures which are installed or retrofitted within urban stormwater systems.

Non-structural WSUD Measures

Non-structural stormwater WSUD measures are institutional and pollution-prevention practices designed to prevent or minimise pollutants from entering stormwater runoff. They typically do not involve fixed or permanent facilities, and usually work by changing community behaviour through government regulation, persuasion and economic instruments (Taylor & Wong 2002). Research studies undertaken in countries such as Australia, New Zealand, the United States and Germany (Sieker & Klein 1998; Taylor & Wong 2002; Taylor et al. 2007) have found a trend of increasing use of non-structural stormwater measures including education campaigns. They also found that the combination of non-structural and structural stormwater measures proved to be the best solution in overcoming stormwater management problems.

CRC for Catchment Hydrology in their research categorised non-structural WSUD measures into the following five core groups (Taylor & Wong 2002) and explained further in Stormwater Management Manual for Western Australia: Non-structural controls (Taylor 2005):

1. Town planning controls:
   - Stormwater planning controls that promote WSUD and BMPs on construction sites including erosion and sediment control.
   - Site-based non-structural WSUD measures for new residential developments, applied to public open space, residential housing lots layout, road layout, street-scaping layout, and conservation.
   - Site-based non-structural WSUD measures for new commercial/industrial areas, applied to green parking design and on-site detention for large areas.
2. Strategic planning and institutional controls:
   - Stormwater management plans for stormwater quality improvement and aquatic ecosystems protection.
   - Self funding mechanisms of stormwater facilities.
   - Risk assessments.
   - Integrating stormwater management with other aspects of the water cycle.
   - Building capacity of government staff, consultants, developers and community.
3. Pollution prevention procedures:
   - Site-based non-structural measures for land development and construction sites including drainage controls, erosion and sediment controls, dust controls, waste management controls, and soil amendment
   - Infrastructure maintenance operations including street sweeping, stormwater measures maintenance, road pavement repairs, public open spaces maintenance, vehicle, equipment and plant maintenance, building maintenance, building wash-down and graffiti removal, industrial and commercial site practices, loading and unloading areas maintenance, swimming pools discharges management, storage of dangerous goods, sewerage maintenance ,and septic system management.
   - Waste management practices including domestic waste and recycling collection, litter collections, bin design and cleaning, animal wastes management, illegal dumping management, hazardous household chemicals collection.
   - Management of wash-water from boats and mobile industries.
4. Education and participation programs:
   - Education program on source control measures using printed material, media campaigns, signs provision, community programs, displays, community water quality programs, launches, local action committees and groups, consumer programs, business programs, and school education programs.
   - Training
   - Community participation
   - Regional stormwater awareness programs
   - Education and participation campaigns for garden care practices, industrial and commercial premises.
   - Technical focused stormwater education on WSUD involving new estates.
5. Regulatory controls:
   - Law enforcement in relation to diffuse sources of stormwater pollution
   - Stormwater discharge regulation
   - Illegal discharge elimination programs
   - Vegetated buffer areas provision.

Structural WSUD Measures

WSUD structural measures are stormwater treatment measures which collect, convey, and detain or retain stormwater to improve water quality. They treat runoff by removing contaminants and protecting and enhancing the environmental, social and economic values of receiving waterways. Selection of appropriate treatment measures depends on site conditions, target pollutants and hydrological geometry of the catchment.

A treatment measure can be addressed towards the target pollutants found in stormwater runoff according to the range of particle size grading including dissolved pollutants which are assumed to have particle size less than 0.45 µm. Inter-relationships between stormwater pollutants physical sizes, suitable treatment measures and appropriate hydraulic loading are presented in Figure 2.

As can be seen from Figure 2, treatment measures which target coarse solids such as gross pollutant traps and sediment basins, can operate under high hydraulic loading. However as the target pollutants physical size reduces, the treatment processes change to include biological adsorption and transformation of the pollutants, and these occur under low hydraulic loading which require larger land areas for treatment flows.

