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Bio-ecological drainage system (BIOECODS) for water quantity and quality control

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ABSTRACT
Land use change in urbanizing watersheds can have a significant impact on hydrologic and hydraulic process as well a degradation of water quality on receiving waters. The Bio-Ecological Drainage System (BIOECODS) consists of elements of storage, flow retarding and infiltration engineering. Swales, dry ponds, detention ponds and wetland are the main components of BIOECODS that function as flow attenuation and water quality treatment devices. The BIOECODS is a pilot project that meets the requirements of the Stormwater Management Manual for Malaysia and has been constructed at the Engineering Campus of the University Science Malaysia, Nibong Tebal, Penang. BIOECODS represents an alternative to the traditional hard engineering-based drainage system to manage stormwater quantity and quality for urban areas.

This article discusses how the BIOECODS could be implemented to control stormwater quantity from an urbanized area and reduce the water quality impact on the receiving water.

Keywords: Stormwater management; control at source; BMPs; sustainable urban drainage system; stormwater modelling.

1 Introduction

The traditional approach in stormwater management shifted during the 1970s to a storage approach with a focus on detention, retention and recharge. Later on, during the 1980s and 1990s stormwater came to be considered as a significant source of pollution, and the main goal of stormwater management shifted to protection of the natural water cycle and ecological system by the introduction of local source control, flow attenuation and treatment in natural or mostly constructed biological systems, such as ponds, wetlands and treatment facilities. It is generally accepted that stormwater should be attenuated locally.

These comprehensive Best Management Practices (BMPs) for stormwater management are becoming very popular topics for development of urban drainage in developed countries. Stormwater BMPs are widely used in drainage planning in the United Kingdom [6], United States [13], Germany [9], Australia [4], and Japan [3]. BMPs can be defined as a multi-disciplinary approach in applying appropriate technology to preserve the natural environment, enhance living standards and improving the quality of life.

The implementation of integrated measures of Stormwater BMPs in Malaysia is still in an early stage. Conventional stormwater drainage systems, consisting of a concrete drainage system had been widely practiced in Malaysia, but unfortunately this practice has a significant impact on the environment as a whole. The conventional drainage system has not been proven to solve the existing flood problem in Malaysia. It can be clearly seen from the annual budget spent by the Department of Irrigation and Drainage (DID) Malaysia that flood mitigation cost have increased every year. Therefore there is a need to seek a holistic and sustainable solution, not only to mitigate existing flood problems but also to prevent the occurrence of such problems in new area to be developed [1].

In order to solve the current problem DID is embarking on a new approach of managing stormwater runoff called "control

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at source". Sustainable urban drainage is a concept that includes long-term environmental and social factors in the planning and design of drainage systems. This approach takes into account the quantity and quality of stormwater runoff, and the amenity value of surface water in the urban environment. The Department of Irrigation and Drainage is producing a new urban drainage manual, known as Stormwater Management Manual or SWMM, which has been effectively used since 1st January 2001. Thereafter, approval for all federal, state and private development will depend on compliance with new guidelines. These new guidelines require the developers to apply BMPs to control stormwater quantity and quality to achieve Zero Development Impact Contribution.

Realizing that the new stormwater BMPs approach should be introduced in Malaysia, the University Science Malaysia, in collaboration with the Department of Irrigation and Drainage Malaysia, have constructed the Bio-Ecological Drainage Systems (BIOECODS) at the Engineering Campus, in Nibong Tebal, Penang. It is hoped that this BIOECODS will be an example of BMP in stormwater management, mainly in Malaysia and the general South Asia Region. BIOECODS represents an alternative to the traditional hard engineering-based drainage system with the application of swales, subsurface modules, dry ponds, wet pond, detention pond, and constructed wetland. The construction of BIOECODS covers an area of 300 acres and was completed in December 2002. His Excellency the Governor of Penang launched BIOECODS at the national level on 4th February 2003.

2 Why we need stormwater BMPs

BMP has been used for quantity control and recently also to control the pollution of urban runoff. In the planning and design of stormwater facilities, quantity and quality control is much needed in Malaysia, because urbanization had altered the characteristic cycle of many watersheds [12].

2.1 Impacts of urbanization on runoff

The effect of urbanization on watersheds (Figure 1) has been well documented, but details are included herein to show the importance of control at source approach for both quantity and quality aspects [12].

Undeveloped land has very little surface runoff, most of the rainfall soaks into the topsoil and evapotranspirates or migrates slowly through the soil mantle, as interflow to the stream, lake or estuary. As a result of this process, rainfall effects are averaged out over a long period of time (Figure 1). However, as the watershed develops and the land is covered over with an impervious surface (e.g. roads, parking lots, roofs, driveways and sidewalks) most of the rainfall is transformed into surface runoff.

The resulting effect on the hydrology of the receiving water can be dramatic, especially for streams. A given rainstorm now produces significantly more runoff volume than before and flow peaks are increased by a factor of 2 to more than 10. The overall hydrologic effect is that the flow frequency curve for a developed area is significantly higher than for an undeveloped area as shown in Figure 2. This change in the flow frequency curve manifests itself in two ways. Firstly, as just mentioned, the peak runoff rate for a given return period storm increases (point A in Figure 2). Secondly, the effect of urbanization is to significantly increase runoff and the frequency of the predevelopment peak flows (point B in Figure 2).

2.2 Flow impact on receiving waters

The increase in the magnitude and frequency of storm runoff flow peaks can cause severe stream channel erosion and increased flooding downstream. The most commonly observed effects are the physical degeneration on natural stream channels. The higher frequency of peak flows causes the stream to cut a deeper and wider channel (Figure 3), degrading or destroying the in-stream aquatic habitat. The eroded sediments are deposited downstream in slower moving reaches of the stream or at the entrance to lakes or estuaries, harming the aquatic life in this area.

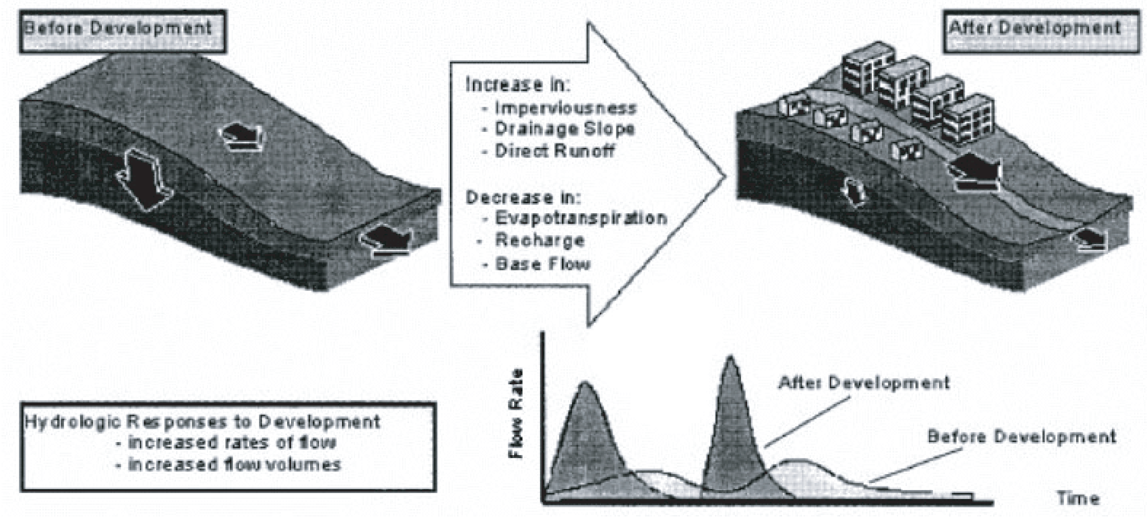


Figure 1 Impact of urbanization on hydrology [12].

