Constructed wetlands for flood prevention and water reuse

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Abstract
This paper reviews the contribution that constructed wetlands can make to Integrated Urban Water Management by increasing stormwater storage and infiltration volumes and reducing the volumes of stormwater discharged to the sewer system and to wastewater treatment plants. Examples are given of constructed wetlands as stand-alone systems or as a component of a treatment train of Best Management Practice (BMP) drainage systems in cities in Europe, Australia, Asia and the United States. The criteria for selecting constructed wetlands for retrofitting drainage systems and the influence of the level of maintenance on their whole-life cost are considered.

The benefits of the reuse of water stored in wetlands by conserving drinking quality water supplies and thus reducing water treatment volumes, costs and energy consumption are discussed. An aquifer storage transfer and recovery (ASTR) programme in Australia is described which will provide drinking water from urban stormwater and examples are given of cities developing the reuse of water stored in wetlands for the irrigation of public parks.
Keywords Constructed wetlands; stormwater management; flood prevention; water reuse

INTRODUCTION

The United Nations has predicted that the global population will increase from currently 6.8 billion to 9.1 billion persons by 2050 (UN, 2009). Changes in our current approach to water resource management are urgently required and the development and implementation of measures to ensure the sustained supply of safe clean water to populations throughout the world. Urban water supplies are under increasing pressure to meet the demands of growing populations and changing industries. In many parts of the world this is occurring within the context of an increased frequency of extreme events such as flooding or extended droughts. The International Water Association (IWA) notes that cities will require at least a doubling of the overall efficiency in the use of water and the reduction of pollution. The IWA 'Cities of the Future', programme states that 'vanguard programmes are required for stimulating advances in the leading edge of urban water efficiency, resource recovery and ecological sustainability. One of its five goals is to optimise the design and operation of existing systems in the built environment in the short term (IWA, 2010).

In the European Union 6th Framework project 'Sustainable Water management Improves Tomorrow's Cities Health' (SWITCH, 2010), Stormwater Management is one of six research themes. Its objectives include the development of concepts of sustainable stormwater resource use which cities can utilise for their own stormwater management strategies, and to identify catchment-scale stormwater management strategies for integration into urban land management planning. The research theme has investigated and produced reports on the use of alternative hybrid and retrofit technological approaches including constructed wetlands for stormwater control which contribute aesthetically to the urban environment and provide acceptable levels of prevention/protection against flooding, water pollution and water shortage when exposed to extreme events and conditions (Scholes and Shutes, 2007; Shutes, 2009).

To ensure a secure water supply into the future, cities must become 'water sensitive' by reducing water use per capita, minimising wastewater, encouraging water recycling, and mitigating anthropogenic impacts on aquatic ecosystems. Water Sensitive Urban Design (WSUD) involves a pro-active process which recognises the opportunities for urban design, landscape architecture and stormwater management infrastructure to be intrinsically linked (Wong, 2006). Urban stormwater and treated effluents will be reused for landscape irrigation, and groundwater recharge in the Cities of the Future. All three components, i.e., water supply, stormwater, and wastewater will be considered and managed in a closed loop (Novotny and Brown, 2007). One of the features of future cities will be localised drainage networks comprising more surface rather than underground systems. The increase in stormwater storage volumes and infiltration volumes provided by Sustainable Urban Drainage systems (SUDS) or Best Management Practices (BMPs) including constructed wetlands, will reduce the volumes of stormwater discharged to the sewer system and to wastewater treatment plants (WWTPs), thus lowering the energy costs of operating WWTPs. The introduction of stormwater reuse contributes to Integrated Urban Water Management (IUWM) within the urban water cycle by conserving drinking quality water supplies (by using the lowest quality of water for lowest quality needs) and generating water supplies for urban agriculture and other uses.

Cost-benefits will also accrue from a reduction in water pollution and flooding. The enhancement of urban biodiversity and the landscape from the use of wetlands, ponds and basins will also have a cost-benefit in terms of increasing property values. Direct and indirect improvements in the quality of life and health of the urban population will result from an integrated programme of stormwater, wastewater, water supply and demand management and environmental education. A summary of the benefits to an IUWM programme of introducing or retrofitting a drainage system with constructed wetlands and other BMP types is shown in Table 1.