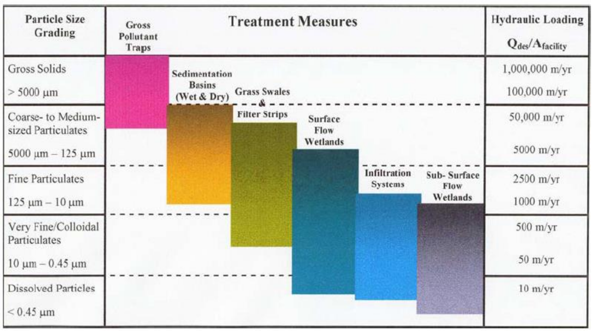

Figure 2: Typical stormwater treatment measures, target pollutant sizeand hydraulic loading (Wong 2000)

In applying WSUD measures to a specific catchment, it is more effective to combine two or more treatment measures. A series of treatment measures for stormwater pollutant removal is analogous to the carriages in a train and is therefore referred to as a ‘treatment train’ (Wong 2006). A treatment train provides a guarantee of a better performance and overcomes factors which may limit the effectiveness of a single measure.

Different WSUD measures for managing stormwater quality will provide different levels of treatment. Mouritz (2006) divides WSUD treatment measures into three different levels, i.e. primary, secondary and tertiary treatment. Primary treatment measures that target litter, gross pollutants and coarse sediment include gross pollutant traps, trash racks, sediment traps and oil collectors. Secondary stormwater treatment measures that aim to remove sediments, heavy metals partially and bacteria include vegetated buffer strips, grass swales, detention basins, bioretention filters, infiltration trenches and infiltration basins. Tertiary treatment measures that aim to remove fine sediments, nutrients, bacteria and heavy metals include constructed wetlands.

COMMON WSUD STRUCTURAL MEASURES

Some common WSUD structural measures are selected to be discussed further in the next sections. They are gross pollutant traps, vegetated swales incorporating buffer strips and bioretention, detention/retention basins, con-structed wetlands, and infiltration systems.

Debris and Gross Poluttan Trap

Gross pollutants are large pieces of urban debris which are flushed from the catchment into the stormwater system during storm events. These pollutants, which typically include urban-derived litter and vegetation debris, can look unpleasant, have bad smell/odour, and be a threat to aquatic biodiversity. Gross pollutants are generally the most noticeable water pollution indicator to the community, due to their visibility (Wong et al. 2000). Allison et al. (1997) have defined that gross pollutants are the debris items larger than 5 mm.

A study by Cooperative Research Centre (CRC) for Catchment Hydrology in Melbourne has found urban areas contribute about 20 to 40 kilograms (dry mass) per hectare per year of gross pollutants to stormwater, with significant amount of litter items, comparably about one item per person per day (Allison et al. 1997). The study also found that the gross pollutants mobilisation rate is highly correlated with rainfall.

To reduce gross pollutants in urban waterways, both structural measures (gross pollutant traps) and non-structural efforts are required to be applied. Non-structural measures include changing the attitudes of the community, public awareness, litter bin provision, street sweeping, government regulation and law enforcement (Taylor 2005).

Gross pollutant traps are stormwater pre-treatment measures that are very important to be applied within a treatment train. They protect downstream stormwater treatment measures from clogging and malfunction.