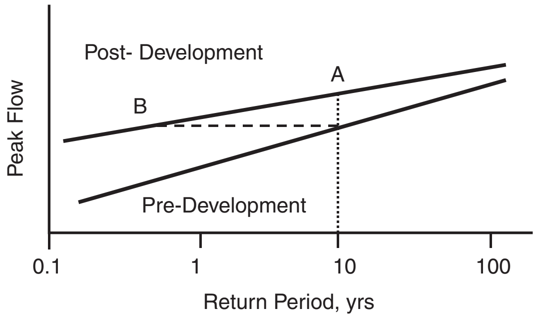


Figure 2 Effect of urbanization on frequency curve [12].

Figure 3 Typical channel erosion due to increase of discharges in the river channel (Pari river, Ipoh).

The hydro-period of the wetlands in the watercourse are also drastically changed, experiencing high flows for short periods during and after rainfall events, followed by a period of much reduced or zero flow, due to the reduction of interflow. Freshwater wetlands can dry up or become unsightly bogs. Saltwater wetlands can deteriorate due to increases in the frequency of large freshwater flows into them, or they may convert to freshwater wetlands if the rainfall frequency is high enough to keep a supply of freshwater running through them. The effect of these changes in the wetland causes a significant stress to the native biota or species [12].

2.3 *Water quality impacts of urbanization*

Changes in stream water quality are associated with two phases of urbanization. During the initial phase of development, an urban stream can receive a significant pulse of sediment (Figure 4) eroded from upland construction sites, even if erosion and sediment controls are used. Sediment contributions from the land surface typically decline to less than predevelopment contributions after upland developments stabilize and an increase occurs in the stream bank erosion. In the second phase of urbanization, the dominant source is the washing off of accumulated deposits from impervious areas during storms. Table 1 shows the general constituent of urban runoff. In urban streams, higher loading can cause water quality problems such as turbid water, nutrient enrichment, bacterial contamination, organic matter loads, toxic compounds (Figure 5), temperatures increases and increases in the quantity of trash or debris.

Figure 4 Sedimentation in the river will reduce the hydraulic capacity of river (River Kelang, Kuala Lumpur).

Table 1 Typical constituent in urban runoff [5].

		Site median EMC[a]	
Constituents	Typical coefficient of variation	For median urban site	For 90th percentile urban site
TSS (mg/L)	1–2	100	300
BOD (mg/L)	0.5–1	9	15
COD (mg/L)	0.5–1	65	140
Total P (mg/L)	0.5-1	0.33	0.70
Soluble P (mg/L)	0.5–1	0.12	0.21
TKN (mg/L)	0.5–1	1.50	3.30
NO_{2+3}-N (mg/L)	0.5–1	0.68	1.75
Total Cu (μg/L)	0.5–1	34	93
Total Pb (μg/L)	0.5–1	144	350
Total Zn (μg/L)	0.5–1	160	500

[a] Event mean concentration.

Figure 5 Effluent from domestic waste causes water pollution in the river.

3 Stormwater BMPs

Urban stormwater management, simply stated, is everything done within a catchment to remedy existing stormwater problems and to prevent the occurrence of new problems [14]. This involves the development and implementation of a combination of structural and non-structural measures to reconcile the conveyance and storage function of stormwater systems, with the space and related needs of an expanding urban population. It also involves the development and implementation of a range of measures or BMPs to improve the quality of urban stormwater runoff prior to the discharge of receiving waters.

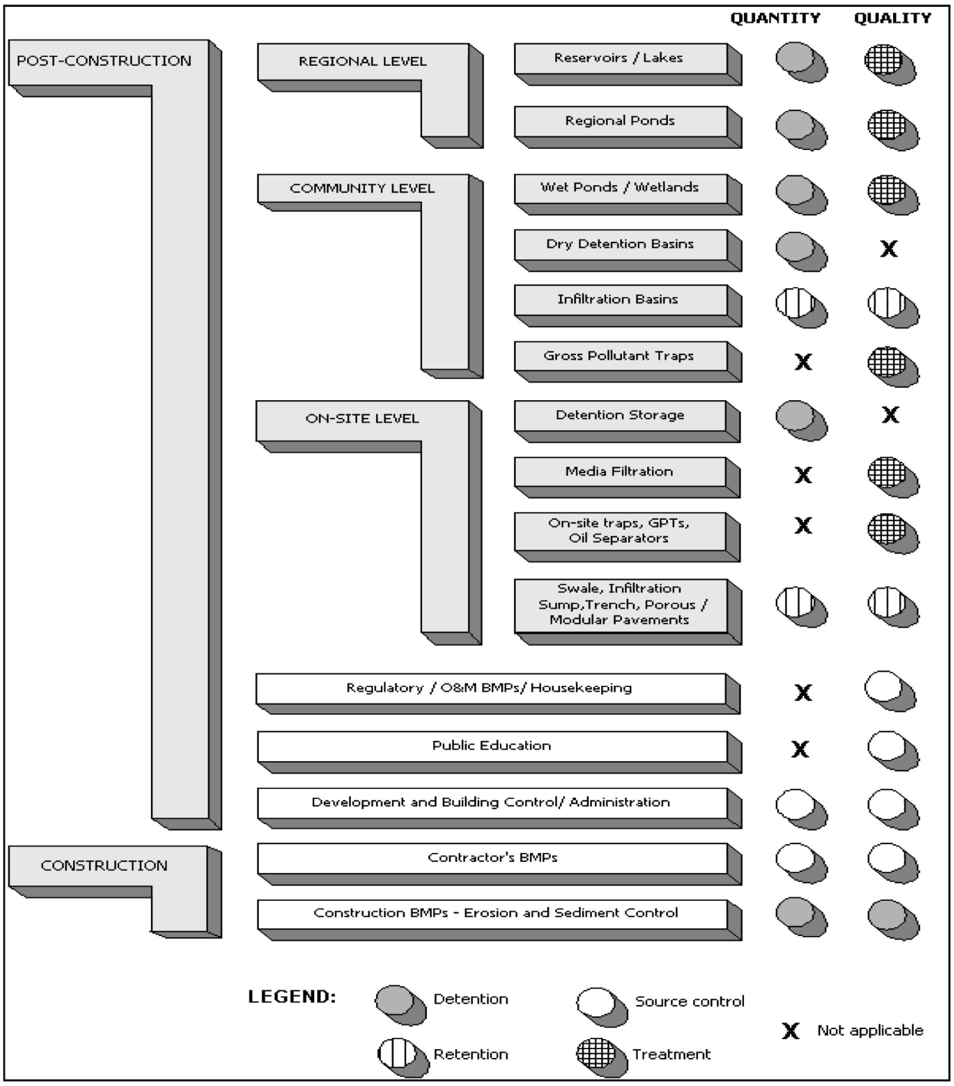


Figure 6 Typical measures of stormwater BMPs [8].

