UNIVERSITI SAINS MALAYSIA

Laporan Akhir Projek Penyelidikan Jangka Pendek

Assessment Of Bioengineering Techniques For Sustainable Urban Drainage Application

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2015

UNIVERSITI SAINS MALAYSIA

SHORT TERM RESEARCH PROJECT REPORT

ASSESSMENT OF BIOENGINEERING TECHNIQUES FOR SUSTAINABLE URBAN DRAINAGE APPLICATION

(GRANT NO.: 304.PREDAC.60312035)

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DECEMBER 2015

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INTRODUCTION

1.0 BACKGROUND

Bioengineering is a construction method of using living plant or plants combined with dead or organic materials. The practice results the combined use of biological, ecological and engineering concepts to produce a living, functioning system to prevent erosion and control sediment from trapping in the habitat and cost the lives in the habitat. The use of plants for river bank protection and erosion control has a long tradition in Europe. Recently, existing bank erosion and stabilization techniques have been rediscovered and improved. These old techniques have been rediscovered and improved in the first half of nineteenth century, with new technical and biological knowledge. Today, there is a variety of bioengineering techniques available to suit different situations and requirements. Biotechnical engineering techniques have become part of geotechnical and hydraulic engineering and have helped bridge the gap between classical engineering disciplines, land use management, landscape architecture and biological sciences.

These biotechnical engineering (bioengineering) techniques are developed by a system of trial and error. Most of these techniques are based on long-term practical experience. These "soft" engineering practices can provide possibilities to complement and improve or in some cases even replace traditional "hard" river-training constructions, such as placement of gabions or rock. These also offer a more ecologically acceptable way of bank stabilization that still compiles the land use and safety requirements.

The purpose of this study was to investigate the effectiveness and applicability of techniques for bank stability and protection against erosion as aviable alternative to traditional channelization and hard armoring techniques. Primarily by literature review, this study assessed the suitability of techniques for urban environment and also the viability of the techniques for application in Malaysia. After a brief introduction to bioengineering techniques, hydraulic characteristics, strengths and weaknesses, suitable technique alternatives, and a cost-benefit of techniques are discussed and presented.

1.1 RESEACRH OBJECTIVE

Objective of study are:

1) To investigate the effectiveness and applicability of techniques for bank stability and protection against erosion.

2) To assess the suitability of techniques for urban environment.

3) To assess viability of the techniques for application in Malaysia.

1.2 RESEARCH SCOPE

This study focused on selected types of material of bioengineering techniques for local condition purposed.

1.3 NEED OF RESEARCH

The effectiveness and applicability of selected bioengineering techniques in bank stability and protection can be confirmed via this research. The study also determines the suitability of bioengineering techniques particularly as bank stability and protection against erosion for urban environment condition.

CHAPTER 2
LITERATURE REVIEW

2.0 INTRODUCTION

One of the tools available for protecting stream banks and channels in an environmentally sensitive area from the negative consequences of bank erosion and sloughing is the application of bioengineering techniques. Bioengineering is the combination of biological, mechanical, and ecological concepts to control channel degradations and bank erosion through the use of vegetation or a combination of vegetation and construction materials (DID, 2012).

Living plants have been used for a very long time throughout the world in structures against soil erosion, as traces have been found dating back to the first century BC. Widely practiced in Western Europe during the eighteenth and nineteenth centuries, bioengineering was somewhat abandoned in the middle of the twentieth century, before seeing a resurgence in recent times (Evette et al., 2009). Only in the first half of this century, however, have these old techniques been rediscovered and improved with new technical and biological knowledge. Today, there is a variety of biotechnical techniques available to suit different situations and requirements. Biotechnical engineering techniques have become part of geotechnical and hydraulic engineering and have helped bridge the gap between classical engineering disciplines, land use management, landscape architecture and biological sciences (Donat, 1995).

Biotechnical engineering techniques rely on biological knowledge to build geotechnical and hydraulic structures and to secure unstable slopes and banks. Whole plants or their parts are used as construction materials to secure unstable sites, in combination with other (dead) construction material. Thus, biotechnical engineering does not replace traditional hydraulic or geotechnical engineering (e.g. geotextiles, or concrete blocks), but complements and improves other technical engineering techniques (Donat, 1995).

Many governmental agencies favored stone or concrete riprap because over time, a high degree of precision and confidence in construction has developed from research and analysis. In engineering viewpoints, these techniques have been successful or their immediate protections of properties or infrastructure adjacent to the stream after projects were completed. What was thought successful in the past is being reevaluated in context of impacts resulting from excessive and rapid urbanization, and public awareness of these new environmental issues. Increasing failures of traditional channelization and armoring techniques are generating questions as to whether traditional practices are appropriate in every setting (Li and Eddleman, 2002). The interest in natural techniques called biotechnical engineering was raised, and the benefits and advantages of biotechnical engineering were gradually re-examined (Riley, 1998).

2.1 FACTORS INFLUENCING CHANNEL EROSION

When the ability of the stream to transport sediment exceeds the availability of sediments within the incoming flow, and stability threshold for the channel exceeded, erosion occurs. This technical note deals with the latter case of instability and distinguishes the presence or absence of erosion (threshold condition) from the magnitude of erosion (volume) (Fischenich, 2001). Erosion occur when the hydraulic forces in the flow exceed the resisting forces of the channel boundary. The amount of erosion is a function of the relative magnitude of these forces and the time over which they are applied. The interaction of flow with the boundary of open channels is only imperfectly understood (Fischenich, 2001). Table 2.1 shows the factors influencing erosion.

Sediment composition
Climate
Subsurface conditions
Channel geometry
Biology
Anthropogenic factors

Table 2.1: Factors Influencing Erosion (Fischenich, 2001)

Factor	Relevant characteristics
Flow properties	• Magnitude, frequency and variability of stream discharge • Magnitude and distribution of velocity and shear stress • Degree of turbulence
Sediment composition	• Sediment size, gradation, cohesion and stratification
Climate	• Rainfall amount, intensity and duration • Frequency and duration of freezing
Subsurface conditions	• Seepage forces • Piping • Soil moisture levels
Channel geometry	• Width and depth of channel • Height and angle of bank • Bend curvature
Biology	• Vegetation type, density and root character • Burrows
Anthropogenic factors	• Urbanization, flood control, boating, irrigation

Schueler (1991) had classified the major stream impacts caused by urbanization and one (1) of them is changes in urban stream morphology that causes some negative consequences as follow below:

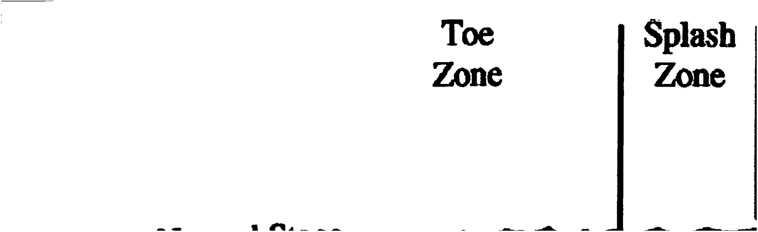
(i) stream channel widening and down cutting;
(ii) increased streambank erosion;
(iii) shifting bars of coarse-grained sediments;
(iv) elimination of pool/riffle structure;
(v) imbedding of stream sediments;
(vi) stream relocation/enclosure or channelization; and
(vii) stream crossings form fish barriers

Many urban stream restoration activities target accelerated streambank erosion, but there are many other impacts of urbanization that affect the ecology of streams (Paul and Meyer 2001). Urban streams typically have flashier hydrographs, elevated concentrations of nutrients and contaminants, altered channel morphology and stability, and reduced biotic richness, this has been called an "urban stream syndrome" (Meyer et al., 2005; Walsh et al., 2005 a, b). Because it does not directly address the causes of accelerated erosion, bioengineering can only treat a symptom (bank erosion) of the overall problem (watershed urbanization). This and other small-scale restoration practices do not have large ecosystem effects, as reach-scale approaches cannot compensate for catchment-scale degradation (Larson et al., 2001; Moerke and Lamberti, 2003; Shields et al., 2003).

If stream bank management or other maintenance measures are at stake, then in all situations the prime question to be asked is: "Is a certain measure in this specific situation really necessary?" This question is probably the best and single most economically efficient guide to help decide which techniques should be used, where, and to what extend (Donat, 1995).

2.2 CLASSIFICATION OF BIOENGINEERING TECHNIQUES

Two basic types of lining classes are rigid linings such as concrete, and flexible linings such as rock rip raps, rock mattresses, and all RECPs (Kilgore and Cotton 2005; Witheridge 2010). Rigid linings are nonerodible, permanent and long life, but they are susceptible to failure from foundation instability and unreliable hydraulic pressure release. Construction of rigid linings requires specialised equipment and costly materials. As a result, the cost of rigid channel linings is typically higher than an equivalent flexible channel lining (Kilgore and Cotton 2005).


Toe
Zone
Splash
Zone

Biotechnical techniques can be classified according to their strength levels from low to intermediate and to high. They include (Li and Eddleman, 2002):

(i) low-strength surface protection such as hydro seeding;
(ii) intermediate surface treatments; and
(iii) high strength bank and slope reinforcement.

Another classification system is based on streambank zones with different relative elevations, inundation frequencies, and durations (Allen and Leech, 1997). Figure 2.1 show four (4) different zones of streambanks.

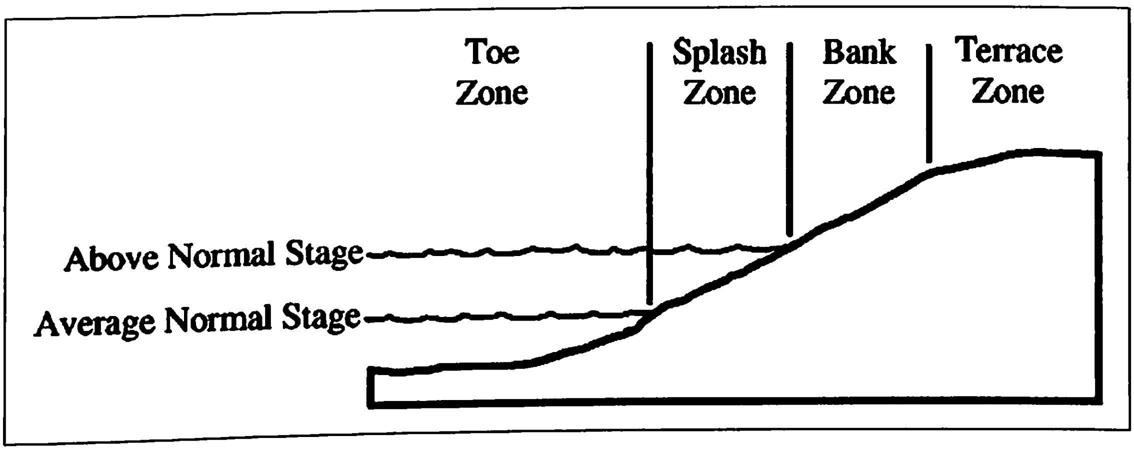


Figure 2.1: Streambank Zones (Allen and Leech, 1997)

Where;

- *Toe zone*: The bank portion between the bed and average normal stage.
- *Splash zone*: The bank portion between normal high-water and normal low-water levels.
- *Bank zone*: The bank portion above the normal high-water level.
- *Terrace zone*: The bank inland from the bank zone.

The variety of construction techniques can be classified according to purpose, material or construction characteristics. However, it is not always easy to distinguish between these different groups of biotechnical techniques and strategies. Such a differentiation is often artificial, as similar techniques, with minor changes, are used in both, a classical geotechnical and river engineering context. Biotechnical structures for soil stabilization are either point-by-point systems (structures of single root stocks), linear systems (structures of rows of root stocks) or covering systems (surface-covering mattress of plant webbings). To design with any of these systems requires an understanding of the mechanisms they exploit in the building process itself. The material used and the purpose of the structure allows the techniques to be classified as follows (Donat, 1995):

(i) surface protection techniques (covering techniques);
(ii) stabilization techniques using live materials;
(iii) techniques combining dead and live material;
(iv) supplementary techniques; and
(v) support structures using non-living material.

Although these techniques are classified based on the strength level or streambank zones, they can be applied simultaneously (Allen and Leech, 1997). Combining different biotechnical techniques even with structural components (Henderson, 1986) is actually more effective than using any specific one alone. Figure 2.2 shows combined different biotechnical techniques.

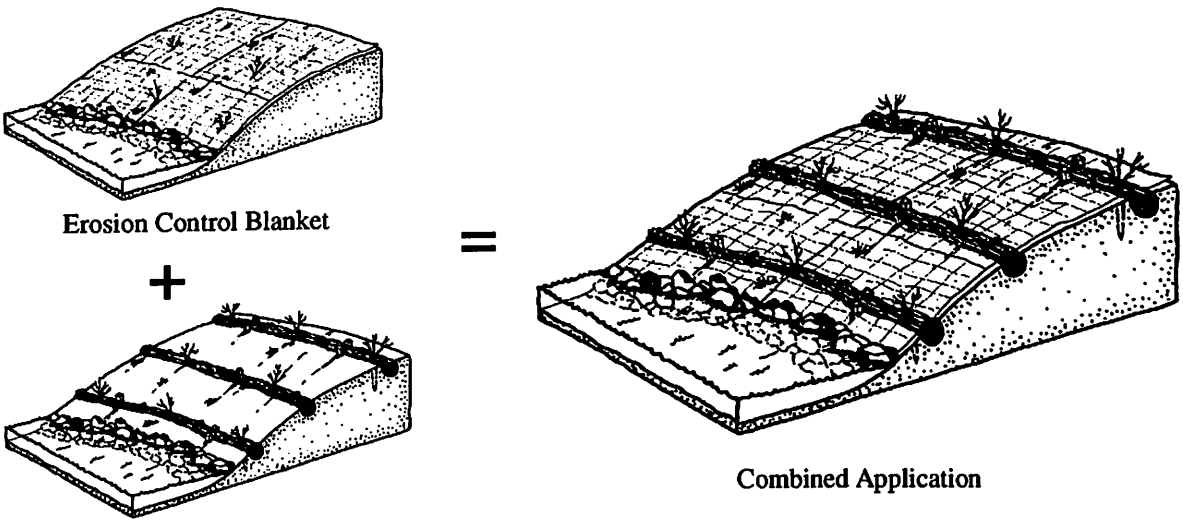


Figure 2.2: Combined application of erosion control blanket and live fascine (Allen and Leech, 1997).

2.3 ADVANTAGES OF BIOENGINEERING TECHNIQUE

The application of bioengineering techniques give a lot of advantages in technical, biological, economic and aesthetic characteristics. These advantages make biotechnical techniques a worthwhile consideration and become one of the best tools for protecting urban stream and bank rehabilitation from the negative consequences of sedimentation and bank sloughing.

However, by recreating quality bank habitat, bioengineering has the potential to contribute locally to a more diverse and functional stream ecosystem. Although many studies have addressed the effectiveness of bioengineering practices at reducing accelerated erosion due to anthropogenic impacts (e.g., Henderson, 1986; Abernethy and Rutherford, 1998; Schaefer, 2000; Brown, 2000).

2.4 STREAM PROCESSES (DID,2012)

Stream management problems may arise from either underlying processes of change in the river system or localised perturbations. Stream instability can be the result of natural processes or human activities. It is therefore important to identify the dominant stream processes present if stream management strategies are to be implemented, which are appropriate and unlikely to cause adverse responses elsewhere in the system.

Stream instability can be initiated by natural and human induced causes such as:

- long term alteration to the hydrologic and/or sediment regime;
- a catastrophic flood or sequence of major floods;
- crossing of a geomorphic threshold; and
- direct or indirect human interference.

a) Bank Erosion Processes

Bank erosion can be the effect of morphological processes such as:

- meander processes;
- channel avulsion; and
- bed degradation, or
- combination of the above, or
- the product of localised processes unrelated to the more general morphological changes in the river system.