A number of different types of gross pollutant traps are available. Each of them has different specification and may have different target pollutants. Followings are some gross pollutant traps gathered from some references (Victorian Stormwater Committee 1999; Allison et al. 1997; Wong et al. 2000; Martens et al. 2007):

- ✓ Grated entrance screens; consist of metal screens that cover the inlet of the drainage network to prevent the entry of gross pollutants.
- ✓ Side entry pit traps; baskets placed below the invert of road gutters, inside the drainage pit and used to retain materials larger than the basket mesh size (5-20mm).
- ✓ Litter collection devices; baskets that sit below the entry point of the inlet pipe. Debris larger than basket pore size is retained.
- ✓ Trash racks; consist of either vertical or horizontal steel bars, typically spaced 40 to 100 mm apart. Trash racks are installed in stormwater drainage pipes to intercept floating and submerged materials.
- ✓ Gross pollutant traps; sediment trap with trash racks constructed of vertical bars. They consist of a large concrete lined wet basin upstream of a weir, used to collect floating and submerged debris.
- ✓ Floating debris traps; made by stringing partly submerged floating booms across very slow moving waterways, used to collect floating objects.
- ✓ Baffled pits; stormwater pits modified with a series of baffles, used to trap floating debris and encourage heavy sediments to settle in the pit.
- ✓ Circular settling tanks; cylindrical tanks that are divided into an upper diversion chamber and a lower retention chamber. While stormwater is directed by a diversion weir into the lower retention chamber and exits the chamber through an outlet riser pipe, sediments are collected in the base of the retention chamber.
- ✓ Release nets; cylindrical nets that are secured over the outlet of a drainage pipe and capture all materials larger than the pore size of the net

Vegetated *Swales / Filter Strips / Bioretention Swales*

1) Vegetated Swales

A vegetated swale is a broad, commonly parabolic or trapezoidal shallow channel with vegetation covering the side slope and bottom. Vegetated swales are used in road medians, verges, carpark areas, and park and recreation areas. They are often used as an alternative to kerb and gutter with low flow velocities, therefore protects waterways from damage or erosion. The swales act as stormwater quantity improvement measure by reducing runoff volume and peak discharge (Fiener & Auerswald 2005), as well as stormwater quality improvement device by promoting pollutant removal (Deletic & Fletcher 2006; Schueler 1995; EPA 1999)

Vegetated swales support the achievement of WSUD objectives by disconnecting impervious areas from downstream waterways. The swales provide an important pre-treatment function for tertiary treatment systems such as wetlands and bioretention basins.

Swales are commonly designed with side slopes no steeper than 3:1, and with longitudinal slopes of between 1% and 4% in which they can generally operate best to convey stormwater and treat stormwater quality (SEQHWP 2006). Subsoil drains need to be installed beneath the swales if longitudinal slopes are less than 1% to avoid stagnant ponding and waterlogging. On the contrary, for slopes steeper than 4%, check dams should be constructed across the swale base at intervals along the invert of the swales (see Figure 3). The check dams reduce flow velocities and protect the vegetation from erosion.

Figure 3: Vegetated swale with check dams (DCR 1999b)

2) Filter Strips

Filter strips (or buffer strips) are open vegetated areas where runoff flows over while travelling to a discharge point. Runoff flowing across the filter strips should be distributed as sheet flow. Therefore filter strips typically require uniformly distributed flow or sheet flow that originates from roads or carparks, or otherwise require flow spreaders across the width of the strips to convert shallow concentrated flow to sheet flow before entering the filter strips.

Filter strips are typically provided as a pre-treatment for other WSUD measures such as around detention/retention basins and wetlands. They are often provided incorporating vegetated swales. Filter strips not only reduce sediment loads but also reduce runoff volume and discharge rate through infiltration and reduction in velocity.

Pollutant Removal Performance of Swales Systems

Studies in the United States of America have shown that vegetated swales were capable of removing many stormwater pollutants, with reported removal efficiencies of 83% for sediment, 75% for hydrocarbons, 67% for lead (Pb), 63% for zinc (Zn) and 63% for aluminium (Al) (Schueler 1995). EPA (1999) has reported similar results with high removal efficiencies of some pollutants including 81% for total suspended solids (TSS), 67% for oxygen demanding (OD) substances, 62% for hydrocarbons, 42% for cadmium (Cd), 51% for copper (Cu), 67% for lead (Pb) and 71% for zinc (Zn), but ineffective for removing nutrients with removal efficiencies of only 9% for phosphorus and 38% of nitrate.