There is increasing recognition in developed countries overseas that stormwater management needs to be undertaken in a safer and more ecologically sustainable manner. Stormwater should be regarded as an asset and a resource to be valued, rather than the traditional attitude of regarding it as a nuisance to be disposed of as quickly as possible. Many rivers, lakes, and coastal waters are currently degraded by urban stormwater due to excessive flows, poor water quality, removal of riparian vegetation, and the destruction of aquatic habitats. This has resulted fundamentally from a primary focus on a *conveyance-oriented approach* to stormwater management. Stormwater management practices need to be broadened to consider environmental issues such as water quality, aquatic habitats, riparian vegetation, and social issues such as aesthetics, recreation, and economics. Typical measures used for stormwater management are represented in Figure 6.

4 Sustainable urban drainage system

In general, sustainable urban drainage system is an approach to manage stormwaters in developments that replicate the natural drainage [7]. Runoff is collected and stored to allow natural cleaning to occur at source prior to infiltration or controlled release to watercourses. Sustainable urban drainage systems allow natural drainage to function in the landscape surrounding the development, with the aim being to prevent pollution, control flooding, recharge groundwater and enhance the environment. There are four general design options such as filter strips and swales, filter drains and permeable surfaces, infiltration devices and basins and ponds. It is important to understand how these techniques work together, to provide the aims of sustainable urban drainage systems in the most practical, cost-effective and beneficial way. Such an approach is, or should be applied not only to urban stormwater but also surface water within a river basin. Increasing the number of roads, or highways in urbanized areas brings pollutants to rivers therefore source control should function in the landscape surrounding development with the aim of preventing pollution, control flooding, recharge groundwater and enhance the environment. Source control should encompass restoration of stream courses, construction of protective grass and bush covered land strips along streams and rivers, and ponds and wetlands. Such measures are usually designed mainly in order to reduce pollution loads, but actually they work as runoff attenuation facilities. Therefore the quality and quantity of the runoff from developing areas can be maintained to be the same as the predevelopment condition. These systems are more sustainable than conventional drainage methods because they:

- Manage runoff flow rates, reducing the impact of urbanization on flooding
- Protect or enhance water quality
- Are sympathetic to the environmental setting and the needs of the local community
- Provide a habitat for wildlife in urban watercourses
- Encourage natural groundwater recharge (where appropriate)

Urban drainage is moving away from the conventional thinking of designing just for flooding but balancing the impact of urban drainage on flood control, quality management and amenities as shown in Figure 7.

Sustainable Urban Drainage Management uses the concept of the surface water management train, illustrated in Figure 8. Natural catchment drainage techniques can be used in series to change the flow and quality characteristics of the runoff in stages.

The management train starts with prevention, or good housekeeping measures, for individual premises and progresses through to local source control, larger downstream site and regional control. Runoff need not pass through all of the stages in the management train. It could flow straight to a site control, but as a general principle it is better to deal with runoff locally, returning the water to the natural drainage system as near to the source as possible. Only if the water cannot be managed on site should it be conveyed elsewhere. This may be due to the water requiring additional treatment before disposal or the quantities of runoff generated being greater than the capacity of the natural drainage system at that point. Excess flows would therefore need to be routed off site.

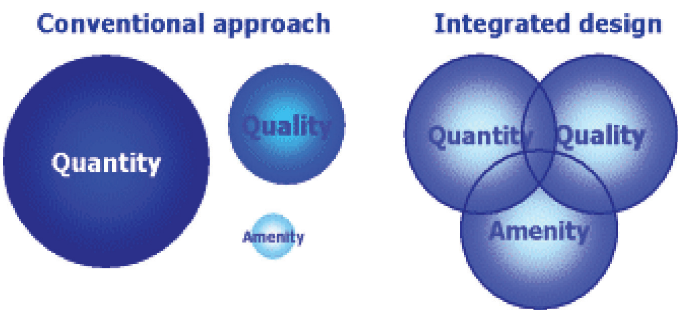


Figure 7 Conventional approach vs sustainable approach [7].

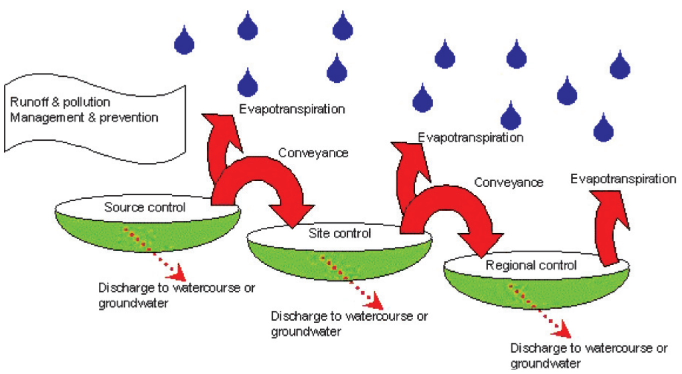


Figure 8 Sustainable urban drainage management train [7].

The design of Sustainable Urban Drainage System (SUDS) will require active decisions between different options, often depending on the risks associated with each course of action. The risks of an area flooding have to be balanced with the costs of protecting the area from different flood levels.

The management train concept promotes the division of the area to be drained into sub-catchments, with different drainage characteristics and land uses, each with its own drainage strategy. Dealing with the water locally not only reduces the quantity that has to be managed at any one point, but also reduces the need for conveying the water off the site. When dividing catchments into small sections it is important to retain a perspective on how this affects the whole catchment management and the hydrological cycle [7].

5 Alternative stormwater management pilot study at USM Engineering Campus

The USM Engineering Campus (Figure 9) is located in Mukim 9 of the Seberang Perai Selatan District, Penang. It lies between latitudes 100° 29.5′ South and 100° 30.3 North and between longitudes 5° 9.4′ East and 5° 8.5′ West. The locality is known as Sri Ampangan, Nibong Tebal, Penang which is about 2 km south-east of the town of Nibong Tebal, about 1.5 km north-east of the town of Parit Buntar (Perak) and about 1.5 km north-west of the town of Bandar Baharu (across River Kerian in Kedah). The area of the campus is about 320 acres and made up mainly of oil palm plantation land and is fairly flat.