Table 1 IUWM benefits from the development of BMP drainage systems

Technical	Environmental	Community	Costs	Planning
↓Pollution & flooding ↓Runoff volumes to CSOs, WWTPs ↓Impermeable surface area ↑Stormwater storage volumes	↑Maintaining receiving water volumes ↑ Water quality ↑Wildlife habitats ↑Biodiversity and landscape	↑Environmental education, information and training ↑Stakeholder consultation ↑Community participation	↓Drainage system costs ↓O&M costs ↓WWTP runoff treatment costs ↓Retrofit costs	↑Landscape and flood management planning ↑Control of impermeable surfaces ↑Surface water drainage

↑ represents an increase; ↓ represents a decrease

Flood prevention

The European Water Framework Directive was the main driver behind the review of drainage systems and the implementation of SUDS/BMPs in the following examples of European cities. The Greater Dublin Strategic Drainage study recommended the use of SUDS to be greatly increased in the city and its surrounding region. In addition to the benefits of stormwater control and the prevention of flooding, SUDS will bring benefits to developers as well as the public by enhancing the value of existing and new properties (Doyle et al., 2003). On the river Tolka which is prone to flooding in the city and region of Dublin, retrofit wetlands have been introduced since 2001 on problem surface water sewers prior to discharge to the river (D’Arcy and Chouli, 2007). In Tolka Valley Park, the retrofitting of a pond receiving stormwater and misconnected domestic wastewater as a constructed wetland, has reduced nutrient discharges and algal scum and enhanced biodiversity with the reintroduction of the common frog, one of three amphibian species in Ireland (Dublin City Council, 2010).

Augustenborg is an inner city suburb of Malmo, southern Sweden which previously experienced flooding during heavy storms from Combined Sewer Overflows (CSOs). An open stormwater system was introduced in 2001 and drainage to the combined sewer system was disconnected. Community participation was an important factor in the implementation of stormwater disconnection. Stormwater now passes through a complex system of green roofs, swales, channels, detention ponds and small wetlands, (Villarreal et al., 2004). The ponds and small wetlands are designed to attenuate 10-year event rainfall, and the green roofs are effective at reducing total runoff. In the Netherlands, the Nijmegen Water Plan (1997) aimed to disconnect 20% of paved surfaces in urban areas within a decade. Grass swales, infiltration trenches and wetland systems have been developed and visual water arts projects implemented to raise public awareness of stormwater. Emscher is a region (named after the river) of Germany which is drained by surface water channels that act as combined sewers. The system is currently being replaced over a period of 15 years with sanitary sewers and retrofit source-based stormwater management systems such as constructed wetlands, where feasible. The total amount of stormwater carried by the system is aimed to be reduced by 15%. A GIS-based planning tool has been used to highlight and prioritise the feasible level of disconnection in each sub-area. A survey of 182 drainage sites in Glasgow and Edinburgh, Scotland, indicated appropriate individual BMP techniques or short BMP treatment trains for retrofitting existing drainage systems and for future developments (Scholz, 2007). Glasgow has higher volumes of rainfall runoff and considerably more regeneration sites with potential for developing constructed wetlands than Edinburgh, which has a lack of affordable space and will therefore rely on retrofitting other BMP types. A BMP Decision Support Matrix was prepared comprising of dominant criteria including the area available for the BMP and the quality of the runoff and it specifies the technical conditions for the implementation of the corresponding BMP. The supplementary criteria included catchment size and land value and were weighted according to their relative importance for each BMP technique.

The rapid urbanisation of Kaohsiung city in south Taiwan, its location in a plain below mountains and its sub-tropical climate with high rainfall has increased its susceptibility to flooding. The city and county governments have constructed flood detention ponds, artificial lakes and wetlands to reduce the discharge to stormwater drainage systems. The wetland park systems not only regulate the water flow rate and reduce the build-up of sediment sludge in wet weather, but also provide recreation, amenities and environmental education. Some of the restored and created wetlands in the lower terrains can also be used as detention ponds to regulate floods in wet weather. The former pond in Shezihlinpi Wetland Park was seriously polluted by sewage discharge and garbage dumping. It was restructured as a wetland park in which the contaminated water is pre-treated by a constructed wetland before being discharged into the natural wetland. The wetland park has an area of 3.75 ha, an average water depth of 1.5 m and a storage volume of approximately 56,250 m^3. The new park provides a focal point for the community to meet and relax and participate in its management. Singapore introduced a programme for water sensitive urban design in 2006 which includes constructed wetlands for the treatment of stormwater and other wastewaters. The Sungai Buloh surface flow stormwater treatment constructed wetland was completed in 2009 with an area of 1000 m^2 and 6000 plants of 6 species and a nutrient removal performance of 64.4% for total nitrogen and 24.4% for total phosphorus (Sim, 2010).