Conversely, Deletic and Fletcher (2006) in their observations in Brisbane found more significant removal of nutrients in vegetated swales. They confirmed that the swales investigated in Brisbane removed 46% of total phosphorus (TP) and 56% of total nitrogen (TN). They also found lower removal efficiency of TSS with only 69% as compared to the results reported by Schueler (1995) and EPA (1999) above.

A study in Veneto Region (north-east Italy) undertaken by Vianello et al. (2005) showed that vegetative filter strips can also reduce the concentration of herbicides.

Water quality treatment processes in Vegetated Swales and Filter Strips

The water quality treatment processes which occur in filter strips and vegetated swales are relatively complex, and involve physical and biochemical processes. Pollutant removal through physical processes is achieved by settling, filtration and infiltration of the particulates or suspended solids, and consequently include particle-bound pollutants such as phosphorus (Martens et al. 2007). Biochemical processes occur in relation to certain pollutants, such as hydrocarbons which are digested or processed by vegetation and soil micro-organisms. Therefore, in order to optimise pollutant removal, adequate contact time between stormwater runoff and vegetation and soil surface is required (Victorian Stormwater Committee 1999).

Furthermore, Clar et al. (2004a) noted that the removal of soluble pollutants in vegetated swales or filter strips depends on the infiltration rate, because removal occurs when pollutants infiltrate into the soil where some of which is subsequently taken up by vegetation roots. Other factors which influence pollutant removal performance of filter strips and vegetated swales are length, slope, soil permeability and vegetation height and density, area of catchment, particle sizes, pollutant concentration, settling velocity, runoff velocity and flow rate, and contact time (Schueler 1987; Martens et al. 2007; Clar et al. 2004a).

3) Bioretention Swales

Bioretention swales consist of excavated trenches which are filled up with porous media (typically sandy loam) and planted with vegetation on the surface (see Figure 4). The bioretention component is typically located at the downstream end of a swale system or can be complemented as a continuous trench along the full length.

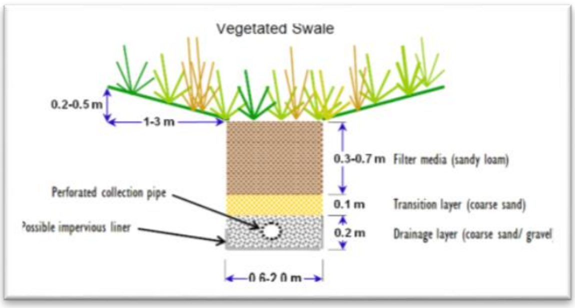

Figure 4: Cross section of typical bioretention swale (SEQHWP 2006)

Stormwater quality treatment processes in bioretention swales are operated in combination by the swale component and the bioretention system. The swale component promotes pre-treatment of stormwater by removing coarse to medium sediments, whilst the bioretention system removes finer particulates including associated contaminants and suspended solids through filtration, infiltration and biological uptake.

It has been reported that bioretention swales can remove pollutants more effectively than vegetated swales with the average removal efficiencies of 90% for coarse sediment, 80% for total suspended solids (TSS), 50% for total nitrogen (TN), 60% for total phosphorus (TP) and 80% for heavy metals (Martens et al. 2007).

Sediment Transport Model

The particles transported through the grass/vegetation swale system are usually very small, mostly below 20 µm (Neibling and Alberts 1979 as cited in Deletic (2001)). Therefore, it can be assumed that they are transported as fine suspended solids, because the coarser particles have been deposited before or when they just enter the system.

It is understood by researchers that there is a positive correlation between pollutant removal (including TSS, TN and TP) and the length of swale or buffer strip. The relationship indicates that that there is an exponential decrease of such pollutants along the length of the systems (Clar et al. 2004a; Deletic 2005; Deletic & Fletcher 2006).