The project initially implemented a conventional drainage system. Later the Department of Irrigation and Drainage in cooperation with the USM River Engineering and Urban Drainage Research Centre (REDAC) has proposed a new ecological drainage concept to be implemented. The required drainage planning specifies that alternative new ecological drainage systems should be used in line with the university-planning concept. The project objective was to develop and evaluate an alternative drainage system to the conventional drainage system, appropriate to the climate and local conditions in the area. Due to local boundary conditions, the storm runoff should be infiltrated

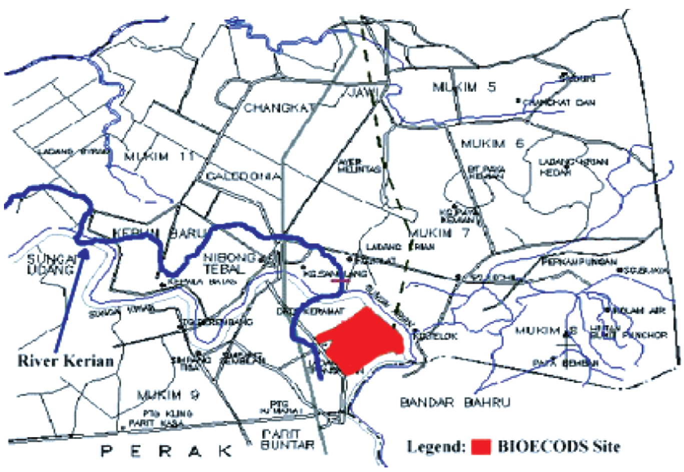


Figure 9 Location of USM Engineering Campus.

into ground where possible, or otherwise drained only with a significant delay. Particular emphasis was focused on the opportunity of creating attractive and integrated drainage planning into the "green planning" for the whole site. This means that the building of the university campus will take consideration towards eco-development by which some of the oil palm trees and "nypah" palm forests along the riverbank could be preserved [10].

The USM Engineering Campus project (Figure 10) has taken a series of measures to reduce runoff rates, runoff volumes and pollutant loads by implementing a source control approach for stormwater management as suggested in the Stormwater Management Manual for Malaysia. This includes a series of components, namely ecological swales, on-line sub-surface detentions, and dry ponds as part of the BIOECODS that contribute to the treatment of the stormwater before it leaves the campus. This system was designed to combine infiltration, delayed flow, storage and purification as pre-treatment of stormwater before discharging to a constructed wetland. In addition to source control, these measures include integrating large-scale landscapes into the development as a major element of the stormwater management system. The concept of the BIOECODS is to integrate the drainage components (i.e. ecological swales, on-line sub-surface detentions, and dry ponds) with the ecological pond components (i.e. a wet pond, a detention pond, a constructed wetland, a wading stream and a recreational pond) for further treatment of the stormwater runoff. In combination, these increase runoff lag time, increase opportunities for pollutant removal through settling and biofiltration, and reduce the rate and volume of runoff through enhanced infiltration opportunities.

As a whole, BIOECODS is designed to provide time for the natural processes of sedimentation, filtration and biodegradation to occur, which reduces the pollutant load in the surface water runoff. In addition, BIOECODS can be designed to fit into their environmental setting, adding considerably to the local amenity and/or local biodiversity. Stormwater from the built areas is routed overland into open conveyance swales planted with native cow grass and sub-surface conveyance made from special materials, rather than through storm sewers. The swales provide initial stormwater treatment, primarily infiltration and sedimentation. The landscape and dry ponds are the second component. The landscape and dry ponds diffuse the flows conveyed by the swales, and the reduced stormwater velocities maximize the campus sedimentation, infiltration and evaporative water treatment. Additionally, the natural adsorption and absorption of the landscape soils enables the soil to hold many contaminants. The aerobic condition of the soil promotes hydrocarbon breakdown. The landscape is able to infiltrate a substantial portion of the annual surface runoff volume due to the increased soil permeability, which is created by the deep root systems of the landscape vegetation. The detention pond provides the function of a stormwater detention, solids settling, and biological treatment. Finally, the constructed wetland provides both stormwater detention and biological treatment prior to the runoff entering the recreational pond. All of these benefits help to ensure that the final discharge from a SUDS will not pollute rivers, nor create flooding downstream. Although BIOECODS are drainage devices that rely on natural processes, BIOECODS must be designed, built and maintained in the context of the development control system in Malaysia.

Based on published BMP effectiveness information and hydrologic modeling, the USM Engineering Campus development can be expected to reduce surface runoff volumes by 65% and reduce solids, nutrients, and heavy metal loads by 85% to 100%. The long term result is not only to reduce costs to the developer, but also reduce maintenance costs for the community. There is also a substantial benefit to downstream neighbors. By treating stormwater where it falls on the land, the USM campus is reducing its contribution to downstream flooding and sedimentation.

6 Design concept

Planning was carried out with the help of the rainfall-runoff model XP-SWMM, which contains information needed for designing BIOECODS. The schematic diagram of BIOECODS for USM Engineering Campus is shown in Figure 11 and the flow sequence can be summarized as follows (Figure 12):

(a) *The Perimeter swale (Figures 13 and 14) is used to cater for any excess water from individual buildings, whilst the flow from impermeable surface will be directed to the individual swale*. The perimeter swale is defined as a grass-earthen channel combined with a subsurface twin Geo-strip enclosed within a permeable geotextile design.

Figure 10 Layout plan of USM Engineering Campus.

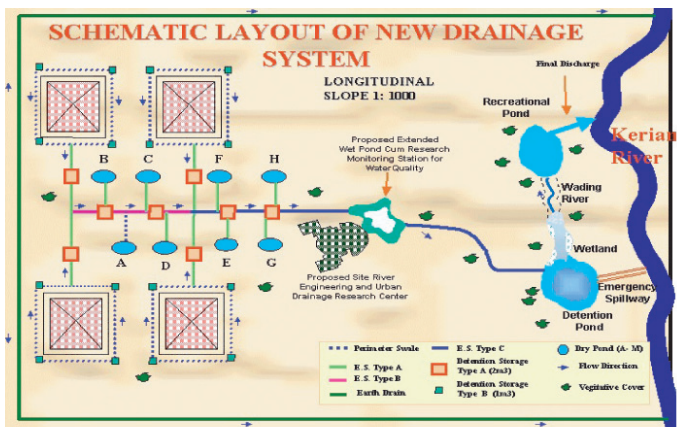


Figure 11 Schematic layout of BIOECODS.

(b) *The flow from an individual swale (perimeter swale) will be conveyed to an inter-lot swale (ecological swale) as a main conveyor.* The ecological swale is a grass-earthen channel, combined with a subsurface module enclosed within a permeable geotextile design. The ecological swale is shown in Figure 13 categorized as Type A (Figures 15 and 16), Type B (Figures 17 and 18) and Type C (Figures 19 and 20) depending on the size and capacity. Type A consists of one single module, Type B consists of two single modules and Type C consists of three single modules.

(c) *The excess stormwater is stored as subsurface detention storage (Figure 21).* The storage modules have been designed to be placed at the connecting point, junction and critical point of the system. The storage module is categorized into Type A and Type B with different storage capacities and can be arranged accordingly to suit the site conditions.