The mechanism of bank failure will generally involve more than one failure modes. It normally involves mass failure such as collapse caused by undermining and slumping (sloughing), rotational or slip circle failure, and initial detachment of individual particles involving attrition or fretting. Other modes of failure include erosion by overland flow entering or leaving the main channel creating a headward erosion gully and tunnel erosion (piping failure).

b) Causes of Bank Erosion

Typical factors, which may contribute to bank erosion, include:

- altered water-sediment ratio in the watercourse;
- altered flow patterns including tidal currents and heights;
- general or local steam bed degradation (i.e., lowering) resulting from altered flows;
- changes in stream flow velocities;
- loss of bank vegetation;
- wave action; and
- soil pore water pressure.

Some typical failure modes are illustrated in Figures 2.3 and 2.4.

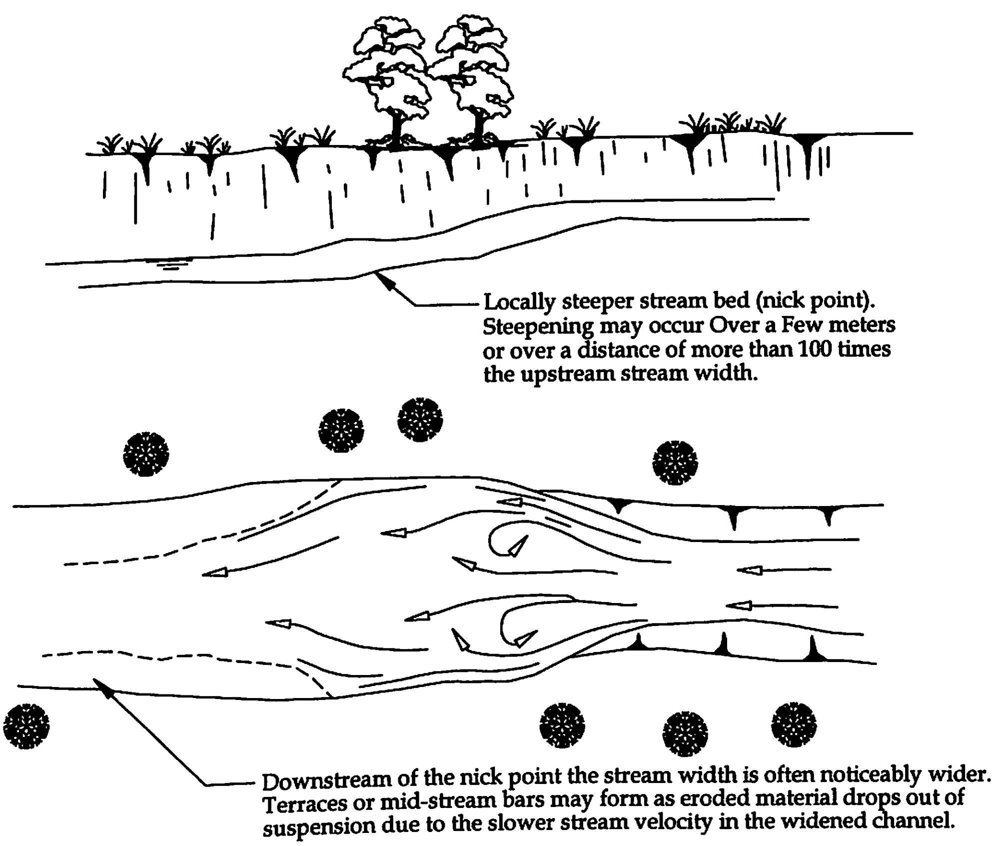


Figure 2.1: Typical Characteristics of Bed Scour

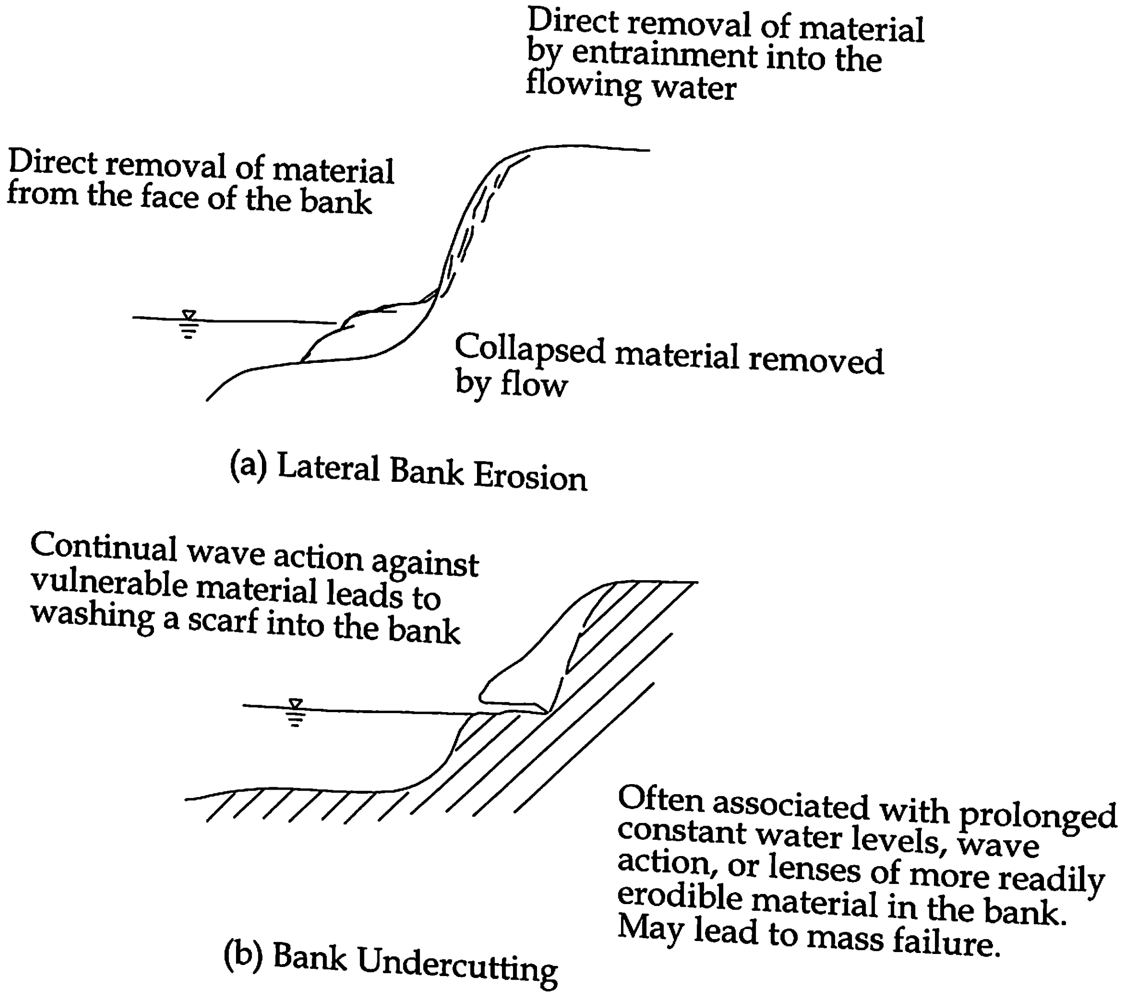


Figure 2.2: Bank Failures by Attrition and Fretting

2.5 WATERCOURSE MANAGEMENT TECHNIQUES (DID,2012)

The techniques listed in Table 2.2 are not an exhaustive list but represent the most commonly applied techniques suitable for urban streams and rivers. However not all techniques described would be suitable in an urban environment due to site specific constraints. Public safety, aesthetics, and cost will often determine the adoption of a technique.

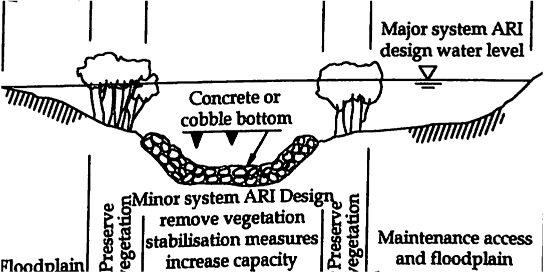
Bank armouring • Rock rip-rap	Direct protection against erosion
Bank armouring • Articulated concrete block mattress	Provides protection and stability to eroding banks. Suitable for a range of bank conditions including fretting and direct attrition.
Bank armouring • Rock filled wire baskets and mattresses	Provides protection and stability to eroding banks.
Bank armouring • Brushing	Provides bank protection for a limited time to enable "permanent" vegetation to become established on the bank. The technique is effective against fretting and attrition erosion. It may also contribute to lowering the risk of mass failure by reducing the risk of material being removed from the toe of the bank.
Bank stabilisation • Battering	Reduce public safety hazard caused by steep banks, reduce erosion hazard caused by fast flowing overland flow, increase bank stability against rotational failure or mass failure, and create conducive environment for vegetation establishment.
Bank stabilisation • Reinforced vegetation	Act as a separating layer between river flows and an eroding bank. Often combined with bank battering.

Table 2.2: Watercourse Management Techniques Suitable for Urban Streams and Rivers

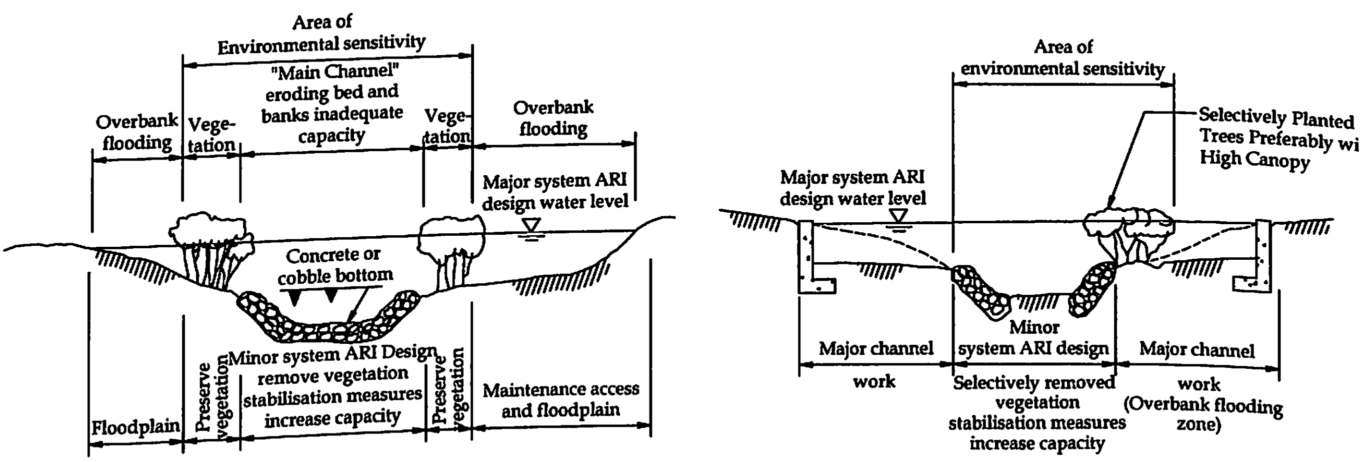
Techniques	Application	Limitation
Bank armouring • Rock rip-rap	Direct protection against erosion	Requires a supply of hard sound rock.
Bank armouring • Articulated concrete block mattress	Provides protection and stability to eroding banks. Suitable for a range of bank conditions including fretting and direct attrition.	a) Toe apron requires anchoring. b) Where the stream is prone to bed scour an extensive toe apron is required.
Bank armouring • Rock filled wire baskets and mattresses	Provides protection and stability to eroding banks.	Usually fail by wire breakage due to high sediment loads carried by stream or by vandalism or by undermining.
Bank armouring • Brushing	Provides bank protection for a limited time to enable "permanent" vegetation to become established on the bank. The technique is effective against fretting and attrition erosion. It may also contribute to lowering the risk of mass failure by reducing the risk of material being removed from the toe of the bank.	Only provides short term protection.
Bank stabilisation • Battering	Reduce public safety hazard caused by steep banks, reduce erosion hazard caused by fast flowing overland flow, increase bank stability against rotational failure or mass failure, and create conducive environment for vegetation establishment.	Land take behind the bank line may be required if flat slopes are to be applied.
Bank stabilisation • Reinforced vegetation	Act as a separating layer between river flows and an eroding bank. Often combined with bank battering.	Limited effectiveness below normal river level.

Table 2.2: Watercourse Management Techniques Suitable for Urban Streams and Rivers (Continued)

Techniques	Application	Limitation
Bank stabilisation • Retaining and training walls	Normally used as an alignment training technique but also provides protection and stability to eroding banks. Suitable for bank conditions involving: a) fretting; and b) direct attrition.	a) Where the stream is prone to bed scour the wall may be de-stabilised by undermining. b) Pile driving equipment may be required.
Bank stabilisation • Bio-reinforced embankments	Provides bank protection against undermining, piping, rotational, and slumping failure modes.	Requires a supply of suitable vegetative material. Toe scour may occur especially where the reinforced bank is terminated above the low water line.
Bank stabilisation • Reinforced earth proprietary products	Used to re-establish an eroded river bank or to reinforce an existing bank.	Requires a facing to limit the risk of continued scour.
Grade control structures • Check weirs	Used to reduce the effective hydraulic grade and control stream bed degradation (deepening) by promoting controlled sedimentation upstream of the weir. When the upstream ponding area is full of sediment the check weir behaves in the same manner as a Rock Chute.	Maybe subject to damage under certain depths of inundation. Disturbance of the bank is necessary to anchor the weir and prevent outflanking.
Land and water management • Fish refuges	Used to create variation in fish habitat that provides a variation in water temperature and velocity as well as protection from predators.	Stream must be sufficiently wide if jetties or boardwalks are contemplated. A good fishing location may be inadvertently created if there is a high level of people access along the stream.


Major system ARI
design water level
Concrete or
cobble bottom
Minor system ARI Design
remove vegetation
stabilisation measures
increase capacity
Preserve
Vegetation
Preserve
Vegetation
Maintenance access
and floodplain
Floodplain

Figures 2.5 and 2.6 provide examples of slightly improved natural channels. Stabilisation measures in Figure 2.5(a) include check structures, riprap, minor grading, and short sections of retaining walls. In general, little or no channel capacity improvements are included. In Figure 2.5(b), channel capacity has been increased to lower or confine the design storm flow by excavating outside of the environmentally sensitive area and constructing retaining walls. Figure 2.6 shows possible drainage improvements for composite channels. Stabilisation measures in Figure 2.6(a) include check structures, riprap, grading, and retaining walls. Improvements to the main channel increase capacity for minor flood flows and may confine or reduce the depth of the design flood. In Figure 2.6(b), the main channel area has been left undisturbed (i.e. that area containing the base flow plus the immediate vegetation area) and the overbank conveyance capabilities improved by excavating the floodplain area. This 'improved' natural channel has increased capacity to safely convey the major system design flow. Provision should be provided for maintenance access to the channel. In stabilising the main channel and overbank, vegetation should be retained as much as possible to meet the objectives of enhancing stability and capacity. Multiple uses of the overbank flooding area should be encouraged, especially if the main channel capacity is substantial, i.e. overbank flooding is infrequent.