Physical pollutant removal processes within the grass strips and swale systems have been observed and modelled by researchers such as Deletic (2001), Muñoz-Carpena et al. (1999) and Fiener & Auerswald (2005). Deletic (2001) developed a classical transport equation for sediment transport through the grass as follows:

$$\frac{\partial(hq_{s,s}/q)}{\partial t} + \frac{\partial q_{s,s}}{\partial x} = Dis\frac{\partial^2(hq_{s,s}/q)}{\partial x^2} - \lambda_s q_{s,s}$$

where:

$q_{s,s}$ is the sediment loading rate of fraction s per unit width [$MS^{-1}L^{-1}$]

Dis is the dispersion coefficient [L^2S]

λ_s is the trapping efficiency for fraction s per unit length [L^{-1}] which is obtained from,

$$\lambda_s = \frac{T_{r,s}\left(\frac{lV_s}{Vh}\right)}{l}$$

where:

l is the grass length [L]

V_s is the Stokes settling velocity [LS^{-1}] of the particle with diameter d_s [L]

V is the average mean flow velocity between grass blades [LS^{-1}]

h is the depth of the flow [L]

$T_{r,s}$ is the trapping efficiency for sediment factor s, which is a function of the particle fall number $N_{f,s}$ and can be expressed by semi-empirical equation below,

$$T_{r,s} = \frac{N_{f.s}^{0.69}}{N_{f,s}^{0.69} + 4.95}$$

While numerous studies have focused on the physical removal processes in the grass strips and swale systems, limited information is available to explain the biochemical processes by vegetation and soil micro-organisms involved in removing hydrocarbons and dissolved pollutants. The processes are far more complex and remain little understood. Therefore, appropriate studies should be addressed to provide better understanding of these processes.

Detention/Retention Ponds/Basins

Detention/retention ponds/basins (thereafter in this section will refer as ‘retention basins) are stormwater facilities that provide storage for stormwater runoff to be retained during storm events and then slowly released through a designed outlet. Retention basins can also allow infiltration of stormwater during the detention period. Therefore, the main objective of retention basins relates to stormwater quantity control.

Some retentions basins have a permanent pool in order to also function as a recreation and landscape amenity. However, during very dry weather, the pool could be totally dry. In order to maintain sufficient volume of water in the permanent pool, a reliable source of runoff or ground water is required (Clar et al. 2004b).

In the past, the aim of retention basins was mainly focused on reducing stormwater peak discharge through retention and reducing stormwater quantity through infiltration, and only little attention was paid to the stormwater quality aspect. However, the growing public awareness on environmental issues has led to the application for stormwater quality treatment.

Retention basins provide downstream flood control and channel erosion control by temporarily storing stormwater runoff in the basin during rainfall events, therefore protect downstream wildlife and aquatic habitats. Retention basins can also provide aesthetic and recreation benefits as well as water supply for irrigation or fire protection (Clar et al. 2004b).

Water quality treatment

Retention basins provide long-term storage of stormwater runoff to allow physical settling of fine suspended sediments, which includes particle-bound pollutants such as phosphorus (Martens et al. 2007). Sediments that are deposited in the basin bed are also protected from re-suspension. A better result in improving stormwater quality will be achieved where retention basins are combined with other WSUD measures, forming a treatment train.

According to Schueler (1992), monitoring studies have shown that retention basins have sediment removal efficiencies ranging from 50% to 90% and TP removal efficiencies ranging from 30% to 90%. The pollutants removal efficiencies of a retention basin have also been monitored by Birch et al. (2005). The results showed that TSS concentration in stormwater was reduced by an average of 50%, whereas the concentration of Cu, Pb and Zn were also reduced by an average 68%, 93% and 52%, respectively.