(d) *The excess stormwater is also stored on the dry ponds constructed with a storage function.* The dry pond (Figure 23) is a detention pond, which has been integrated with the ecological swale to temporarily store the storm runoff. This detention basin is designed to store up to 150 mm of excess rainfall and designed to blend in with the surrounding landscape. The modular storage tank (Figure 22) is placed beneath the detention basin where the stormwater is drained out by infiltration. The outflow path of the storage module is connected to the ecological swale at the lowest point, in order to drain the dry pond system in less than 24 hours.

(e) All of the excess water from built-up areas flows to a detention pond (Figure 25) via a wet pond (Figure 24).

(f) *With respect to the need for water quality improvements, the wetland is designed as a community treatment facility.* As much as 90% of the total volume of annual stormwater runoff will flow through an area supporting growing plant material (Figures 26 and 27). Contaminants are removed either by direct absorption into plant tissues (soluble nutrients) or by physical entrapment and subsequent settlement on the wetland bed. The end product is expected to improve the aesthetic value for surrounding areas with the existence of the "Crystal Clear Blue Water Lake" (Figure 28).

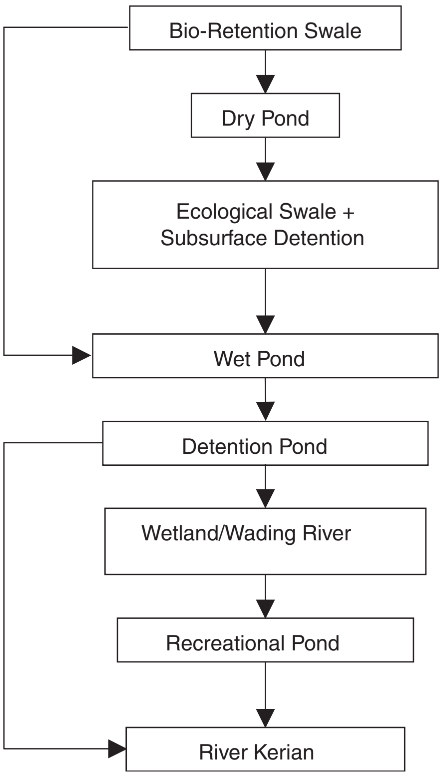


Figure 12 Flow sequence of BIOECODS.

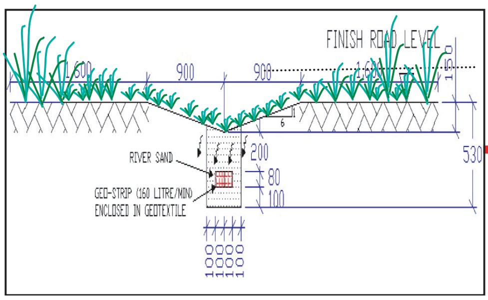


Figure 13 Typical cross section of perimeter swale.

Figure 14 Typical view of perimeter swale.

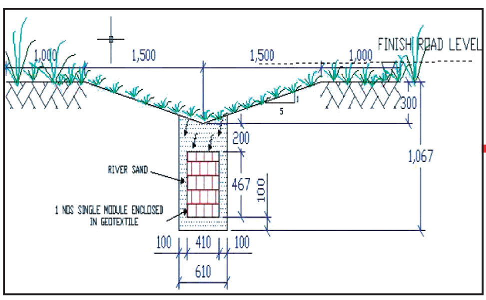


Figure 15 Typical cross section ecological swale Type A.

Figure 16 Ecological swale Type A.

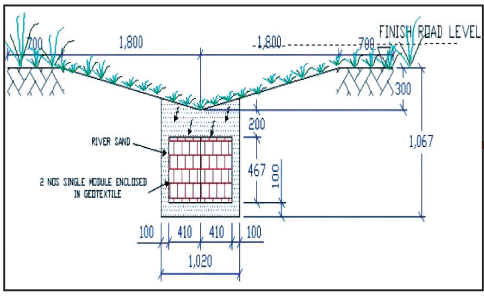


Figure 17 Typical cross section ecological swale Type B.

Figure 18 Ecological swale Type B.

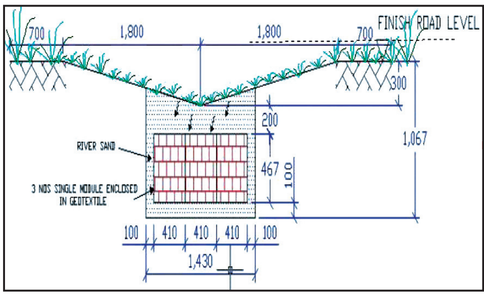


Figure 19 Ecological swale Type C.

Figure 20 Ecological swale Type C (outlet).

Figure 21 Modular subsurface detention.

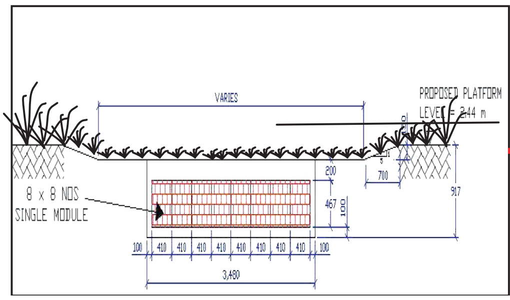


Figure 22 Typical cross section do dry pond.

Figure 23 View of constructed dry pond.

Figure 24 View of wet pond.

Figure 25 View of detention pond.

Figure 26 View of wetland.

Figure 27 Wetland cell.

Figure 28 Crystal clear blue lake.

Figure 29 River Kerian.

(g) *The excess stormwater is drained from the detention pond into River Kerian (Figure 29) through two stage outlet designed to manage the minor (10-year ARI) and major (50-year ARI) storm events.*

6.1 Design criteria for ecological swale

The ecological swale built for BIOECODS is a double layer of a surface swale and a subsurface drainage module overlaid with a layer of sand. The surface swale is a soft-lined grass-earthen channel with a gentle slope, a form of flow retarding facility. The sub-surface drainage module is enclosed within a permeable hydro-net and a layer of sand. The stormwater from the surface

Table 2 Design criteria for ecological swale.

Design Parameter	Criteria
Longitudinal slope	1 : 1000
Manning roughness coefficient	Surface swale = 0.035 Subsurface drainage module = 0.1
Design rainfall	10-year ARI and Check for 100-year ARI
Maximum period of surface water inundation at surface swale	24 hours

swale infiltrates into the sub-surface drainage module through a layer of topsoil and river sand. This is a pre-treatment device that removes pollutant mainly particulate material by filtration and absorption to filter material.

The primary mechanisms for pollutant removal in grass swale are filtration by vegetation, settling of particulates, and infiltration into the subsurface zone. As stormwater runoff travels through the swale, the vegetation reduces peak velocity while infiltration reduces flow volumes. Attenuation of runoff flow promotes the pollutant removal. The subsurface drainage module is made from recycled plastic materials and the drainage cell traps water at the source where it can be retained in drainage module. By treating contaminated water at the source, flow generated is reduced and therefore no accumulation of toxic chemicals occurs. The design criteria for the ecological swale as constructed at USM Engineering is shown in Table 2.