(a) With Stabilisation Measures

(b) With Increased Capacity

Figure 0.5: Typical Channel (ASCE, 1992)

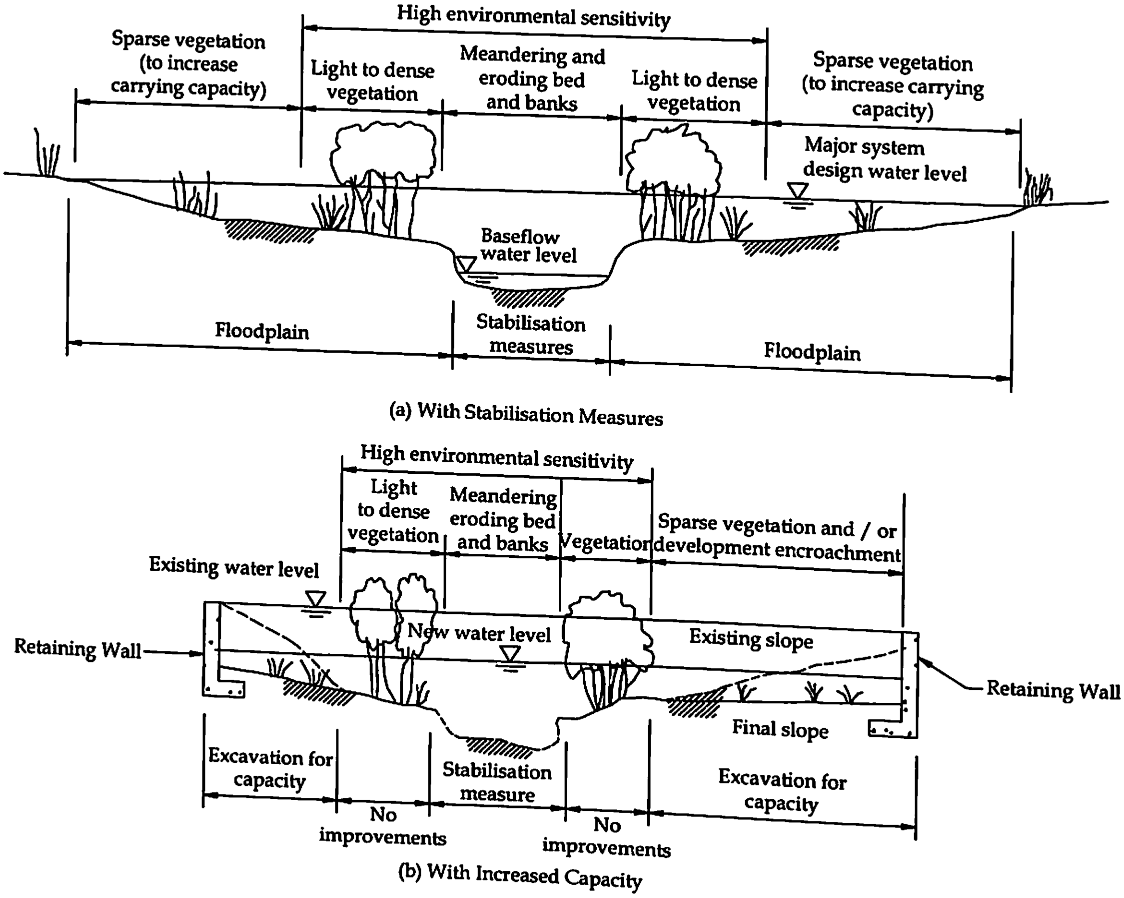


Figure 2.6: Composite Channel (ASCE, 1992)

2.6 CHANNEL DESIGN CONSIDERATION (DID,2012)

The design of 'natural channels' involves the creation of channels with the attributes of natural watercourses pertinent to the location within the watershed and should be based on a sound understanding of fluvial geomorphic principles. Guidelines on natural channel design methodology are provided by OMNR (1994).

The suggested design steps are:

a) Define Design Objectives - Identify the objectives to be met for the design. Multiple objectives regarding conveying flood flows, aquatic habitat, recreation, aesthetics and maintenance may exist and frequently will appear to be in conflict.

b) Define Existing Conditions - The existing flow regime, sediment load, channel, valley and catchment conditions can be obtained or estimated.

c) Define the Expected Conditions - The expected flow, sediment loading and channel slope conditions can be estimated or calculated.

d) Identify Inconsistencies - Any inconsistencies between the existing and expected conditions should be identified and resolved.

e) Design Parameters - The design parameters for the channel for unconstrained design conditions should be developed to satisfy the objectives.

f) Identify Constraints - Constraints to the channel design are to be identified. Some of the more common constraints include funding, property boundaries, roads, services, flooding, and stakeholders or management disputes.

g) Identify Compromises - Compromises may be required to determine the optimum design conditions by considering all the site constraints.

h) Develop Design - The design of the channel system should emphasise on creating a channel in dynamic equilibrium with appropriate habitat features.

i) Evaluate Design - The resulting design should be compared to the optimum design and the extent of any discrepancies (there are usually some) are to be identified and assessed as to their importance in achieving the overall design objectives.

2.6.1 *Developing a Channel Design*

Every watercourse is uniquely defined by the catchment hydrology, geology and soils, climate, vegetation, landuse, stream use, and its geological age (stream maturity). In designing an alluvial channel consideration should be given to the following criteria.

a) Planform

This refers to the shape or stream configuration when viewed on a plan. It covers characteristics such as stream sinuosity (a measure of meander shape, size and frequency), meander length and amplitude, channel pattern (straight, multi-channel, braided), and presence of ox-bow lakes, meander cutoffs, etc. An examination of a stream's planform can give an indication of whether the meanders are migrating, increasing or decreasing, or whether different reaches of the stream are aggrading (areas of deposition) or degrading (eroding).

b) Bedform

Bedforms can provide important clues to the stream processes that are taking place. The presence of recently formed or growing mid-stream bar(s) will generally indicate an area of deposition, which may have ramifications on the stability of the banks opposite the bars. The presence of pools and riffles will usually conform to a natural frequency of occurrence along a reach. In sand bed streams they are hardly noticeable, often only being defined by regular alternating deposits of coarser and finer bed deposits.

c) Flow resistance

This design characteristic influences the velocity profile both vertically and horizontally across a section. It is affected by bedform, bed and bank material, vegetation and natural or artificial obstructions in the channel or on the floodplain. The removal of bank vegetation will usually lower the surface resistance to flow thus increasing the near bank flow velocity. If the velocity increases above the scour threshold value for the bank material erosion will occur.

d) Stream slope

This is a measure of the longitudinal slope of the stream thalweg (line traced by the lowest point on successive cross sections). An examination of the stream slope can assist in identifying any sudden changes in slope, which may indicate the presence of stream instability due to bridge, dam or other in-stream structure. The causes of slope change can be natural or artificial (i.e. bridges, dams, or other in-stream structure or activity such as gravel or sand extraction). Changes in slope may be sudden (i.e. a waterfall or riffle) or gradual and only noticeable over a considerable distance.

e) Stream width and depth

When stream width is usually considered together with depth and the ratio of the two dimensions can provide further clues as to the dominant stream processes in the reach. In an alluvial stream a high width to depth ratio will often indicate that the stream is in a deposition stage where the load carrying capacity of the stream is greater than the sediment input at the top of the reach. Urban watercourses are often relatively deep and narrow which is a reflection on the increased water supply following urbanisation of the catchment.

f) Vegetation

When specifying the vegetation for a channel design an assessment of the height and extent of flooding for a range of flood frequencies and durations should be made. The plants should be selected according to the expected flooding regime, light conditions and soil types present. Unless the stream bank is particularly stable, care should be exercised when planting large trees close to the top of the bank where they maybe subject to undermining from stream flow or high winds which may cause them to fall into the stream and expose the bank. Natural vegetation is often unable to cope with the expected hydraulic loading and consideration can be given to reinforcing the vegetation with either temporary or permanent matting or other proprietary products.

2.6.2 *Stable Channel Design*

The stability of a channel or the suitability of various channel linings can be determined by first calculating both the mean velocity and tractive stress. Allowable tractive stresses for various types of soil, linings, ground covers, and stabilization measures including soil bioengineering treatments, are listed in Table 2.3. Additionally, product literatures from manufacturers can provide information on allowable tractive stresses or velocities for various types of erosion control products. Table 2.4 shows the factors influencing erosion. A general procedure for the application of information presented by Fischenich (2001) is outlined in the following paragraphs.

Step 1 - Estimate Mean Hydraulic Conditions

Flow of water in a channel is governed by the discharge, hydraulic gradient, channel geometry, and roughness coefficient. This functional relationship is most frequently evaluated using normal depth or backwater computations that take into account principles of linear momentum conservation. The latter is preferable because it accounts for variations in momentum slope, which is directly related to shear stress.

Step 2 - Estimate Local/Instantaneous Flow Conditions

The computed values for velocity and shear stress may be adjusted to account for local variability and instantaneous values higher than mean. A number of procedures are available to serve this purpose. Most commonly applied are empirical methods based upon channel form and irregularity. For straight channels, the local maximum shear stress can be calculated from the following simple equation:

$$\tau_{max} = 1.5\tau \quad (2.1)$$

For sinuous channels, the maximum shear stress should be determined as a function of the planform characteristics using Equation 2.2:

$$\tau_{max} = 2.65\tau\left(\frac{R_c}{W}\right)^{-0.5} \quad (2.2)$$

where,

R_c = Radius of curvature (m); and

W = Top width of the channel (m).

Equations 2.1 and 2.2 adjust for the spatial distribution of shear stress; however, temporal maximum in turbulent flows can be 10 to 20 percent higher, so an adjustment to account for instantaneous maximum should be added as well. A factor of 1.15 is usually applied.

Step 3 - Determine Existing Stability

Existing stability should be assessed by comparing estimates of local and instantaneous shear and velocity to values presented in Table 2.3. Both the underlying soil and the soil or vegetation condition should be assessed. If the existing conditions are deemed stable and are in consonance with other project objectives, then no further action is required. Otherwise, proceed to step 4.

Step 4 - Select Channel Lining Material

If existing conditions are unstable, or if a different material is needed along the channel perimeter to meet project objectives, a lining material or stabilization measure should be selected from Table 2.3, using the threshold values as a guideline in the selection. Only material with a threshold exceeding the predicted value should be selected. The other project objectives can also be used at this point to help select from among the available alternatives. Fischenich and Allen (2000) characterize attributes of various protection measures to help in the selection.

Feasibility of erosion control product should be used (Greenfix, 2013):

1) Weather (rain or wind)
2) Time to establish vegetation – functional longevity
3) Protection (failure criteria)
4) Properties of surface soils
5) Overall concept of watershed, flows and frequency
6) Maintenance of watershed
7) Aesthetics
8) Constructability issues
9) Regional climate
10) Available of quality assured materials
11) Cost and installation

Table 2.3: Permissible Shear and Velocity for Selected Lining Materials (Fischenich, 2001)

Boundary Category	Boundary Type	Permissible Shear Stress (N/m^2)	Permissible Velocity (m/s)	Citation (s)
Soils	Fine colloidal sand	0.96 – 1.44	0.46	A
	Sandy loam (noncolloidal)	1.44 – 1.92	0.53	A
	Alluvial silt (noncolloidal)	2.15 – 2.39	0.61	A
	Silty loam (noncolloidal)	2.15 – 2.39	0.53 – 0.69	A
	Firm loam	3.59	0.76	A
	Fine gravels	3.59	0.76	A
	Stiff clay	12.45	0.91 – 1.37	A, F
	Alluvial silt (colloidal)	12.45	1.14	A
	Graded loam to cobbles	18.19	1.14	A
	Graded silts to cobbles	20.59	1.22	A
	Shales and hardpan	32.08	1.83	A
Gravel/Coble	25 mm	15.80	0.76 – 1.52	A
	50 mm	32.08	0.91 – 1.83	A
	150 mm	95.76	1.22 – 2.29	A
	300 mm	191.52	1.68 – 3.66	A
Vegetation	Class A turf	177.16	1.83 – 2.44	E, N
	Class B turf	100.55	1.22 – 2.13	E, N
	Class C turf	47.88	1.07	E, N
	Long native grasses	57.46 – 81.40	1.22 – 1.83	G, H, L, N
	Short native and bunch grass	33.52 – 45.49	0.91 – 1.22	G, H, L, N
	Reed plantings	4.79 – 28.73	N/A	E,N
	Hardwood tree plantings	19.63 – 119.70	N/A	E,N
Temporary Degradable RECPs	Jute net	21.55	0.30 – 0.76	E, H, M
	Straw with net	71.82 – 79.00	0.30 – 0.91	E, H, M
	Coconut fiber with net	107.73	0.91 – 1.22	E, M
	Fiberglass roving	95.76	0.76 – 2.13	E, H, M
Non-Degradable RECPs	Unvegetated	143.64	1.52 – 2.13	E, G, M
	Partially established	191.52 – 287.28	2.29 – 4.57	E, G, M
	Fully vegetated	383.04	2.44 – 6.40	F, L, M

Table 2.3: Permissible Shear and Velocity for Selected Lining Materials (Fischenich, 2001)

Boundary Category	Boundary Type	Permissible Shear Stress (N/m^2)	Permissible Velocity (m/s)	Citation (s)
Riprap	d_{50} = 150 mm	119.70	1.52 – 3.05	H
	d_{50} = 225 mm	181.94	2.13 – 3.35	H
	d_{50} = 300 mm	244.19	1.52 – 3.96	H
	d_{50} = 450 mm	363.89	1.68 – 4.88	H
	d_{50} = 600 mm	483.59	4.27 – 5.49	E
Soil Bioengineering	Wattles	9.58 – 47.88	0.91	C, I, J, M
	Reed fascine	28.73 – 59.85	1.52	E
	Coir roll	143.64 – 239.40	2.44	E, M, N
	Vegetated coir mat	191.52 – 383.04	2.90	E, M, N
	Live brush mattress (initial)	19.15 – 196.31	1.22	B, E, I
	Live brush mattress (grown)	186.73 – 392.62	3.66	B, C, E, I, N
	Brush layering (initial/grown)	19.15 – 299.25	3.66	E, I, N
	Live fascine	59.85 – 148.43	1.83 – 2.44	C, E, I, J
	Live willow stakes	100.55 – 148.43	0.91 – 3.05	E, N, O
Hard Surfacing	Gabions	478.80	4.27 – 5.79	D
	Concrete	598.50	> 5.49	H

[1] Ranges of values generally reflect multiple sources of data or different testing conditions.

A. Chang, H.H. (1988).
B. Florineth. (1982).
C. Gerstgraser, C. (1998).
D. Goff, K. (1999).
E. Gray, D.H., and Sotir, R.B. (1996).
F. Julien, P.Y. (1995).
G. Kouwen, N., Li, R.M., and Simons, D.B., (1980).
H. Norman, J.N. (1975).
I. Schiechtl, H.M. and R. Stem. (1996).
J. Schoklitsch, A. (1937).
K. Sprague, C.J. (1999).
L. Temple, D.M. (1980).
M. TXDOT (1999).
N. Data from Author (2001).
O. USACE (1997).

Table 2.4 shows recorded shear stress and velocities withstood by TRM's and ECB's (UCC, 2013).

Table 2.4 Recorded Shear Stress and Velocities for TRM's and ECB's by Urban Creeks Council

Bank Material/ Protection	Shear		Velocity			References
	lb/ft²	N/m²	lb/ft²	N/m²		
Sandy loam	0.0167		1.75	0.53	Design	Temple, 1980
Silt loam	0.0218		2	0.61	Design	Temple, 1980
Alluvial silts	0.0218		2	0.61	Design	Temple, 1980
Ordinary firm loam	0.0341		2.5	0.76	Design	Temple, 1980
Very light loose sand, no vegetation or protection			1 – 1.5	0.3 – 0.46	Limit	Fortier & Scobey, 1926
Average sandy soil			2 – 2.5	0.61 – 0.76	Limit	Fortier & Scobey, 1926
Stiff clay, ordinary gravel soil			4 - 5	1.2 – 1.5	Limit	Fortier & Scobey, 1926
Flume trials, fabric reinforced vegetation – failed after 50 hours	5	244			Limit	Theisen, 1992
Flume trials, fabric reinforced vegetation – failed after 8 hours	8	391			Limit	Theisen, 1992
Turf Reinforcement mat, permanent	8	392	20	6.1	Design	Rolanka product literature
Straw reinforcement mat, temporary	0.45	22.05	8	2.4	Design	Rolanka product literature
Jute mat	0.45	22.05			Design	HEC-15
Straw with net	1.45	71.05			Design	HEC-15
Curled wood net	1.55	75.95			Design	HEC-15
Synthetic mat	2	75.95			Design	HEC-15

Table 2.4: Factors Influencing Erosion (Fischenich, 2001)

Factor	Relevant characteristics
Flow properties	Magnitude, frequency and variability of stream discharge; Magnitude and distribution of velocity and shear stress; Degree of turbulence
Sediment composition	Sediment size, gradation, cohesion and stratification
Climate	Rainfall amount, intensity and duration; Frequency and duration of freezing
Subsurface conditions	Seepage forces; Piping; Soil moisture levels
Channel geometry	Width and depth of channel; Height and angle of bank; Bend curvature
Biology	Vegetation type, density and root character; Burrows
Anthropogenic factors	Urbanization, flood control, boating, irrigation

Step 5 - Recompute Flow Values

Resistance values in the hydraulic computations should be adjusted to reflect the selected channel lining, and hydraulic condition should be recalculated for the channel. At this point, reach or section averaged hydraulic conditions should be adjusted to account for local and instantaneous extremes. Table 2.5 presents velocity limits for various channel boundaries conditions. This table is useful in screening alternatives, or as an alternative to the shear stress analysis presented in the preceding sections.