Constructed Wetlands

Constructed wetlands are manmade shallow, extensively vegetated water bodies that are designed and built specifically to enhance the quality of stormwater runoff. Constructed wetlands are intentionally created on non-wetland sites to improve landscape amenity and temporary storage of treated water for reuse schemes in addition to treat stormwater (Martens et al. 2007). During rainfall events, water levels in wetlands rise, and then slowly released through configured outlets. Stormwater is retained in the wetland system typically for up to two or three days (SEQHWP 2006).

A constructed wetland generally consists of an inlet zone, a macrophyte zone as the main area of the wetland, and a high flow bypass channel (see Figure 5). In the inlet zone, it is a constructed a sedimentation pond with a relatively deep open water body with edge and possibly submerged macrophytes. The pond is generally located upstream of the wetland, and it commonly incorporates primary pre-treatment stormwater measures at the inlet to provide coarse sediment and gross pollutant removal. Low flow of stormwater in the pond allows fine sediments to settle in the pond bed, therefore protects the main area of the wetland system (Victorian Stormwater Committee 1999; Martens et al. 2007).

Macrophyte zone is the main zone of the wetland system, comprising of a shallow water body with extensive emergent vegetation. There are some specific zones of vegetation throughout the wetland, where each zone is generally determined by the water depth. As can be seen from Figure 6, constructed wetlands contain four vegetation zones, i.e. zone of shallow marsh vegetation, marsh vegetation, deep marsh vegetation and submerged vegetation (Victorian Stormwater Committee 1999). Open water located near the outlet of the wetland promotes ultra violet exposure, which promotes bacteria die-off.

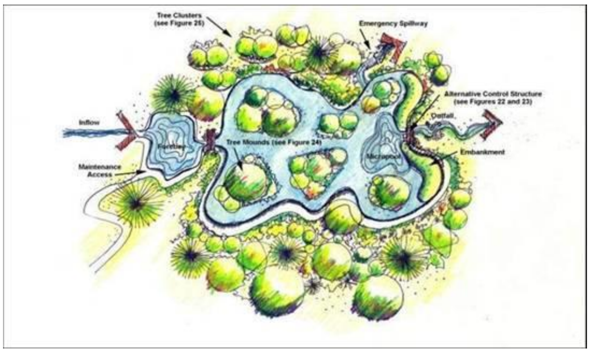

Figure 5: Typical constructed wetland system Source: Virginia DEQ Stormwater Design Specification No. 13

Runoff flows entering the macrophyte zone are controlled in the inlet zone. When the flows exceed the design flow, 'above design flows' are by-passed around the macrophyte zone through the high flow bypass channel. Thereby, this protects the vegetation in the macrophyte zone against scour during high flows (SEQHWP 2006).

Water quality enhancement

Constructed wetlands are useful for enhancing stormwater runoff quality, particularly where stormwater contains high concentrations of soluble material which is difficult to remove by other stormwater treatment devices. High removal rates of particulates and soluble pollutants including nutrients can be achieved by constructed wetlands through settling, vegetation uptake, absorption, filtration and biological decomposition (DCR 1999a).

Wetland vegetation plays an important role in improving water quality by encouraging sedimentation, filtering of nutrients and other pollutants through roots, stems and leaves, and by using nutrients when in the growth phase. Wetland plants also promote the growth of biofilms, which assimilate dissolved nutrients.

Changing deep and shallow zones in wetlands, perpendicular to the stormwater flow, can transform and remove nitrogen through various chemical reactions. The shallow zones are generally well oxygenated and therefore promote mineralisation and nitrification. Mineralisation is the breakdown of organic nitrogen to ammonium while nitrification is the breakdown of ammonium to nitrate. While the water flows to the deeper zones, denitrification occurs, converting nitrate to gaseous nitrogen, which is then released to the atmosphere (Martens et al. 2007). Phosphorus removal in a wetland takes place through sedimentation, filtration, biological uptake and sorption.