6.2 Design criteria for dry pond

The dry pond is a detention device designed to store excess stormwater in the development area. This is a multi-functional facility blended with the landscape for an optimum land use. The dry pond facility is an area with shallow depression, which can retain water up to a maximum depth of 150 mm. A subsurface storage module is placed underneath the dry pond and connected to the subsurface module of the swale. The stormwater in the dry pond recedes by infiltrating through the layer of topsoil and river sand to the storage module underneath and then flows downstream along the subsurface module of the swale. The dry pond functions as an off-line on-site detention to reduce peak discharge. The design criteria of the dry ponds are:

- Maximum period of surface water inundation is 24 hours
- Maximum depth of water inundation is 150 mm.

6.3 Design criteria for ecological pond

The ecological pond, which is placed at the downstream end of BIOECODS, is a community facility that includes a *wet pond*, and a *detention pond* as a facility to control the stormwater quantity, a *constructed wetland* as a water treatment device, a *wading river* connecting the wetland and a *recreational pond* containing the treated water before final discharge to River Kerian. The ecological pond system is strategically placed at the downstream end of the BIOECODS to optimize and effectively attenuate and treat stormwater runoff generated from the built areas of the USM Engineering Campus. A detailed description of the components of the ecological pond is given herein.

The *wet pond* receives stormwater runoff from the main catchment, which is referred to as Engineering School sub-catchment, before discharging the runoff into the detention pond. The wet pond has an area of 4500 m^2 and a volume capacity of 5000 m^3. The wet pond is designed to control quantity of runoff for the minor storm with a 10-year Average Recurrence Interval (ARI) and to serve as a monitoring station with instrumentations installed to measure the hydraulic, hydrologic and water quality parameters.

The *detention pond* has an area of 10,000 m^2 with a volume capacity of 18,000 m^3 and is designed to temporarily store the excess stormwater runoff from the Hostel sub-catchment and the outflow hydrograph of the wet pond. The detention pond is designed to store stormwater runoff up to the maximum of 50-year ARI as suggested in the Stormwater Management Manual for Malaysia [8]. A perimeter bund was constructed to achieve the storage capacity for the design return period. An orifice is provided as an outlet for the low return period (3 months ARI) and three 1.2 m diameter-pipe outlet is provided to cater high flow (10 and 50 years ARI). For the low flow, the runoff will flow to the wetland and for the high flow, the excess runoff is diverted to River Kerian.

The constructed *wetland* is a surface flow type consisting of an inlet zone, a macrophyte zone and an open water zone. Flows are fed into the wetland by an orifice arranged to achieve a uniform flow distribution across the width of the wetland. The design storm for the wetland is 3-month ARI based on Stormwater Management Manual for Malaysia [8]. The design inflow rate for the wetland is 0.25 m^3/s based on the design calculation and detailed design features of the wetland as shown in Table 3.

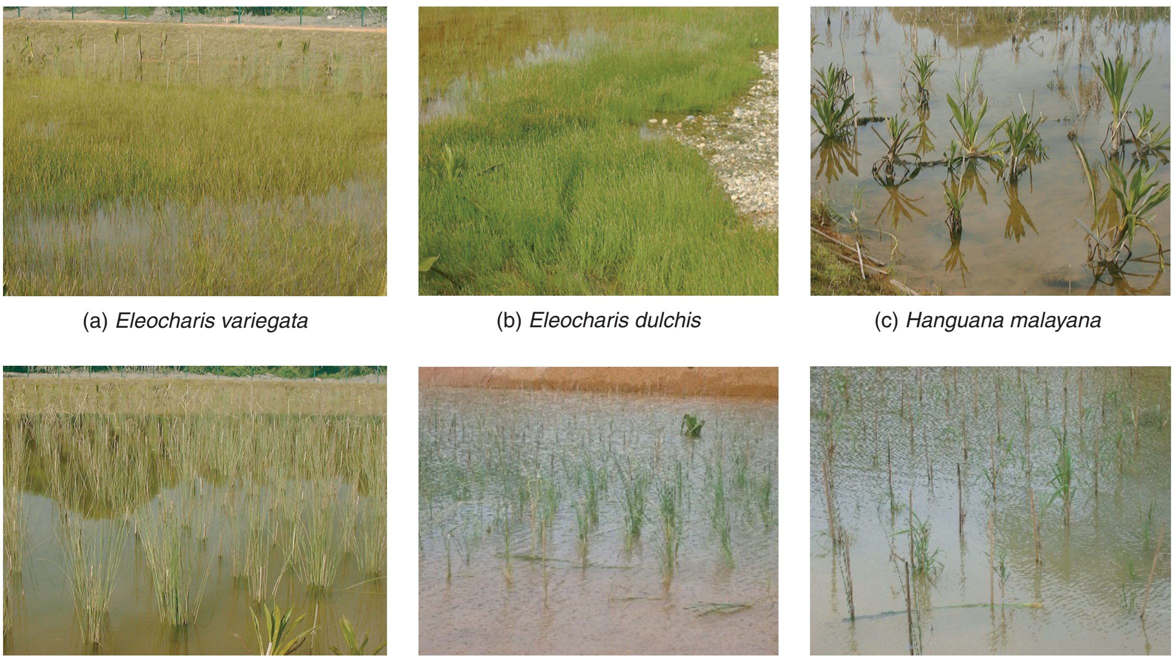
Table 4 and Figure 30 give the types of the wetland species planted. The wetland has an extended oval shape with an inlet and an outlet at the opposite ends. The recommended size for the wetland based on rational design criteria is 9100 m^2. The length of the wetland is 155 m and the width is 60 m (length to width ratio 3 : 1).

Table 3 Design criteria for the constructed wetland.

Catchment area	1.214 km^2
Design storm (3 month ARI)	22.5 mm/hr
Length	155 m
Width	60 m
Wetland surface area	9,100 m^2
Volume	9,100 m^2
% Catchment area	0.7
Design Inflow rate	0.25 m^3/s
Mean residence time	3 days
Slope of wetland bed	1%
Bed depth	0.6 m
Media	Pea gravel and soil mixture
Hydraulic conductivity of gravel	10^{-3} m/s to 10^{-2} m/s

Table 4 Wetland plant species.

Type	Plant name
Type 1 (0.3 m depth)	*Eleocharis variegata*
Type 2 (0.3 m depth)	*Eleocharis dulchis*
Type 3 (0.3 m depth)	*Hanguana malayana*
Type 4 (0.6 m depth)	*Lepironia articulata*
Type 5 (0.6 m depth)	*Typha augustifolia*
Type 6 (1.0 m depth)	*Phragmites karka*



(a) *Eleocharis variegata* (b) *Eleocharis dulchis* (c) *Hanguana malayana*

(d) *Lepironia articulata* (e) *Typha augustifolia* (f) *Phragmites karka*

Figure 30 Wetland species.