Lining	0 – 0.61 m/s	0.61 – 1.22 m/s	1.22 – 1.83 m/s	1.83 – 2.44 m/s
Sandy Soils	Use Caution	Not Appropriate	Not Appropriate	Not Appropriate
Firm Loam	Use Caution	Use Caution	Not Appropriate	Not Appropriate
Mixed Gravel and Cobbles	Appropriate	Use Caution	Use Caution	Not Appropriate
Average Turf	Appropriate	Use Caution	Use Caution	Not Appropriate
Degradable RECPs	Appropriate	Use Caution	Use Caution	Use Caution
Stabilizing	Appropriate	Use Caution	Use Caution	Use Caution
Bioengineering	Appropriate	Use Caution	Use Caution	Use Caution
Good Turf	Appropriate	Appropriate	Use Caution	Use Caution
Permanent RECPs	Appropriate	Appropriate	Appropriate	Appropriate
Armoring	Appropriate	Appropriate	Appropriate	Appropriate
Bioengineering	Appropriate	Appropriate	Appropriate	Appropriate
CCMs & Gabions	Appropriate	Appropriate	Appropriate	Appropriate
Riprap	Appropriate	Appropriate	Appropriate	Appropriate
Concrete	Appropriate	Appropriate	Appropriate	Appropriate

Key :

(dark shading)	Appropriate
(medium shading)	Use Caution
(light shading)	Not Appropriate

Step 6 - Confirm Lining Stability

The stability of the proposed lining should be assessed by comparing the threshold values in Table 2.3 to the newly computed hydraulic conditions. These values can be adjusted to account for flow duration using Figures 2.7 and 2.8 as a guide. If computed values exceed thresholds, Step 4 should be repeated. If the threshold is not exceeded, a factor of safety (FS) for the project should be determined from the following equations:

$$FS = \frac{\tau_{max}}{\tau_{computed}} \quad \text{or} \quad FS = \frac{V_{max}}{V_{computed}} \tag{2.3}$$

Table 2.5: Stability of Channel Linings for Given Velocity Ranges (Fischenich, 2001)

Lining	0 – 0.61 m/s	0.61 – 1.22 m/s	1.22 – 1.83 m/s	1.83 – 2.44 m/s	> 2.44 m/s
Sandy Soils	Use Caution	Not Appropriate	Not Appropriate	Not Appropriate	Not Appropriate
Firm Loam	Use Caution	Use Caution	Not Appropriate	Not Appropriate	Not Appropriate
Mixed Gravel and Cobbles	Appropriate	Use Caution	Use Caution	Not Appropriate	Not Appropriate
Average Turf	Appropriate	Use Caution	Use Caution	Not Appropriate	Not Appropriate
Degradable RECPs	Appropriate	Use Caution	Use Caution	Use Caution	Not Appropriate
Stabilizing Bioengineering	Appropriate	Use Caution	Use Caution	Use Caution	Not Appropriate
Good Turf	Appropriate	Appropriate	Use Caution	Use Caution	Use Caution
Permanent RECPs	Appropriate	Appropriate	Appropriate	Appropriate	Use Caution
Armoring Bioengineering	Appropriate	Appropriate	Appropriate	Appropriate	Use Caution
CCMs & Gabions	Appropriate	Appropriate	Appropriate	Appropriate	Use Caution
Riprap	Appropriate	Appropriate	Appropriate	Appropriate	Appropriate
Concrete	Appropriate	Appropriate	Appropriate	Appropriate	Appropriate

Key :

Shading	Meaning
(dark)	Appropriate
(light grey)	Use Caution
(white)	Not Appropriate

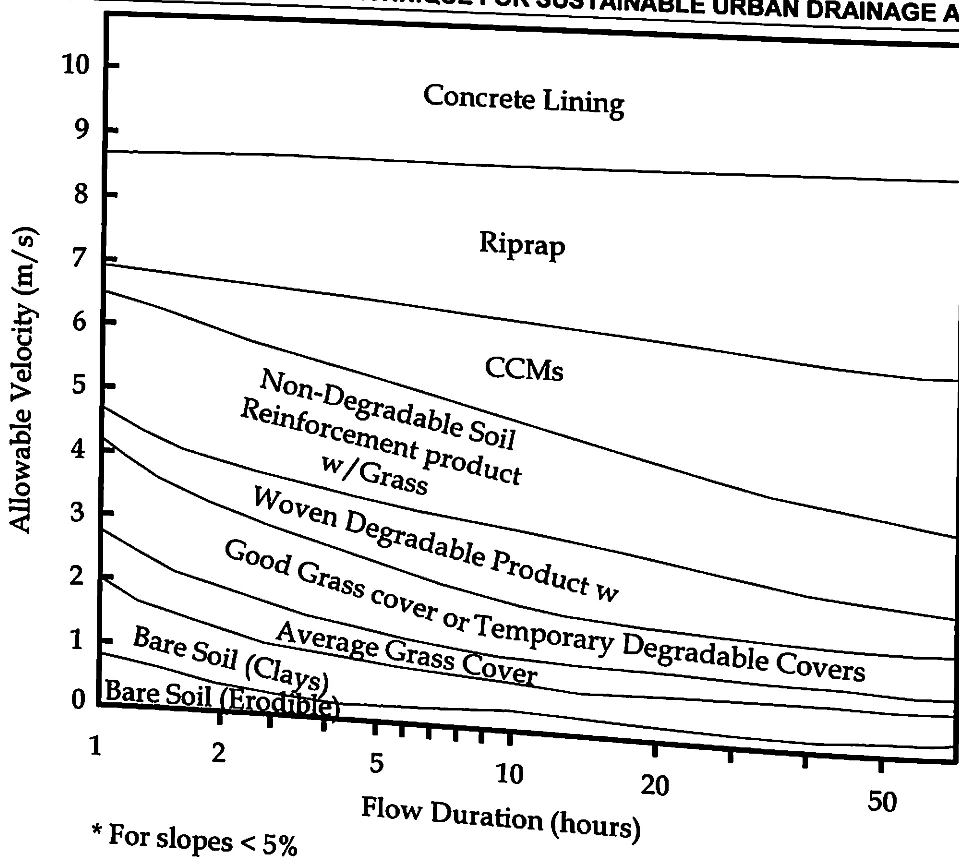
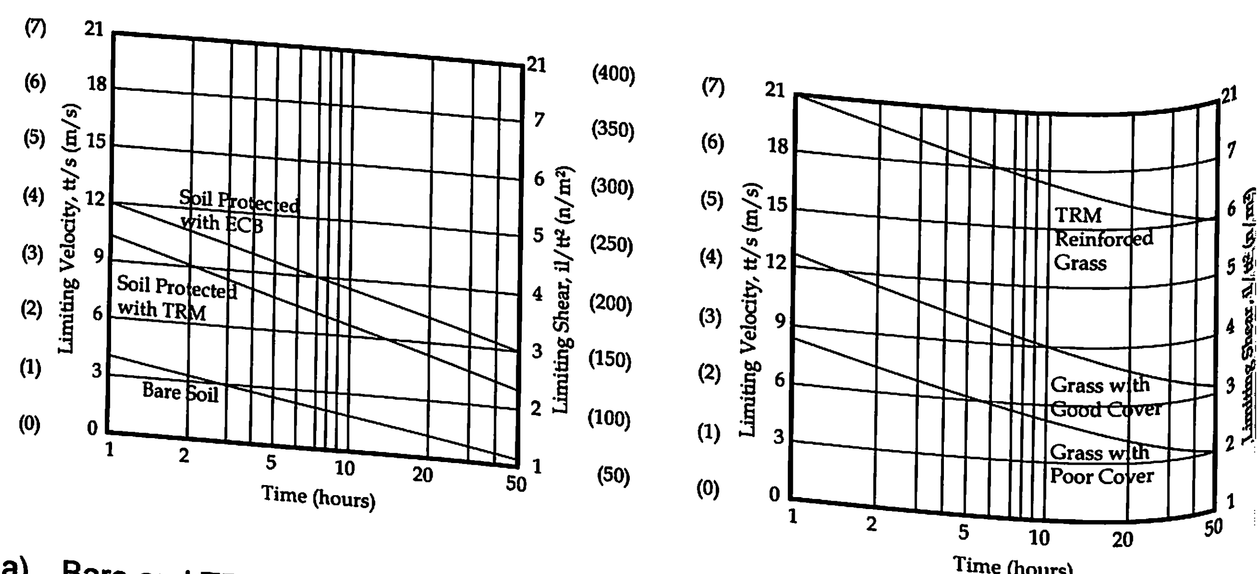


Figure 2.7: Erosion Limits as a Function of Flow Duration (Fischenich and Allen, 2000)



a) Bare and TRM Protected Soils

b) Plain and TRM Reinforced Grass

Figure 2.8: Limiting Value for Velocity and Shear (Sprague, 1999)

2.6.3 *Limitations*

Techniques described in previous section are generally applicable to stream restoration projects that include revegetation of the riparian zone or bioengineering treatment. Detailed design criteria can be found in DID Manual, Volume 2-River Management (DID, 2009).

CHAPTER 3
METHODOLOGY

3.0 Introduction

This study only focused on applicability of channel lining material for sustainable urban drainage application against erosion. Figure 3.1 shows the research approached flow chart. The allowable velocity and shear stress for channel lining materials in test channel will be measure without vegetation. Relevant chart was produced in order to evaluate the effectiveness and applicability of selected channel lining material. The produced chart then will be compare to established chart in MSMA 2nd Edition.

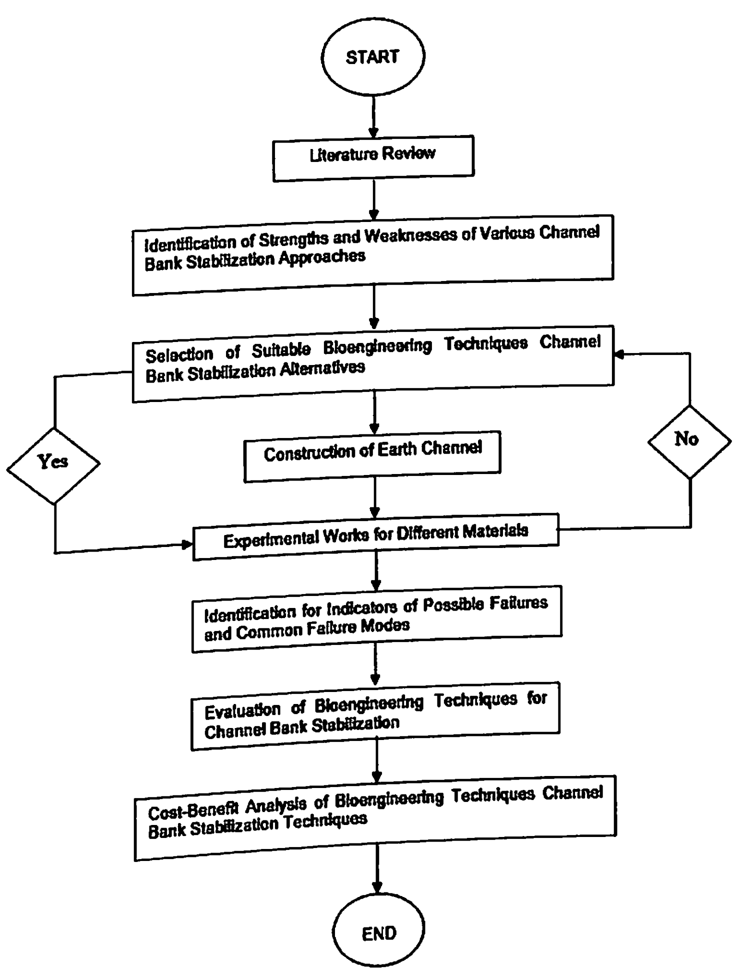


Figure 3.1: Flow Chart of Research Activities

3.1 Description of Methodology

This section will describe about the process in conducting of this research starting with identification of strengths and weaknesses of various channel lining material until evaluation of bioengineering techniques or channel bank stabilization.

3.1.1 *Identification of Strengths and Weaknesses of Various Channel Bank Stabilization Approaches*

A stream is a complex system. A holistic approach to stream problems that incorporates knowledge from multiple disciplines and identifies strengths and weaknesses from different perspectives can create better solutions (FISRWG, 1998). The researchers reviewed disciplines such as hydraulic, hydrology and fluvial geomorphology for their contributions to channel bank stabilization practices. From this review, the researchers organized the various techniques and approaches into traditional engineering, fluvial geomorphology, and biotechnical engineering perspectives.

Information and data collected were consolidated in a format that includes illustrations, figures and texts. This document can provide convenient knowledge of bioengineering techniques for professionals in research, training, education, or practice.

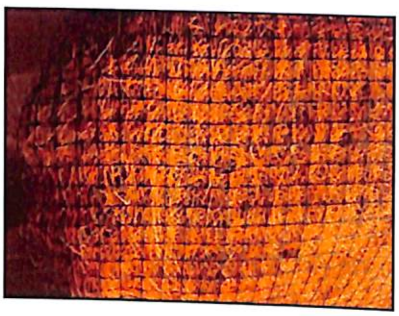
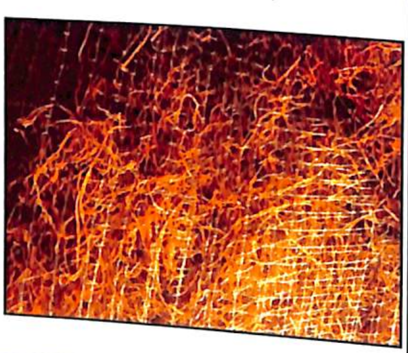
3.1.2 *Selection of Suitable Bioengineering Techniques Channel Bank Stabilization Alternatives*

Bioengineering techniques were evaluated for their applicability as alternatives to channelization and hard-armoring techniques. Data of each technique's applicable bank zones, strength, construction timing, and property was collected. Techniques were selected which evidenced strengths with the potential to compensate for weaknesses of traditional techniques. Two (2) types of channel lining materials of bioengineering technique such as Turf Reinforcement Map (TRM) and Erosion Control Blanket (ECB) are been selected. Both products were designed for erosion protection and the establishment of vegetation up to 12 months. Others technical specification for both selected material are shown in Table 3.1. Technical specification for rolled erosion control product from oversea reference can be used as a comparison purpose are shown in Table 3.2.

The important parameters to consider when specifying erosion control matting are (CIRIA, 2015):

1) Weight – gives some indication of durability
2) Yarn thickness and number of threads – gives some indication of durability and strength
3) Open area – affects water permeability and soil retention properties
4) Yarn quality – affects how long the mesh takes to degrade, its water retention and its flexibility
5) Function when installed – will it be planted up for eventual self-sustainability and cohesion with new developing root systems (in which case a biodegradable material is suitable) or will it need to act as erosion control in the longer term, such as for topsoil retention on slopes (in which case the product should not degrade over the service life of the SuDS).