In the United States, several states provide stormwater and BMP management manuals online. The Iowa Stormwater Management Manual (2008) notes that stormwater wetlands require a minimum drainage area of 10 ha in order to maintain the vegetation and a wetland surface area of 3-5 % of the drainage area in order to reduce peak flows and attenuate floods. The City of Portland Environmental Services provides advice on its Sustainable Stormwater Management programme. This project aims to maximise the retention, treatment and infiltration of street runoff, while providing improved safety and a visual amenity for the neighbourhood. A Green Street programme has introduced pocket wetlands to the sides of streets in order to reduce impermeable surface area, and to enable stormwater to infiltrate and recharge groundwater and surface water. A constructed wetland in Glencoe Rain Garden provides 80% reduction in peak flows, 88% flow volume retention annually over 3 years and protects downstream properties from backups (Kurtz, 2007). There is also a programme of disconnection of roof-draining downspouts from the mains sewers allowing irrigation of gardens and drainage into the soil. In addition to the water quality and ecological benefits to the local Willamette River from reduced CSO discharges, residents experienced an enhancement of their street landscape and improved irrigation of their gardens (Portland Environmental Services, 2009).

BMPs can be retrofitted under a number of conditions including; at the time of building refurbishment; during drainage improvement for large areas such as trading estates or where there are unsatisfactory CSOs; and through incentives to property owners to "disconnect" roof or driveway runoff from the public drainage system (Gordon-Walker et al., 2007). When selecting ponds or wetlands for retrofitting or construction on new developments, the requirements for flow attenuation, water storage or pollution treatment should be considered. Systems with a high degree of permanent pool volume have dissolved oxygen and redox potential conditions that may lead to remobilisation of contaminants in the sediment. These factors are overcome in constructed wetlands, with their characteristic cycles of filling and draining (Wong et al., 1999). Headley and Tanner (2006) suggest that floating treatment wetlands may be suitable for incorporating into stormwater wetland systems and especially those suffering vegetation decline due to inappropriate water depths and excessive inundation. A Water Environment Research Foundation (2009) study found that the level of maintenance specified had a pronounced effect on the whole-life cost for most BMP facilities. For instance, the level of maintenance for retention ponds and wetlands had a much greater influence on whole-life cost than construction cost. Also, the model developed by the WERF study predicted that small sites with a high level of maintenance would have a greater whole-life cost compared with facilities that were 10 times as large, but maintained at low or medium levels. The costs of developing or retrofitting, operating and maintaining a drainage system are normally lower for BMPs than for a traditional system but the high land-take required by wetlands is a major cost factor in their selection.

Stormwater reuse

Stormwater can be used for aquifer and groundwater recharge and reused for non-potable use in homes e.g. garden watering, toilet flushing, hot water supply and car washing and for commercial/industrial use in cooling towers, cleaning processes and electricity generation. The benefits of stormwater reuse include freeing-up capacity within sewerage systems thus facilitating further development; decreased volumes of treated effluent flows to receiving waters; reducing water bills for the community and in less economically developed countries, reducing the incidence of water-related diseases as reused stormwater quality is usually of better quality than water from traditional sources.

Rousseau et al (2008) note that large-scale applications of water reuse of effluent from constructed wetlands are widespread in Australia and the USA but less common in Europe. Australia uses 320 litres of water per capita per day for domestic purposes and its cities will have a predicted 15 % average decrease in rainfall by 2030. A significant volume of rainwater in Australia becomes stormwater runoff and in Sydney, it is estimated that 420 gigalitres of stormwater is discharged to sea every year. The Metropolitan Adelaide stormwater reuse project (2009), part of the Water Smart Australia project, will use constructed wetlands to pre-treat stormwater before pumping it through bores to underground water supplies beneath the city. It will save 1000 megalitres of water per year by using stormwater to replace water drawn from underground supplies for the irrigation of parks and gardens. In Northern Adelaide, the City of Playford's parks and reserves will be irrigated by 570 million litres of water per year from 4 ha of constructed wetlands (Australian Academy of Science, 2008).

The Australian national guidelines for water recycling phase 2 (2009) address urban stormwater reuse and managed aquifer recharge for end uses including drinking water supply, non-drinking purposes and ecosystem protection. An aquifer storage transfer and recovery (ASTR) project aimed to determine if stormwater from an urban mixed residential catchment could be harvested through an engineered wetland and recovered at a potable quality (Figure 1). In the demonstration project in Salisbury, a suburb of Adelaide, stormwater was treated by passing it through a constructed wetland and injecting it via a well into a brackish limestone aquifer 160 m below ground for storage. After 12 months, the stored water was recovered, treated to achieved drinking water quality and was then bottled (CSIRO, 2010).