The *wading river* is located between the constructed wetland and the recreational pond. It is designed as a meandering stream with its bed made up of graded mixture of sand and gravel. It has natural river features such as flood plains on both sides of the main channel, very large boulders protecting the bends and sandy main channel. The wading river is designed to carry the designed discharge of $0.25\,m^3/s$. For river morphology's experimental purposes, it can receive a discharge up to $25\,m^3/s$. The *recreational pond* is located at the end of the system. The pond is designed to provide treated water suitable for recreational purposes. The control outflow structure for the pond is designed to discharge excess flow as well as to provide "active storage" via a rubber flap gate.

7 Materials used in the construction of an ecological swale

An example of the construction of an ecological swale is shown in Figure 31. A short description of the materials (Figure 32) used for the construction of an ecological swale can be summarised as below:

7.1 Geostrip

The geostrip filter drain (Figure 32a) is made from recycled polypropylene making it indefinitely resistant to chemical and bacterial attack when installed in an underground situation. The

(a) Excavation

(b) Module placement

(c) Online subsurface detention

(d) Sand bedding

(e) Grass planting

Figure 31 Construction of an ecological swale.

(a) Geostrip (b) Module

(c) Hydronet (d) River sand

(e) Topsoil (f) Cow grass

Figure 32 Materials used for the construction of ecological swales.

dimension of geostrip is 100 × 80 × 550 mm length. The strip shall be socket jointed to form longer length. The openings of the strip on all the four sides shall have a flow rate at 1% gradient exceeding 80 l/min and a compressive strength of not less than 12 tons/m^2.

7.2 *Module*

The dimension of a single module (Figure 32b) is 405 × 465 × 607 mm. The module is made from recycled polypropylene and the drainage capacity of the module is about 2280 l/min (0.038 m^3/s) with a compressive strength of not less than 8 tons/m^2.

7.3 *Hydronet filter fabric*

All soil and subsurface product interface have a layer of geotextile to prevent fines from entering the drainage system. The geotextile used in this project is a suitable hydronet fabric or hydrophilic geotextiles (Figure 32c) enclosing the geo-strip filter drain or drainage module to guarantee a long life for the installed system and ensures high performance. Hydronet filter fabric has a high permeability of 9.30 mm/s and has a screening capability of 0.38 mm.

7.4 *Clean river sand*

Clean river sand (Figure 32d) is an essential component in the construction of BIOECODS which functions as a filter medium and improves the quality of stormwater runoff. The infiltration process takes place in the sand layer, which induces purification process in the treatment train of BIOECODS. The properties of river sand is identified and based on the sieve analysis according to BS1377. The sand used has a low silt content which otherwise may cause the blockage of BIOECODS.

7.5 Topsoil and grass

A layer of topsoil (Figure 32e) is applied on top of river sand with a thickness of one inches or two inches. The topsoil layer is essential for the planting of grass. Cow grass species (Figure 32f) is planted on the surface swale to obtain a functional soft-line ecological swale for both water quantity and quality control. The grass determines the surface roughness of swale and functions as a stormwater pre-treatment in the management train.

8 Stormwater modelling of BIOECODS using XP-SWMM

The BIOECODS is based on a storage, flow retardation and infiltration engineering concept. The behavior of the system is simulated with XP-SWMM. The simulation is emphasized on the impact of minor flood events on the drainage system. Hence, the basis of the evaluation is the frequent occurrence storm with a design duration and average recurrence interval of 60 min and 10 years, respectively. Figures 33 and 34 show the modelling of BIOECODS using XP-SWMM [2].

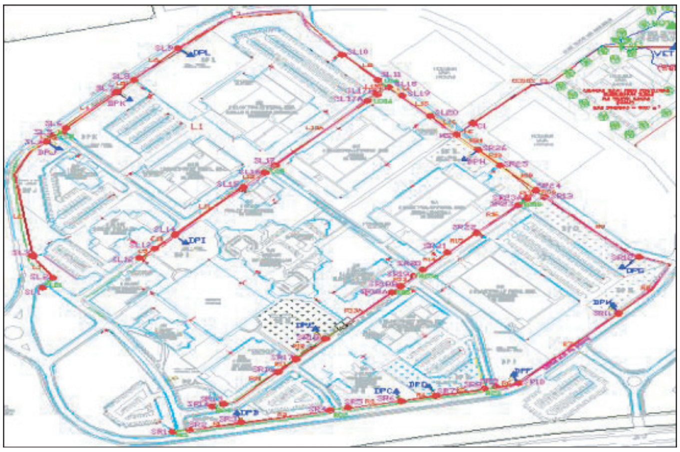


Figure 33 Distribution of school subcatchment for XP-SWMM modelling.

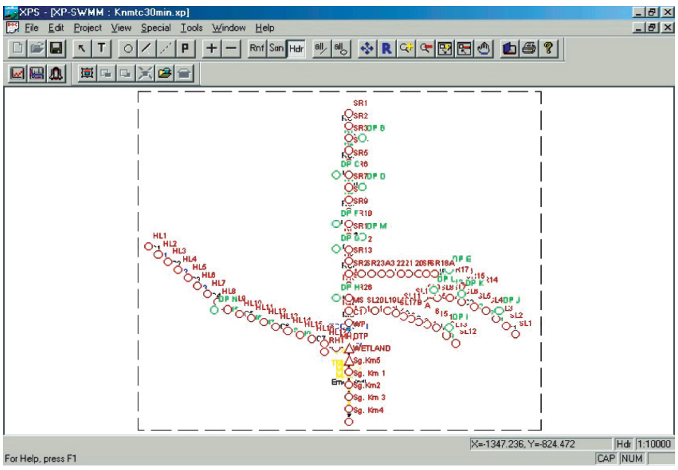


Figure 34 Representation of schematic node BIOECODS in XP-SWMM.

The results generated from the XP-SWMM modelling have confirmed that: the BIOECODS consists of storage, flow retarding and infiltration engineering, capable of attenuating flood discharge and managing stormwater at source. The total inflow into the detention pond consists of an outflow from a wet pond and a discharge from Student Hostel sub-catchment is approximately 1.1 m^3/s (Figures 35–37). This is the post-development discharge that has been routed through the BIOECODS.

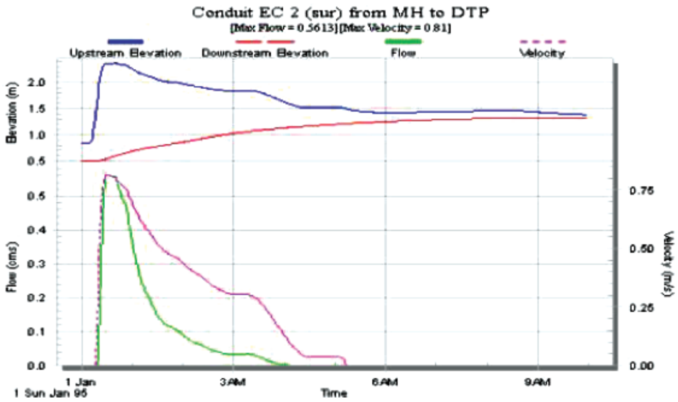


Figure 35 Flow in the surface swale from the Student Hostel subcatchment into detention pond.