Table 3.1: Technical Specification of Tested Material (Fibromat)

<table>
<tr><th>Bioengineering Techniques Material</th><th>Technical Specification</th></tr>
<tr><td>Turf Reinforcement Mats (TRM C350)
</td><td>
<table>
<tr><td>Matrix</td><td>:</td><td>Coir Fibre (C350) / Coir Fibre + Paddy Straw (SC350)</td></tr>
<tr><td>Content</td><td>:</td><td>100% (C350) / 70% + 30% (SC350)</td></tr>
<tr><td>Roll Weight</td><td>:</td><td>2.4m</td></tr>
<tr><td>Roll Length</td><td>:</td><td>21m</td></tr>
<tr><td>Area</td><td>:</td><td>50m²/roll</td></tr>
<tr><td>Functional Longevity</td><td>:</td><td>Approx. 36 months</td></tr>
<tr><td>Applications</td><td>:</td><td>3:1 to 1:1 Slopes</td></tr>
<tr><td>Permissible Shear Resistance</td><td>:</td><td>15.6kg/m² or 152.98N/m²</td></tr>
<tr><td>Flow Velocity</td><td>:</td><td>3.8m/s (estimated)</td></tr>
<tr><td>“n” Value Roughness Coefficient</td><td>:</td><td>0.018 (estimated)</td></tr>
<tr><td>Water Absorption</td><td>:</td><td>25.0% (estimated)</td></tr>
<tr><td>Swell</td><td>:</td><td>233.0% (estimated)</td></tr>
</table>
Netting:
<table>
<tr><th></th><th>Top</th><th>Center</th><th>Bottom</th></tr>
<tr><td>Material</td><td>Black PP</td><td>Balck PP Corrugated</td><td>Black PP</td></tr>
<tr><td>Weight</td><td>3.9kg/100m²</td><td>11.7kg/100m²</td><td>3.9kg/100m²</td></tr>
</table>
</td></tr>
<tr><td>Erosion Control Blanket (ECB DS250)
</td><td>
<table>
<tr><td>Matrix</td><td>:</td><td>Agriculture Straw</td></tr>
<tr><td>Content</td><td>:</td><td>100%</td></tr>
<tr><td>Roll Weight</td><td>:</td><td>2.4m</td></tr>
<tr><td>Roll Length</td><td>:</td><td>42m</td></tr>
<tr><td>Area</td><td>:</td><td>100m²/roll</td></tr>
<tr><td>Functional Longevity</td><td>:</td><td>Approx. 12 months</td></tr>
<tr><td>Applications</td><td>:</td><td>3:1 to 2:1 Slopes</td></tr>
<tr><td>Permissible Shear Resistance</td><td>:</td><td>10.25kg/m² or 100.52N/m²</td></tr>
<tr><td>Netting</td><td>:</td><td>PP UV Stabilized</td></tr>
</table>
</td></tr>
</table>

Desired Time Scale		Type Code	Product Category	Material Composition	Max Slope Gradient (H:V)	Max Channel Shear Stress	
Description	Length					(lb/sq ft)	(Pa)
Short Term	3-12 months	1A	Single Net Erosion Control Blanket	Processed degradable natural and/or polymer fibers mechanically bound together by a single rapidly degrading synthetic or natural fiber nettings	3:1	1.50	72
			Open Weave Textile	Processed rapidly degrading natural or polymer yarns or twines woven into a continuous matrix			
		1B	Double Net Erosion Control Blanket	Processed degradable natural and/or polymer fibers mechanically bound together by a single rapidly degrading synthetic or natural fiber nettings	2:1	1.75	84

Table 3.2: Rolled Erosion Control Product Comparison (ECTC, 2006)

Desired Time Scale		Type Code	Product Category	Material Composition	Max Slope Gradient (H:V)	Max Channel Shear Stress	
Description	Length					(lb/sq ft)	(Pa)
Short Term	3-12 months	1A	Single Net Erosion Control Blanket	Processed degradable natural and/or polymer fibers mechanically bound together by a single rapidly degrading synthetic or natural fiber nettings	3:1	1.50	72
			Open Weave Textile	Processed rapidly degrading natural or polymer yarns or twines woven into a continuous matrix			
		1B	Double Net Erosion Control Blanket	Processed degradable natural and/or polymer fibers mechanically bound together by a single rapidly degrading synthetic or natural fiber nettings	2:1	1.75	84
Extended Term	24 months	2A	Erosion Control Blanket	Processed slow degrading natural or polymer fibers mechanically bound together between two slow degrading synthetic or natural fiber nettings to form a continuous matrix	3:2	2.00	96
			Open Weave Textile	Processed slow degrading natural or polymer yarns or twines woven into a continuous matrix			
Long Term	36 months	3A	Erosion Control Blanket	Processed slow degrading natural or polymer fibers mechanically bound together between two slow degrading synthetic or natural fiber nettings to form a continuous matrix	1:1	2.25	108
			Open Weave Textile	Processed slow degrading natural or polymer yarns or twines woven into a continuous matrix			

Table 3.2: Rolled Erosion Control Product Comparison (Continued) (ECTC, 2006)

Desired Time Scale		Type Code	Product Category	Material Composition	Max Slope Gradient (H:V)	Max Channel Shear Stress	
Description	Length					(lb/sq ft)	(Pa)
Permanent		4A	Turf Reinforcement Mat	Non or partially degradable synthetic fibers, filaments, nets, wire mesh and/or other elements, processes into a permanent, three dimensional matrix of sufficient thickness	2:1	6.00	288
		4B				8.00	384
		4C				10.00	480

Source: Adapted from Erosion Control Technology Council, 2006. *Standard Specification for Rolled Control Erosion Products*

Note:

1) *Shear stress unvegetated rolled erosion control product can sustain without physical damage or excessive erosion (>12.7mm (0.15in) soil loss) during a 30 minute flow event, based on historical experience and large scale testing of products with Manning's roughness coefficients of 0.01 – 0.05. Test methods include ASTM D6459 or others deemed acceptable by the engineer.*

2) *Shear stress fully vegetated turf reinforcement mat can sustain without physical damage or excessive erosion (>12.7mm (0.5in) soil loss) during a 30 minute flow event, based on large scale testing. Test methods include ASTM D6460 or others deemed acceptable by the engineer.*

During Installation

Example of bank stability projects using the materials of TRM and ECB as shown in Table 3.3.

Table 3.3: Example of Bank Stability Project using TRM and ECB

Bioengineering Techniques Material	**Bank Stability Projects**	
	During Installation	**After Installation**
Turf Reinforcement Mats (TRM)		
Erosion Control Blanket (ECB)		

Table 3.4 show the advantages and disadvantages for both lining material from several local and oversea references.

Table 3.4: Advantages and Disadvantages of using TRM and ECB

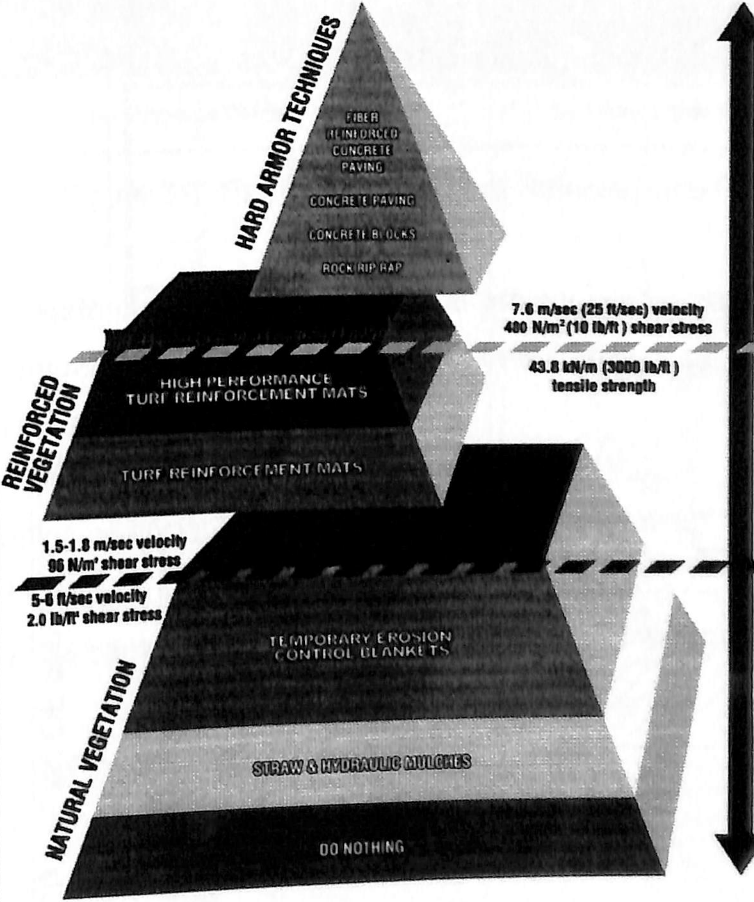
Channel Lining Materials	Advantages	Disadvantages
TRM (Fibromat)	i) Easier to install than rock or concrete and no heavy equipment required. ii) Functioning as a natural filter for runoff water by allowing infiltration, entrapping sediments and absorbing harmful pollutants. iii) Need little maintenance other the periodic mowing. iv) Provide a flexible lining that won't crack and deteriorate like concrete. v) Creating a more natural, aesthetically pleasing and ecologically functional green landscape.	N/A
TRM (USEPA, 1999)	i) Control erosion ii) Stabilize soil to control runoff from land-disturbing activities with steep slopes iii) Prevent scouring in storm water detention ponds, water storage ponds, small open channels, drainage ditches and runoff conveyance systems within parking lot medians, and along stream banks and shorelines iv) Retrofit existing hard armor systems. For example, in 1994, the City of Chattanooga, Tennessee, began a program to improve water quality by protecting aquatic habitat and reducing sediment transport to receiving water bodies. The City chooses to retrofit existing concrete lined storm water channels into vegetative swales. v) Improving water quality, provide aesthetic enhancement, especially in areas lacking vegetative growth	Should not be used:- i) To prevent deep seated slope failure due to causes other than surficial erosion, ii) When anticipated hydraulic conditions are beyond the limits of TRMs and natural vegetation, iii) Directly beneath drop outlets to dissipate impact force (although they may be used beyond the impact zone), iv) Where wave height may exceed 30 centimeters (1 foot)(although they may be used to protect areas up slope of the wave impact zone).

Table 3.4: Advantages and Disadvantages of using TRM and ECB (Continued)

Channel Lining Materials	Advantages	Disadvantages
TRM (Shahkolahi et al., 2014)	i) By protecting the soil from scouring forces and enhancing vegetative growth, TRMs can raise the threshold of natural vegetation to withstand higher hydraulic forces on slopes, streambanks and channels which leads to reduction in soil loss. ii) In addition, the use of natural vegetation provides particulate contaminant removal through sedimentation and soil infiltration, and improves the aesthetics of a site. iii) TRMs, unlike temporary erosion control products, are designed to stay in place permanently to protect seeds and soils and to improve germination. iv) Although most effective when used in fully vegetated areas, TRMs have also been used to prevent erosion in arid, semi-arid and high altitude regions with limited vegetative growth. v) Apart from that, TRMs reduce evaporation and insulates the soil, reduce soil moisture loss, moderate soil temperature, prevent crusting and sealing of the soil surface and increase infiltration vi) Reinforcing vegetation with TRMs has become an acceptable, performance proven, cost effective and environmentally friendly alternative to concrete, rock riprap, rock mattresses and other forms of non-vegetative lining materials due to effectively reducing construction times, construction costs (about 75% reduction), material costs, equipment requirements and most importantly improving water quality and ground water recharge capabilities. vii) TRMs, with shear stresses up to 480 to 576 pa (similar to more than 80cm rock rip-rap), have proven their performance capabilities over the past 35 years in field and laboratory tests.	N/A

Table 3.4: Advantages and Disadvantages of using TRM and ECB (Continued)

Channel Lining Materials	Advantages	Disadvantages
ECB (Fibromat)	i) Immediate effectiveness as it covers the whole soil surface, immediately reducing soil erosion losses. ii) Rainfall protection as it absorbs and dissipates energy released by heavy rainfall where soil, seed and fertilizer are protected from being washed away. iii) Reducing in runoff velocity and hence the capacity of runoff to detach and transport soil particles. iv) Improved soil fertility as its bio-degrades by improving the organic matter content and buffering capacity and moisture retention is enhanced, providing critical water to assist plant establishment during periods of drought. v) Protect young grass as it prevent washout of seedlings and drought stress. vi) Cost effective and user friendly.	N/A
ECB (UCC, 2013)	i) Erosion control blankets can be providing immediate soil surface stabilization. ii) Even if herbaceous vegetation does not grow, the blankets will provide excellent protection for at least one season. iii) Woody cuttings such as stakes, wattles and fascines may be used with erosion control blankets and geotextiles	i) The slopes must be uniform and relatively smooth before installation to ensure complete contact with the soil. ii) The associated labor cost may be higher.
Rolled Erosion Control Products (RECPs) (ECTC,2006)	i) Can provide for some degree of immediate stabilization ii) Numerous manufacturers, each with a number of different products, allow for the selection of a product which meets the individual characteristics of each site iii) Stabilizes disturbed slope and protects surface from erosive forces of raindrop impact. iv) Promotes growth of vegetation. v) Most products degrade over time, eliminating potential maintenance issue.	i) Various products and manufacturers have different design and construction standards. Designer must rely on manufacturer's data. ii) Permanent stabilization and protection is dependent on the establishment of vegetation unless TRMs are used.



HARD ARMOR TECHNIQUES
FIBER REINFORCED CONCRETE PAVING
CONCRETE PAVING
CONCRETE BLOCKS
ROCK RIP RAP
7.6 m/sec (25 ft/sec) velocity
480 N/m² (10 lb/ft) shear stress
43.8 kN/m (3000 lb/ft) tensile strength
REINFORCED VEGETATION
HIGH PERFORMANCE TURF REINFORCEMENT MATS
TURF REINFORCEMENT MATS
1.5-1.8 m/sec velocity
96 N/m² shear stress
5-6 ft/sec velocity
2.0 lb/ft² shear stress
NATURAL VEGETATION
TEMPORARY EROSION CONTROL BLANKETS
STRAW & HYDRAULIC MULCHES
DO NOTHING

Figure 3.2 illustrates the applicability of TRMs within the spectrum of available erosion control techniques. Temporary erosion control blankets and mats, also shown in Figure 3.2, eventually leave vegetation unprotected and unreinforced and should only be used to establish vegetation under mild hydraulic situations USEPA, 1999).