Sim et al. (2008) reported that nutrient removal performance of Putrajaya Wetlands in Malaysia was 82.11% for TN, 70.73% for nitrate (NO^{-3}), and 84.32% for phosphate (PO_4^{3-}). Other studies which have also reported on nutrient removal by constructed wetlands including those conducted by Knight et al. (2000), and Reinelt and Horner (1995). Fletcher et al. (2003) in their literature review have concluded that constructed wetlands can achieve high pollutant load removal with annual efficiencies of up to 95% for litter, up to 95% for TSS, up to 80% for TN, up to 85% for TP, up to 95% for coarse sediment, and up to 95% for heavy metals.

Heavy metals can be removed from the water column through sedimentation, adsorption and plant uptake. The performance of wetlands in reducing heavy metals, particularly Zn, Pb and Cu has been reported by Walker and Hurl (2002) whilst the removal of other metals including Ca, Mg, Mn, and Na has been noted by Kohler et al. (2004). Other researchers have also reported that constructed wetlands can significantly reduce organic pollutants such as pesticides, insecticides, fungicides and hydrocarbons (Kohler et al. 2004; Sherrard et al. 2004; Thurston 1999).

Pathogens can be destroyed by exposure to ultra violet light in open water and by predation, or removed through adsorption. Reinelt and Horner (1995) have reported that urban wetlands in Washington, USA reduced fecal coliforms with mean annual removal at 49%.

Pollutant Removal Models

Pollutant removal processes in constructed wetlands have been observed and modelled by researchers such as Wong and Geiger (1997), Wood and Shelley (1999), and Werner and Kadlec (2000). The most commonly adopted model widely used to compute the performance of constructed wetlands in the removal of stormwater pollutants is a first order kinetic model (Wong & Geiger 1997; Wong et al. 2000; Wong et al. 2001; Carleton et al. 2001; Holland et al. 2005). The model uses a first order decay function, which is simplified from a large number parameters involved. When stormwater carrying pollutants moves through the wetland system, the quality of water is influenced by several physical and biochemical processes which are very complex. However, the overall effect is that contaminant concentration in the water tends to move by an exponential decay process toward an equilibrium value.

The model involves two parameters, i.e. the rate constant k and the background concentration C*, and can be written as the following equation:

$$C_o = C^* + (C_i - C^*)e^{-\frac{k}{q}}$$

Where:

- C_o is the pollutant concentration at the outlet of the wetland (mg/l)
- C_i is the pollutant concentration at the inlet of the wetland (mg/l)
- C^* is the equilibrium value or the pollutant background concentration (mg/l)
- k is the rate constant of pollutant removal parameter (m/yr)
- q is the wetland hydraulic loading (m/yr)

The first order kinetic model given above is also adopted by Cooperative Research Centre (CRC) for Catchment Hydrology, and used in MUSIC (Model for Urban Stormwater Improvement Conceptualisation) software (CRCCH 2005). However, the model seems to be very simplistic because a lot of parameters have been combined into two parameters (k and C*). Furthermore, each calibrated parameter can only be used for the specific device where the data was originally derived. Therefore, it is necessary to develop a synthetic model which can be used widely without a lot of calibration data required, but should be based on the catchment and device parameters.

Infiltration Systems

Infiltration systems capture stormwater runoff and promote infiltration into surrounding soils where the systems are installed. The primary focus of infiltration systems is on stormwater quantity for reducing stormwater runoff volumes and peak flows. However, this raises the implication on stormwater quality improvement through filtration of stormwater runoff in the subsurface soils, prevention of downstream flooding, and protection of downstream aquatic ecosystem.

Through an infiltration system, stormwater is directly disposed into the soil ground, and finally the disposed water reaches the groundwater. Therefore, to protect groundwater quality, an appropriate pre-treatment of stormwater entering infiltration systems is required. Stormwater pre-treatment measures can also help to avoid clogging of the infiltration system.