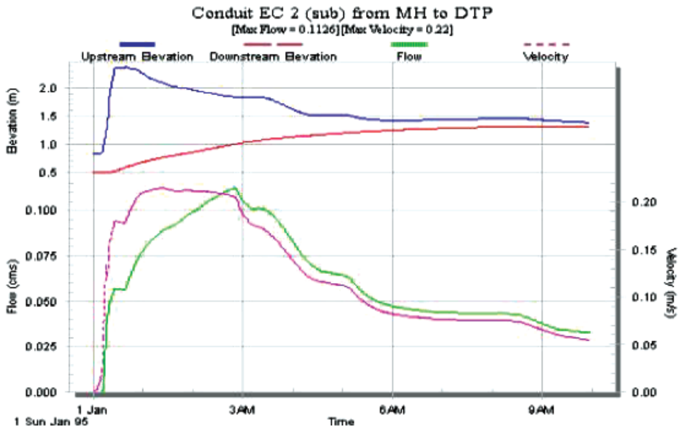


Figure 36 Flow in the subsurface module from the Student Hostel subcatchment into detention pond.

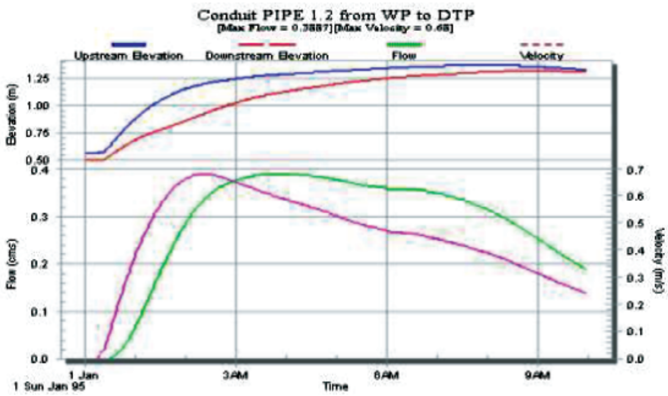


Figure 37 Flow from wet pond to detention pond.

Table 5 Water quality result on 26th July 2002.

Station	pH	SS (mg/L)	DO (mg/L)	BOD (mg/L)	COD (mg/L)	NH3-N (mg/L)
	Parameter					
Road perimeter	7.62	28.1	4.58	15	22.4	0.48
Road perimeter	6.92	11.5	4.22	10	20	0.95
Type B	6.6	6.9	4.39	8	11.7	0.14
Type C	6.5	4	5.78	3	13.7	0

Table 6 Water quality result on 5th September 2002.

Station	pH	SS (mg/L)	DO (mg/L)	BOD (mg/L)	COD (mg/L)	NH3-N (mg/L)
	Parameter					
Perimeter swale (library)	6.16	2	6.5	10	15	0.5
Perimeter swale (student centre)	5.81	2	6.5	7	10	0.32
Ecological swale Type B (Aero school)	5.9	9	6.6	2	4	0.39
Outlet type C	6.31	1	6.8	1	3	0.32

Table 7 Water quality result on 17th October 2002.

Station	pH	SS (mg/L)	Turbidity (NTU)	DO (mg/L)	COD (mg/L)	BOD (mg/L)	TKN (mg/L)	Nitrate (mg/L)	Cu (mg/L)	Zn (mg/L)	Total Phospate (mg/L)	Phospate (mg/L)
	Parameter											
Perimeter swale (student centre)	6.13	84	17.7	7.95	20	13	0.7	0.5	0.229	0.035	0.22	0.01
Ecological swale Type B (mechanical school)	6.7	80.5	44.9	7.45	78	16	0.9	0.6	0	0.043	0.16	0.05
Dry Pond H	7.2	59.5	17.75	7.3	17	13	0.6	0.2	0.013	0.065	0.39	0.05
Outlet Type B	6.3	64	9.39	7.4	12	15	0.1	0.1	0.001	0.053	0.14	0
Outlet Type C	6.08	61.5	5.9	7.65	30	7	0.2	0	0	0.004	0.03	0

9 Water quality sampling and preliminary results

Water quality samples were taken by grab sampling for the storm events on 26th July 2002, 5th September 2002 and 17th October 2002. Samples were taken from upstream to downstream ends of catchments and tested in the laboratory to determine water quality index. Six parameters were tested in the laboratory for the samples taken on 26th July and 5th September 2002. Among the parameters tested were Dissolved Oxygen, pH, Suspended Solids, Chemical Oxygen Demand, Biological Oxygen Demand and Nitrates. The samples taken on 17th October were tested for the parameters recommended by the Stormwater Management Manual for Malaysia [8]. Table 5 shows the results of water quality analysis on 26th July and Table 6 on 5th September 2002. Table 7 is the results taken on 17th September 2002. Figure 38 shows an example of the water quality taken from the BIOECODS sites.

As clearly seen from Figure 38, the last bottle water sample taken from the outlet type C, is much more clearer than the fluid from any of the previous bottles. This gives an indication that a significant amount of purification occurs in the BIOECODS.

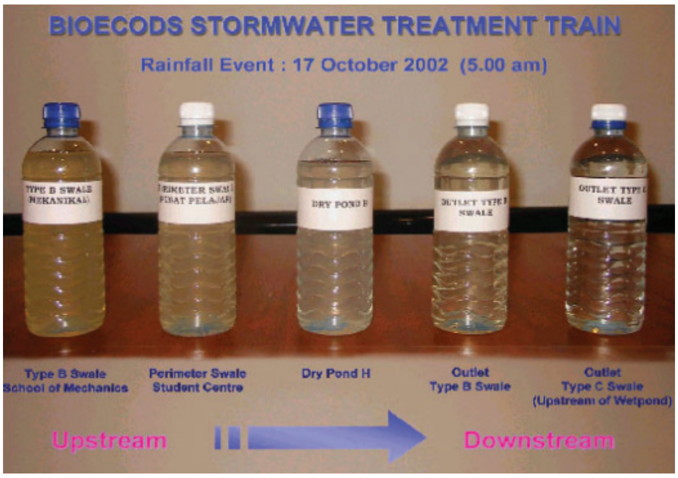


Figure 38 Water quality taken from BIOECODS site.

10 Conclusions

The BIOECODS combines three engineering techniques to manage stormwater based on *"Control-at-Source"* approach namely infiltration, storage and conveyance through the use of swales, subsurface drainage modules, dry ponds and constructed wetland. BIOECODS is an example of an innovative sustainable urban drainage system that will help restore the natural environment. The application of BIOECODS in a new development attempts to solve three major problems commonly encountered in Malaysia namely flash flood, river pollution and water scarcity during dry period.

Preliminary results have confirmed that BIOECODS is capable of attenuating the post-development discharge to the pre-development level and removing pollutants from the surface runoff. The on-going pilot research under tropical climates will collect reliable performance data within a 10-year data collection programme (2003–2012) to verify the results from laboratory and BIOECODS modeling. The completion of the research on BIOECODS technology will allow the definition of the fields of application and the achievable efficiency of the system in different situations to reduce flooding and stormwater pollution problems in particular in Malaysia and the general South Asia Region.

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