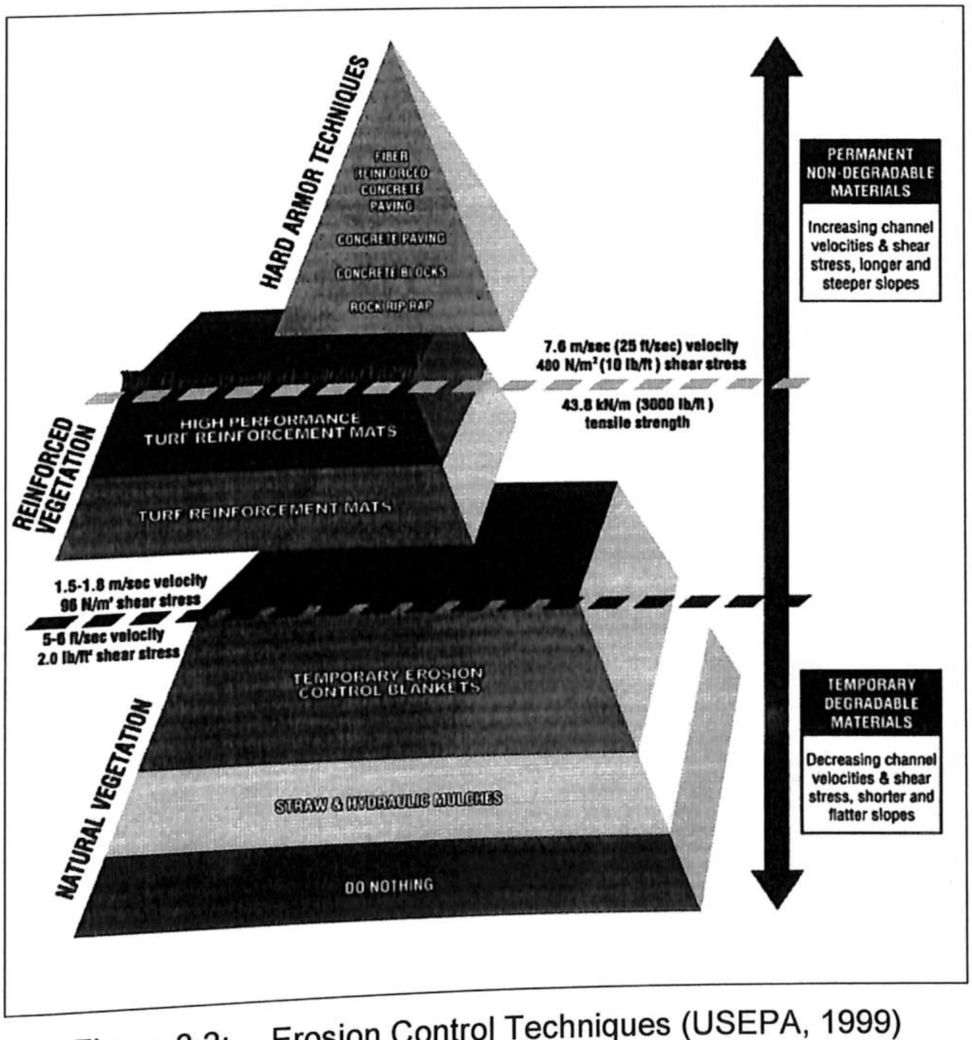
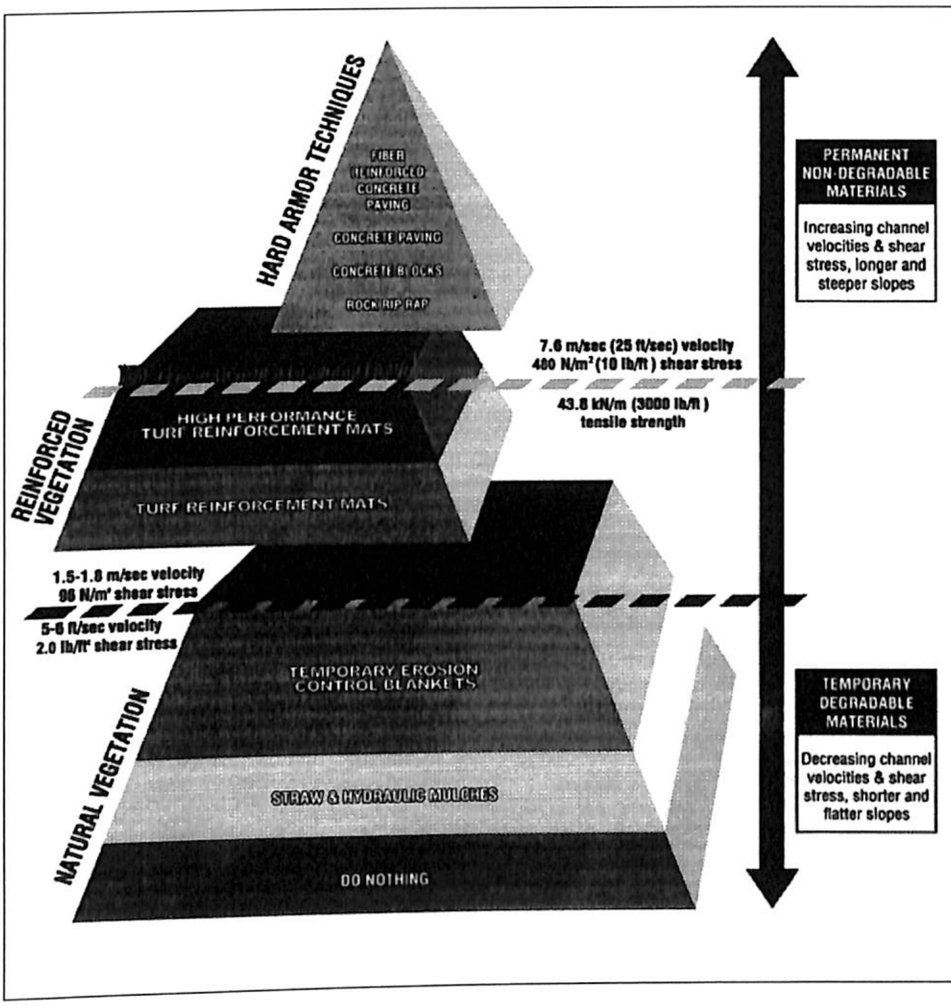


Figure 3.2: Erosion Control Techniques (USEPA, 1999)

3.1.3 *Construction of Test Channel*

The selected site project is located at Physical Laboratory of REDAC, USM Engineering Campus. The layout plan of the physical lab is shown in Figure 3.3. Optional existing conditions of site project are shown in Figure 3.4(a) – (b).

Figure 3.2 illustrates the applicability of TRMs within the spectrum of available erosion control techniques. Temporary erosion control blankets and mats, also shown in Figure 3.2, eventually leave vegetation unprotected and unreinforced and should only be used to establish vegetation under mild hydraulic situations USEPA, 1999).



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3.1.3 *Construction of Test Channel*

The selected site project is located at Physical Laboratory of REDAC, USM Engineering Campus. The layout plan of the physical lab is shown in Figure 3.3. Optional existing conditions of site project are shown in Figure 3.4(a) – (b).

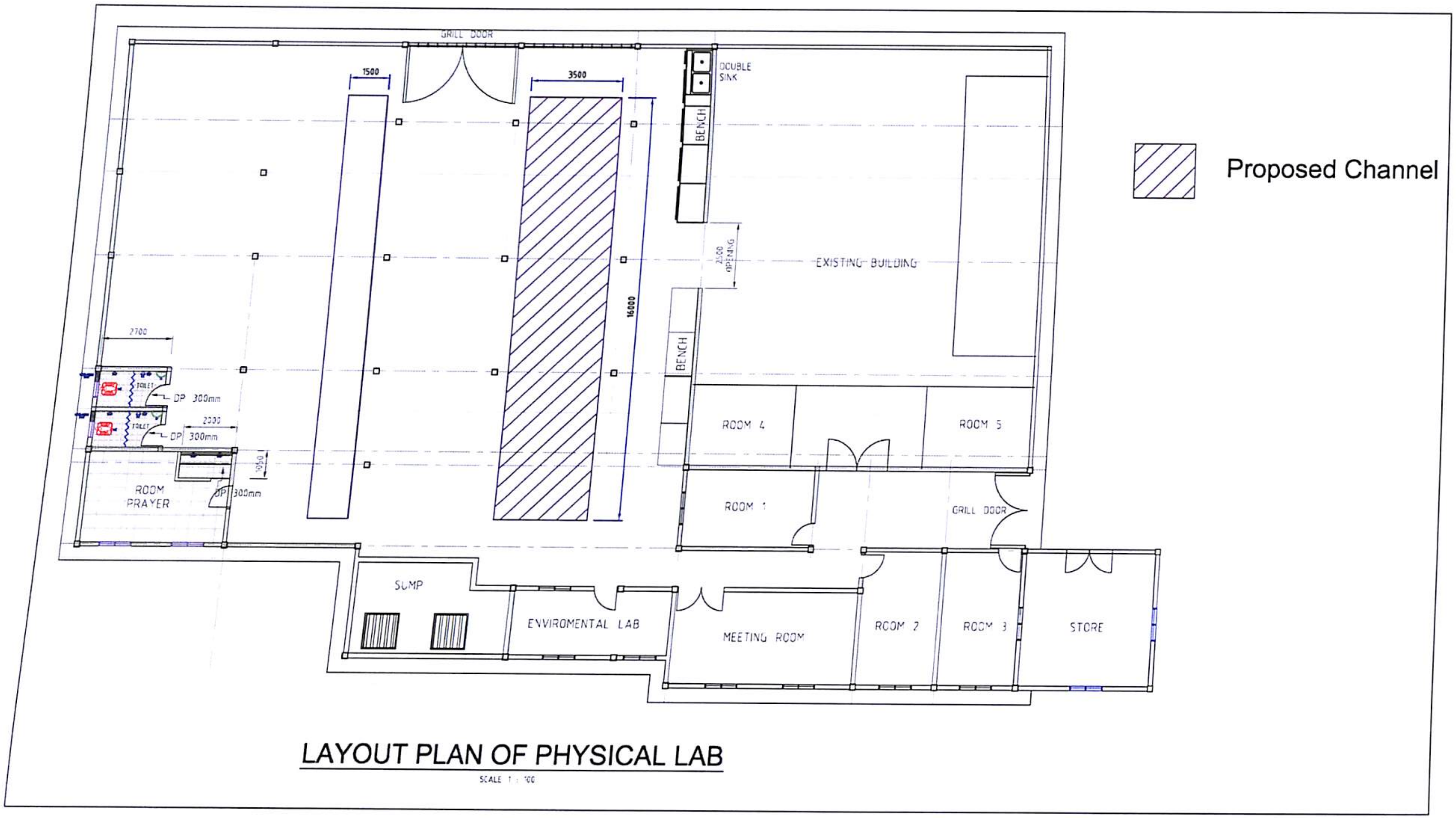
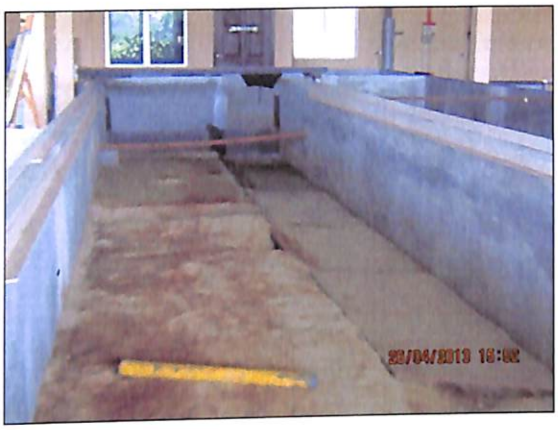


Figure 3.3: The Layout Plan of Physical Lab



(a) Proposed Channel

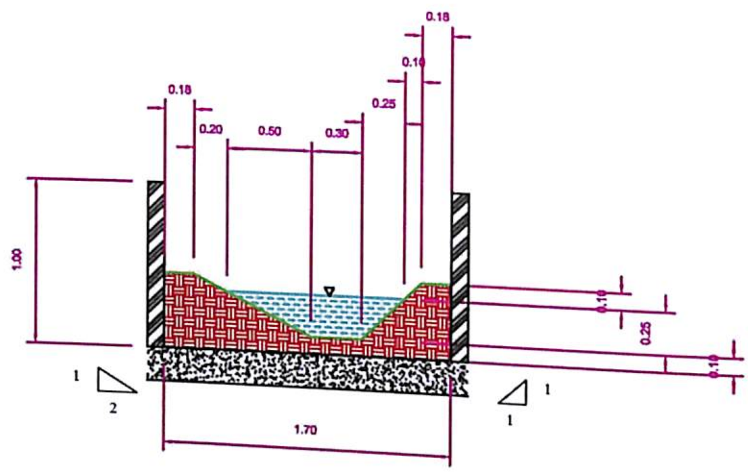
(b) Water Intake from Existing Water Tank

Figure 3.4: Existing Condition of Selected Site Project

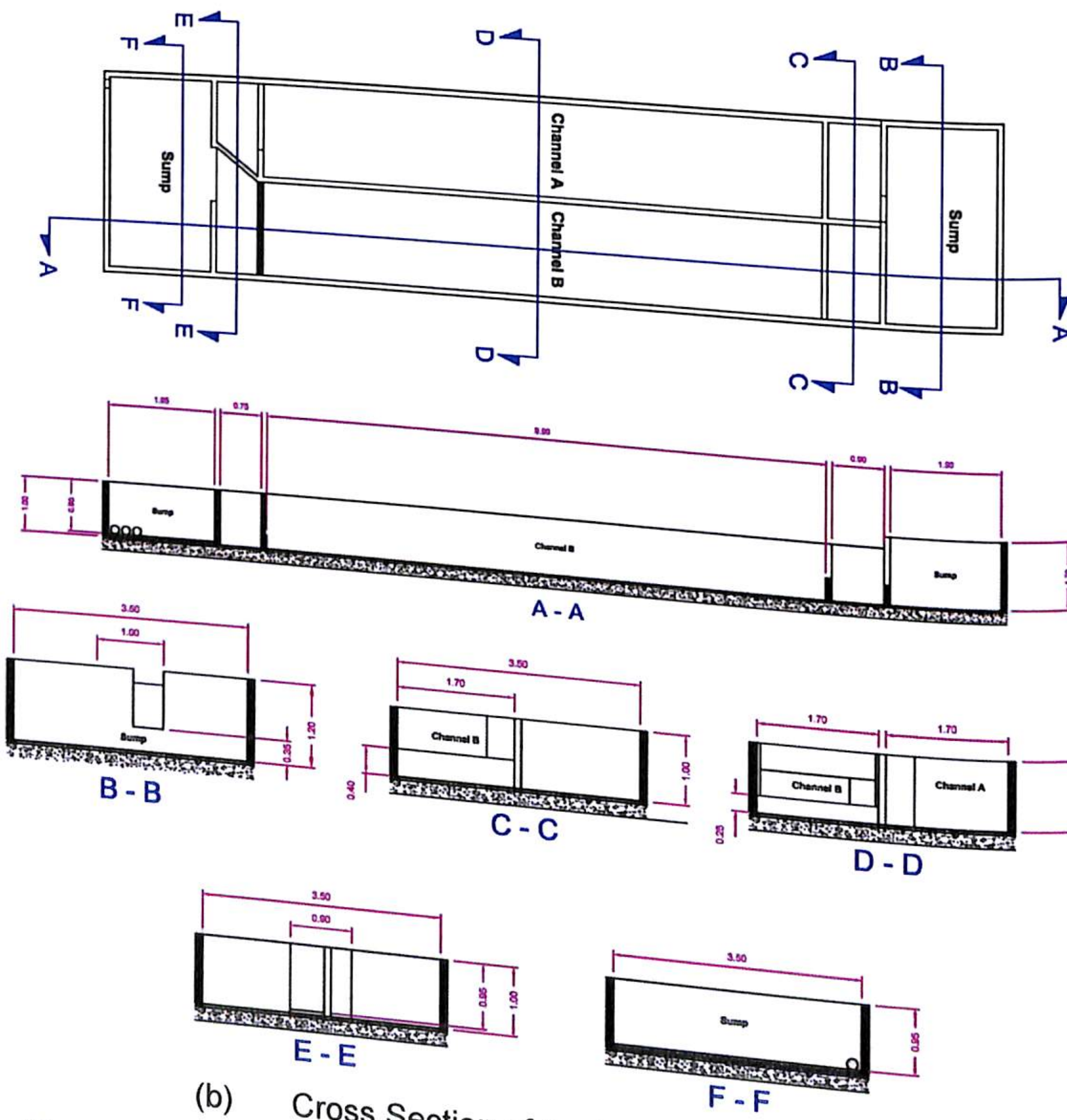
The new earth channel for this research project will be constructed by following the determined design criteria. Design characteristics of the constructed earth channel are as follows:

Manning coefficients,n	=	0.025 (earth channels)
Bed slope, S_o	=	1 / 500 or 0.002
Channel bank slopes	=	1:2 (left bank of the channel) and 1:1 (right bank of the channel)
Channel length	=	10 m
Channel cross section	=	Trapezoidal
Bottom width	=	0.6 m
Top width	=	2.1 m
Depth	=	0.5 m

Figures 3.5(a) - (b) below shows the dimensional of constructed earth channel for the proposed project research. The installation of the selected material at channel bank must always above the highest normal splash zone as shown in Figure 3.6.