Infiltration systems typically have two main functions; to detain stormwater temporarily and to promote infiltration of stormwater into the soil. Hence, they require sufficient detention storages and infiltration areas comprising high permeable materials such as granular materials. The detention storage can be located above or below the ground, and is designed to detain a certain volume of stormwater runoff. When the storage is full, the exceeded runoff is bypassed through the overflow system. The infiltration area is the interface area between the detention storage and the on site soil through which the collected runoff is infiltrated (SEQHWP 2006).

There are a number of infiltration systems which are widely used for urban stormwater control. Among them, leaky wells/ soakwells, infiltration trenches and porous/modular pavements are selected to be discussed further in this section as these are the most commonly used in Australia.

1) Leaky Wells/ Soakwells

Leaky wells or soakwells are the traditional stormwater source control measures which are still widely used, typically in small-scale residential and commercial areas. A Soakwell commonly consists of a concrete or PVC cylinder located vertically above a circular base. Slots around the cylinder and a drainage hole on the base which are covered with geotextile, promote the stormwater runoff stored in the soakwell to infiltrate into the surrounding soil.

Infiltration of stormwater from soakwell is calculated using two approaches. First approach assumes that the infiltration occurs and follows the unsaturated flow model. The model calculates the emptying time base on the infiltration capacity of the soil and the wetted area of the soakwell. The second approach assumes that the flows from the soakwell are below saturated conditions. This model uses the theory of flow through porous media, therefore Darcy’s Law is applied (Browne et al. 2008).

2) Infiltration Trenches

An infiltration trench is a shallow, typically 0.5 – 1.5 m deep, excavated trench filled with gravel or other coarse aggregate, into which stormwater runoff drains. The trench is lined with geotextile fabric to prevent soil migration into the filled material, and covered with topsoil. Infiltration trenches usually have an overflow pipe for large storm events. Infiltration trenches have a similar function with soakwells to detain and infiltrate stormwater.

Infiltration trenches promote pollutant removal by retaining particulates and dissolved pollutants in the trench when stormwater exfiltrates from the trench into the surrounding soil (Victorian Stormwater Committee 1999). The theory and models used for soakwells are applicable for infiltration trenches.

3) Porous Pavement and Modular Pavement

Porous pavements are pervious paved surfaces, typically laid on the top of a highly porous aggregate or gravel base layer with a geotextile in-between. Porous pavements are suitable for areas with light traffic loads such as driveways and car parks. There are two broad groups of porous pavements; the open-graded asphalt/concrete pavements with large porosities and the modular pavement with large gaps between impervious modules (Victorian Stormwater Committee 1999).

Porous pavements allow runoff to infiltrate through the pore spaces of the pavement or through the gaps between modules into the filled aggregate layer, which provides temporary storage as the water gradually infiltrates into the subsoil. Pervious pavements can remove sediments, nutrients, heavy metals and hydrocarbons from polluted stormwater via the processes of adsorption, filtering and biological decomposition. Field studies have also shown that porous pavements are very effective at retaining dissolved metals (Dierkes et al. (2002) as cited in Martens et al. (2007)).

CONCLUSIONS

Water Sensitive Urban Design (WSUD) is a philosophical approach to urban planning and design that aims to minimise the hydrological impacts of urban development on the surrounding environment through the implementation of WSUD measures. WSUD devices which are most commonly used in an urban catchment include gross pollutant traps, detention and retention basins, filter strips, vegetated swales and bioretention swales, constructed wetlands, and infiltration systems.

WSUD devices protect downstream aquatic habitats, treat runoff by removing contaminants, and protect and enhance the environmental, social and economic values of receiving waterways. However, the pollutant removal processes in the various WSUD treatment devices are very complex and there is no scientific information to confirm their efficacy in water quality improvement. Through detailed investigation of selected systems, it is expected to develop better understanding of the processes, and finally to develop mathematical models of the processes.

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