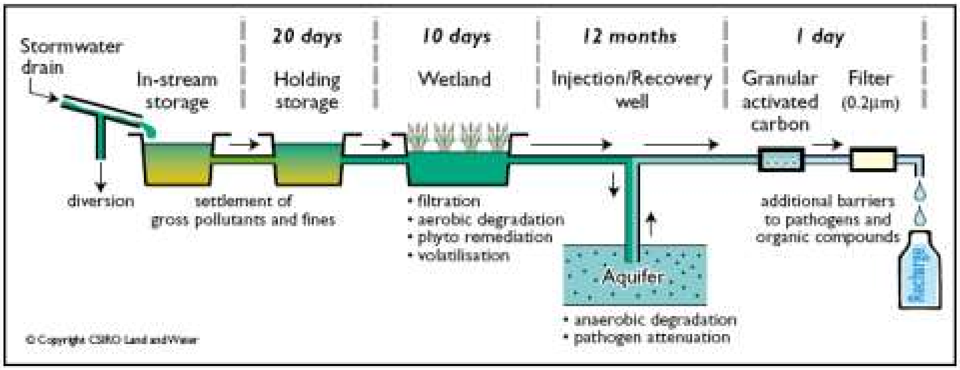

Figure 1 Diagram of system processing stormwater to drinking water **(CSIRO, 2010)**

Stormwater harvesting captures 70% of surface runoff in Salisbury, 300 Ml/year or 2% of demand, of which 40% is passed to water supply to municipal irrigation and third pipe systems and 60% injected to aquifer storage and recharge (ASTR). Salisbury has been a demonstration site for ASTR of stormwater in the European Union (EU) water reclamation technologies for safe artificial groundwater recharge (RECLAIM) project, with the objective of developing hazard mitigation technologies for water reclamation and providing safe and cost effective routes for artificial groundwater recharge. However, because stormwater supply is intermittent in comparison to the continuous supply of reclaimed wastewater, the cost of its storage infrastructure and overall costs are higher than for reclaimed wastewater (McCann, 2010).

The design of Sydney Olympic Park (SOP) is based on the concept of an integrated urban water cycle and includes land rehabilitation, flood alleviation, aquatic habitat restoration, stormwater storage and reuse, pollution control and recreational provision. Thirty different constructed wetlands have been created onsite, a water storage basin has been developed in a disused brick pit and the main stadium has 3Ml/d storage for rainwater. The source of reclaimed water is a ‘sewer mine’ supplemented by surface runoff from the brick pit. Water use at SOP is 48% recycled, 46% direct stormwater reuse and 6% potable. Of the recycled water, 60% is used for irrigation and washdown (Scholes and Shutes, 2007). The World Games 2009 stadium in Kaohsiung City, Taiwan, is a recent example of the application of sustainable design principles to a sports stadium. The total area, including the stadium and surrounding facilities, is 19 ha of which 7 ha were used to construct green belt, bike track, sports-park, constructed wetlands and ponds. The stadium is designed to collect rainwater from the roof and store it in tanks, and to recycle and reuse the grey water, which will be used for irrigating grassland, washing solar cells on the roof, and providing a water source for eco-ponds. The wetlands and ponds in the surrounding parks were designed with gradual slopes and planted with trees, shrubs, and aquatic plant species along the lake shore to imitate a natural river with upstream, middle stream and downstream sections.

CONCLUSION

Constructed stormwater wetlands increase stormwater storage and infiltration volumes and reduce the volumes of stormwater discharged to the sewer system and to wastewater treatment plants (WWTPs). Cost-benefits will also accrue from a reduction in water pollution and flooding. The costs of developing or retrofitting, operating and maintaining a drainage system are normally lower for BMPs than for a traditional system, and although there is a high land cost required by wetlands, the whole-life cost of their maintenance is lower than for small BMPs requiring a high level of maintenance

The reuse of water stored in wetlands contributes to Integrated Urban Water Management (IUWM) within the urban water cycle by conserving drinking quality water supplies and thus reducing water treatment volumes, costs and energy consumption. Stormwater supply is intermittent in comparison to the continuous supply of reclaimed wastewater and the cost of its storage infrastructure and overall costs are higher than for reclaimed wastewater. An aquifer storage transfer and recovery (ASTR) programme in Australia will provide drinking water from urban stormwater and several cities globally are developing the reuse of water stored in wetlands for the irrigation of public parks.

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