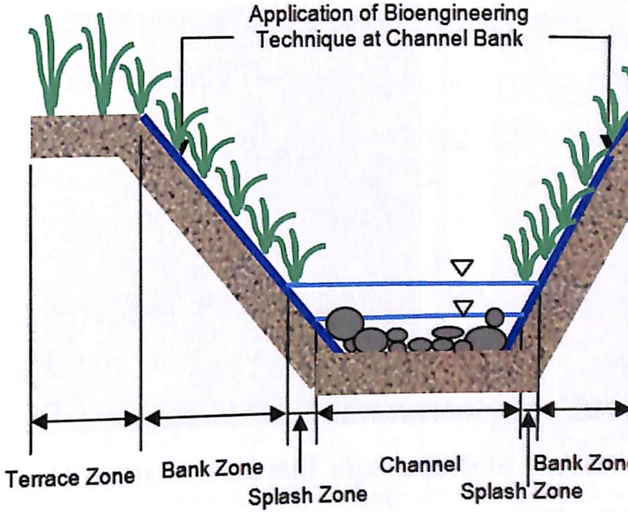


(a) Proposed Shape and Size of the Channel



(b) Cross Section of the Proposed Channel

Figure 3.5: Proposed of Bioengineered Channel Geometry Planform



Application of Bioengineering
Technique at Channel Bank
Terrace Zone
Bank Zone
Splash Zone
Channel
Splash Zone
Bank Zon

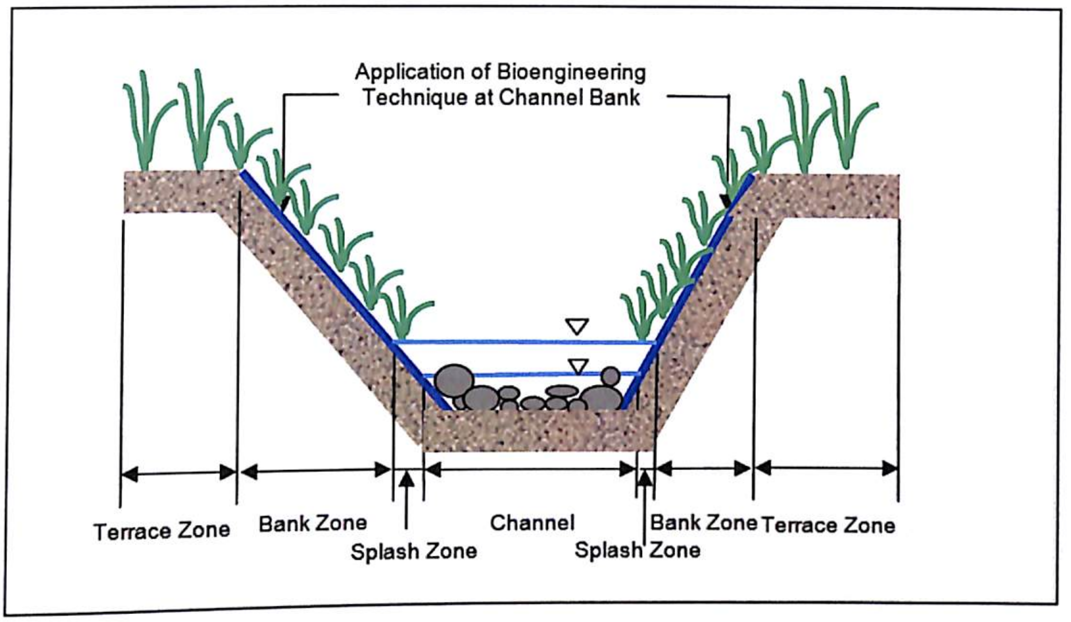


Figure 3.6: Application of Bioengineering Techniques

The first stage for construction of test channel, proposed existing channel need to be clear up from wood debris and minor repair need to be do at the certain part of the channel as shown in Figure 3.7.

Figure 3.7: Dismantling and Cleaning Works in Proposed Channel

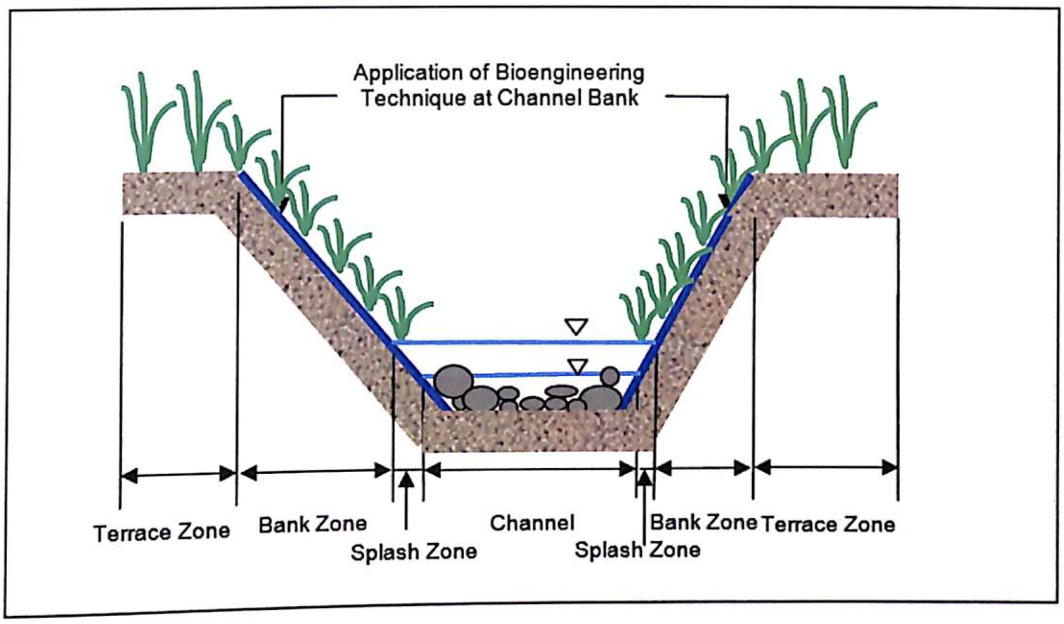


Figure 3.6: Application of Bioengineering Techniques

The first stage for construction of test channel, proposed existing channel need to be clear up from wood debris and minor repair need to be do at the certain part of the channel as shown in Figure 3.7.

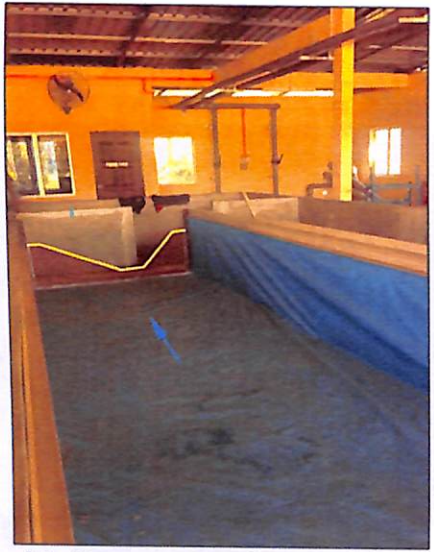
Figure 3.7: Dismantling and Cleaning Works in Proposed Channel

Second stages of construction are to preparing the planform geometry of the proposed test channel. The soil surface must be trimmed fill or cut slope freshly by following the design criteria of test channel. Figures 3.8(a) – (f) shows the preparation works of planform geometry for the proposed test channel in the physical lab.

At the third stages of construction are to laying and stapling the selected lining material of TRM's and ECB's on the soil surface in the test channel. The lining materials must be in intimate contact with the soil surface. This is achieved by allowing the lining materials to drape over the surface undulations and securing to the soil by stapling. The bamboo sticks will be use to stapling the lining material on the soil surface. The lining material will be roll out along the channel bottom and side slopes in the direction of the water flow. Figures 3.9(a) – (f) shows the laying works of lining material on the soil surface in the proposed test channel. An example of installation guide of ECB's are shown in Figure 3.10 (Greenfix, 2013).

(a) Laying Plastic Sheet at the Base

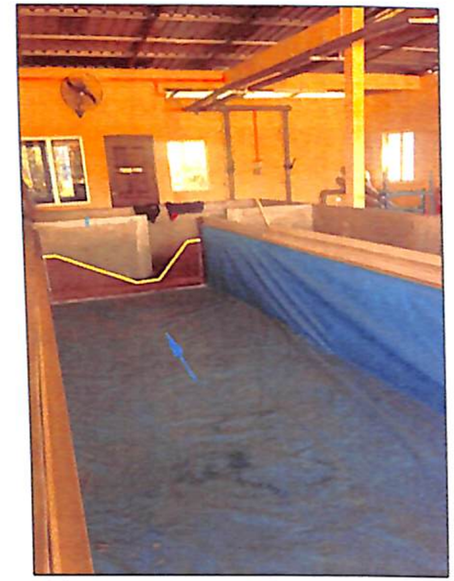
(b) Upstream of Test Channel



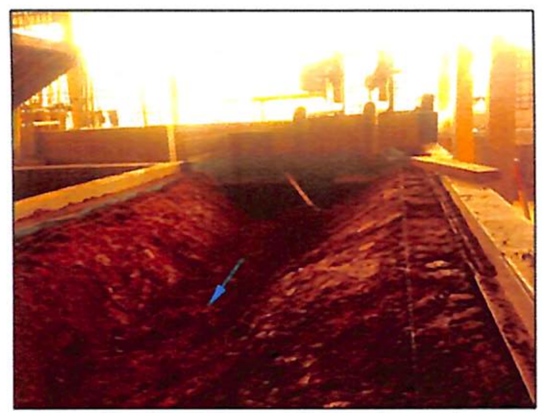
(c) Downstream of Test Channel


(a) Laying Plastic Sheet at the Base


(b) Upstream of Test Channel


(c) Downstream of Test Channel


(d) Soil Filling Works in the Test Channel


(e) Upstream of Earth Channel


(f) Downstream of Earth Channel

Figure 3.8: Preparation Works of Planform Geometry for Proposed Test Channel

(a) Unroll the TRM for Laying Works

(b) Stapling using Bamboo Stick

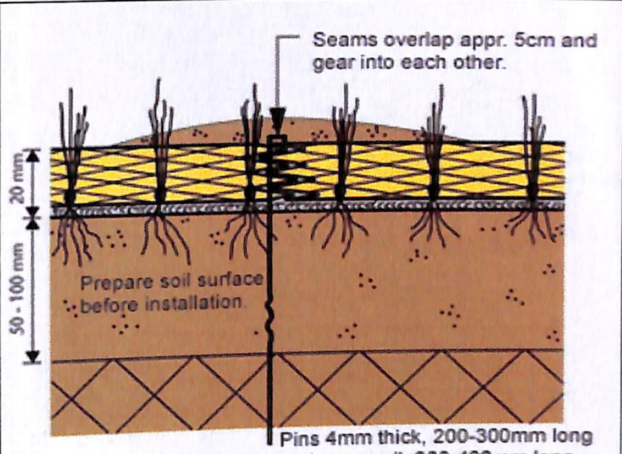
(c) Completion Works of Laying and Stapling TRM

(d) Unroll the ECB for Laying Works

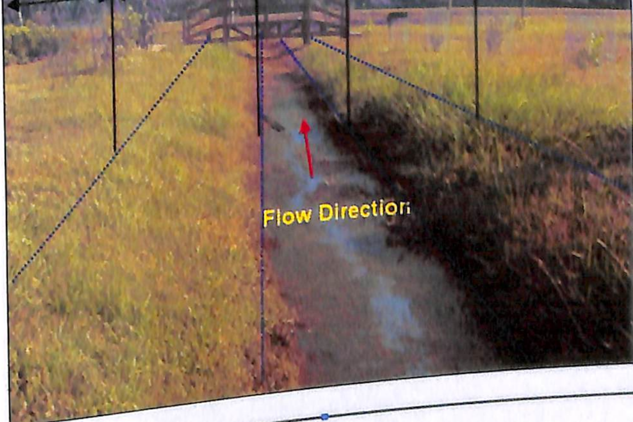
(e) Stapling using Bamboo Stick

(f) Downstream of Earth Channel

Figure 3.9: Laying and Stapling Works of Lining Material in the Proposed Test Channel



Seams overlap appr. 5cm and gear into each other.
20 mm
50 - 100 mm
Prepare soil surface before installation.
Pins 4mm thick, 200-300mm long


Flow Direction

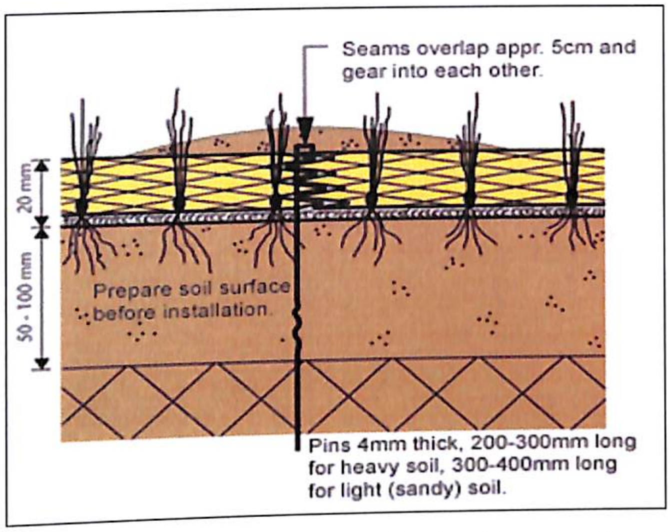


Figure 3.10: Example of Installation Guide for Erosion Control Blanket by Greenfix Company.

The installation of the techniques will be apply along the side slopes (or bank zone) of the earth channel in the direction of the water flow. Figure 3.11 shows the channel zones.

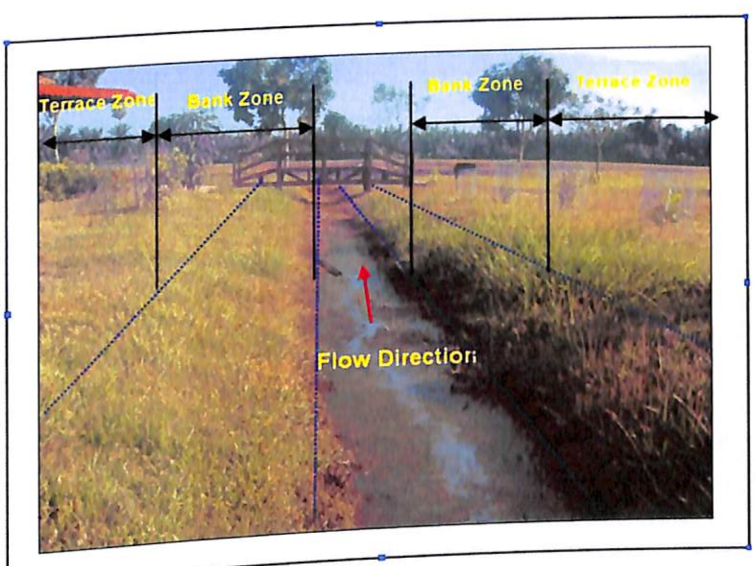
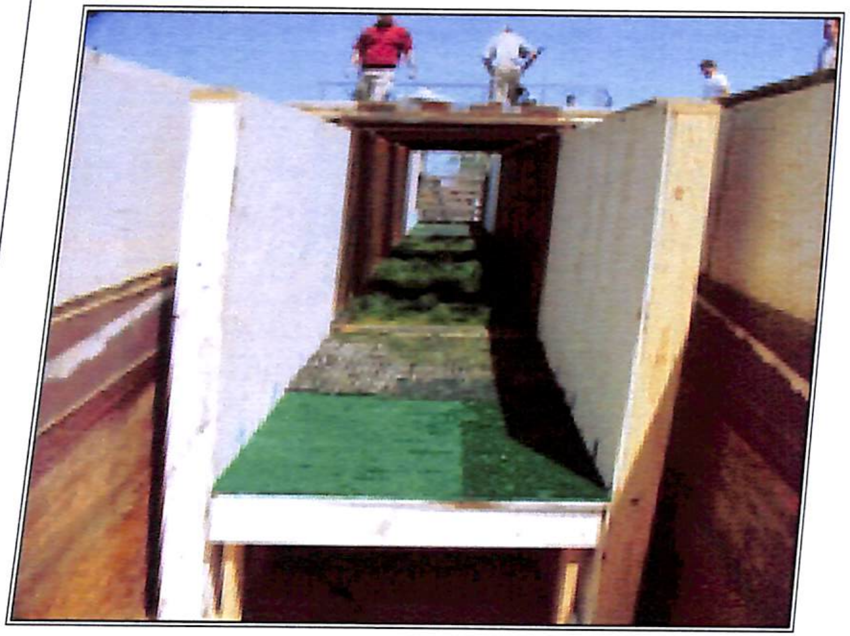
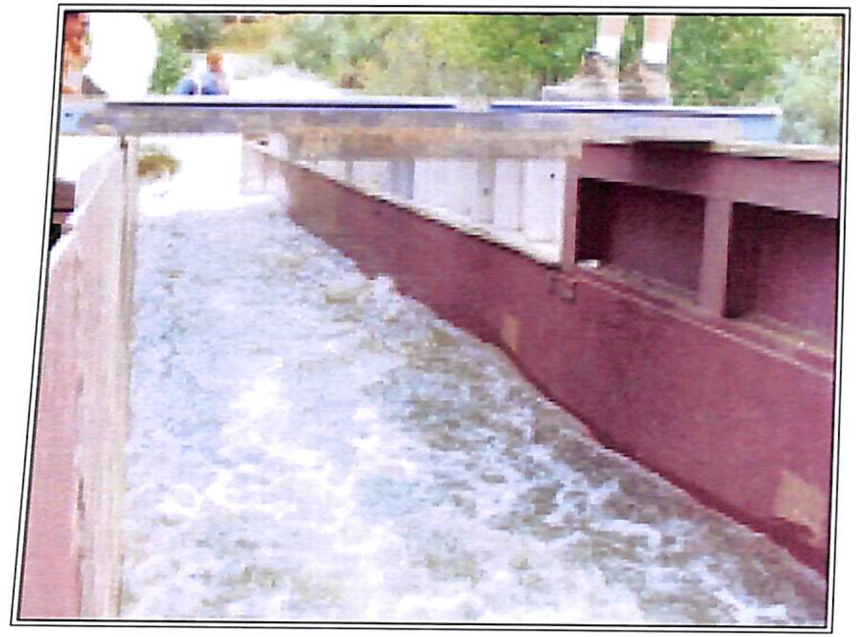


Figure 3.11: Example of Channel Zones

Figure 3.12(a) – (b) show one of an example of completion research project that implementing the bioengineering techniques by using Turf Reinforcement Mats (TRM) as erosion control products conducted by North American Green. There are three (3) phases of testing condition as shown in Figure 3.13(a) – (c) below.



(a) The SC250 stem reinforced vegetation (Retardance Class "C") just after plot placement in the test flume.



(b) Flow generating 9.5 lbs/ft2 (454 Pa) of shear stress with an average of nearly 15 ft/s (4.6 m/s) over unvegetated P550 resulted in NO physical damage to the matting. While this value should not be used for design purposes, it does demonstrate the physical durability of the P550.

Figure 3.12(a) – (b): Application of Bioengineering Techniques at Tested Channel

(Source: North American Green – $Vmax^3$ Tech Facts)

(a) Phase 1: Unvegetated Vmax^3 Performance

(b) Phase 2: Partially Vegetated Vmax^3 Performance

(c) Phase 2: Fully Vegetated Vmax^3 Performance

Figure 3.13(a) – (c): Three (3) Phases of Condition to be Tested
(Source: North American Green – Vmax^3 Tech Facts)

3.1.4 *Experimental Works for Different Materials/Materials to be Tested*

The water will be pumped into the test channel from the existing water tank. The water will flow through the test channel to the downstream of the channel. The function of sump is to collect and store the water from channel before it will circulate to the water tank. This process called pump circulation system where the water in the water tank will reuse continuously and supply water into the test channel as show in Figure 3.14. Figure 3.15(a) – (b) show the water from the tank flow through the test channel.

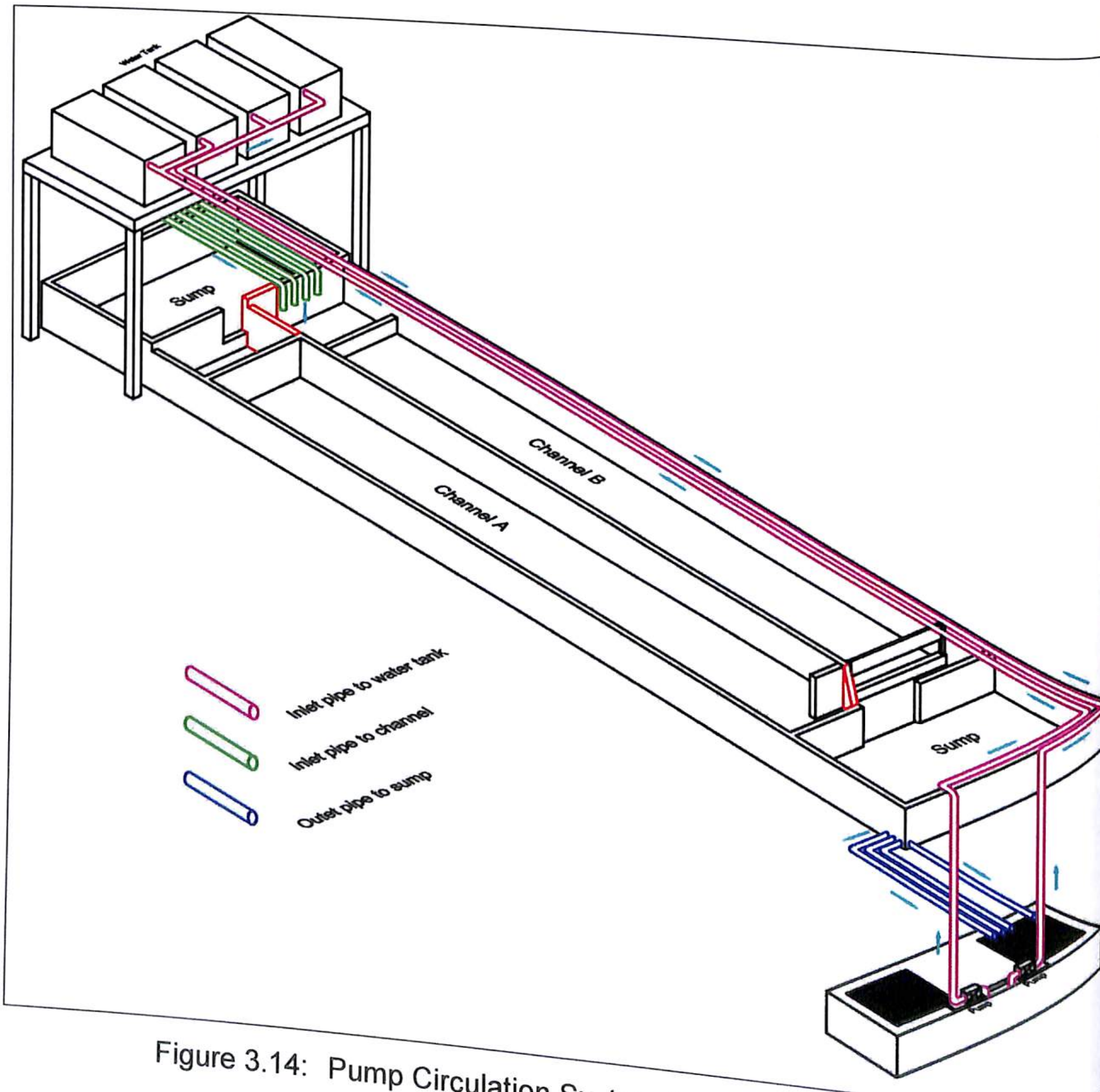
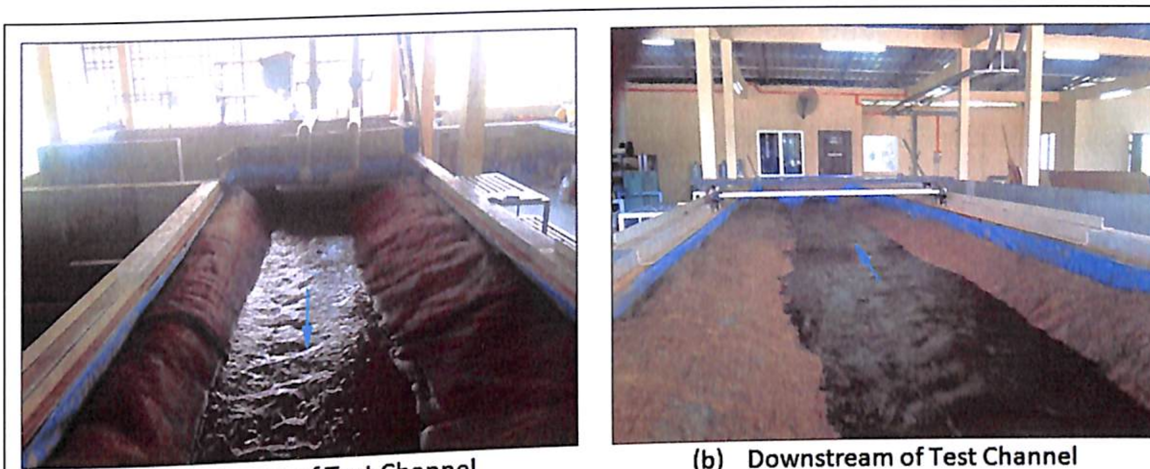


Figure 3.14: Pump Circulation System for Earth Channel

(a) Upstream of Test Channel (b) Downstream of Test Channel

Figure 3.15: Water Flow through the Test Channel

Cause of the backwater effect at the downstream of the channel, only 5m length at the middle part of the test channel will be use for testing. The profile of each 1m cross sectional and velocity of test channel will be measure by using flow meter as shown in Figure 3.16(a) – (c). Flow meter is use for measuring the velocity of open channel. The most accurate method for measuring the flow is to measure the cross sectional area of the stream and then, using a current meter, determine the average velocity in the cross-section.

The flow rate or discharge of a river is the volume of water flowing through a cross-section in a unit of time and is usually expressed as m^3/s. It is calculated as the product of average velocity and cross-sectional area but is affected by water depth, alignment of the channel, gradient and roughness of the river bed. Discharge may be estimated by the slope-area method, using these factors in one of the variations of the Chezy equation. The simplest of the several variations is the Manning equation which, although developed for conditions of uniform flow in open channels, may give an adequate estimate of the non-uniform flow which is usual in natural channels.

The Manning equation states that:

$$Q = AR^{2/3}S^{1/2}$$

Where;

Q = discharge (m^3/s)

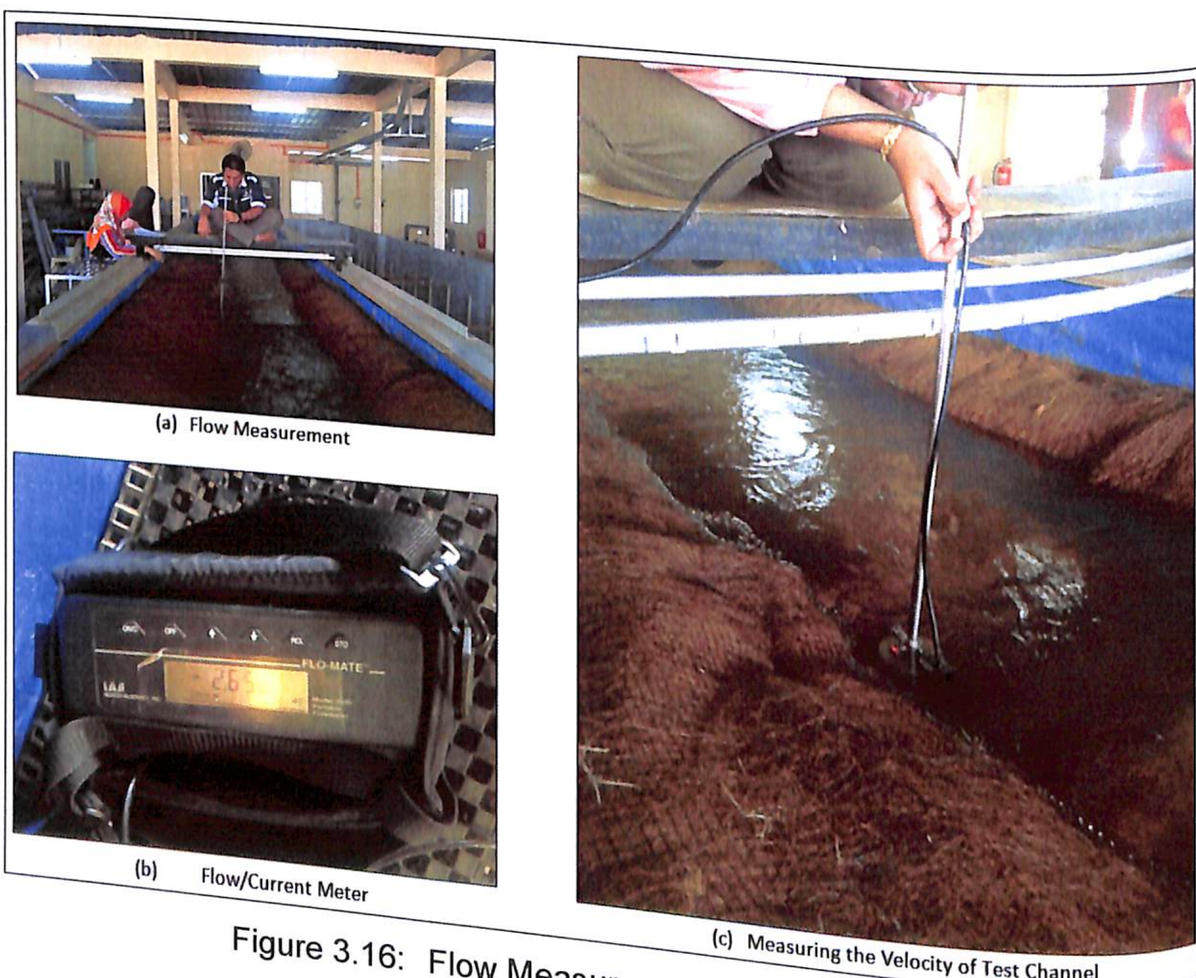
A = cross-sectional area (m^2)

R = hydraulic radius (m) and = A/P

P = wetted perimeter (m)

S = slope of gradient of the stream bed

n = roughness coefficient



(a) Flow Measurement

(b) Flow/Current Meter

(c) Measuring the Velocity of Test Channel

Figure 3.16: Flow Measurement in Test Channel

In 1965, Rouse critically reviewed hydraulic resistance in open channels on the basis of fluid mechanics. He pointed out the effects of cross-sectional shape, boundary non-uniformity, and flow unsteadiness, in addition to viscosity and wall roughness that are commonly considered. Rouse (1965) classified flow resistance into four components (Yen, B., 2002):

1) Surface or skin friction,
2) Form resistance or drag,
3) Wave resistance from free surface distortion, and
4) Resistance associated with local acceleration or flow unsteadiness.

The most important factors that affect the selection of channel n values are (Yen, B., 2002:

1) The type and size of the materials that compose the bed and banks of the channel, and
2) The shape of the channel.

Flow resistance coefficients, such as the Manning's *n*, are used in a wide range of hydraulic and hydrologic analyses. The results of these analyses affect the design, operation, and management of water-resources projects (Soong, David T., et al, 2012).

Values of the roughness coefficient n may be assigned for conditions that exist at the time of a specific flow event, for average conditions over a range in stage, or for anticipated conditions at the time of a future event (Arcement, G.J., Jr., and Schneider, V.R., 1989.)

In an effort to correlate and systematise existing data from natural and artificial channels, Manning in 1889 proposed an equation which was developed into (DID, 2000):

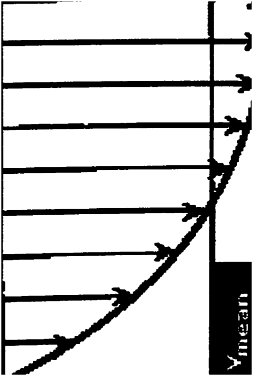
$$V=\frac{1}{n}R^{2/3}S^{1/2}$$

where n is the Manning roughness coefficient. By comparing this equation with the Chezy equation the following relationship can be written (DID, 2000):

$$C=\frac{R^{1/6}}{n}$$

This relationship indicates that the Chezy discharge coefficient is a function of the Manning coefficient and the hydraulic radius. The Manning n was developed empirically as a coefficient which remained approximately a constant for a given boundary condition, regardless of slope of channel, size of channel, or depth of flow. As a matter of fact, however, each of these factors causes n to vary to some extent. In other words, the Reynolds number, the shape of the channel, and the relative roughness have an influence on the magnitude of Manning's n (DID, 2000).

Velocity varies approximately as a parabola from zero at the channel bottom to a maximum near the surface. A typical vertical velocity profile is shown in Figure 3.17. It has been determined empirically that for most channels the velocity at six-tenths of the total depth below the surface is a close approximation to the mean velocity at that vertical line. However, the average of the velocities at two-tenths and eight-tenths depth below the surface on the same vertical line provides a more accurate value of mean velocity at that vertical line.


Vmean

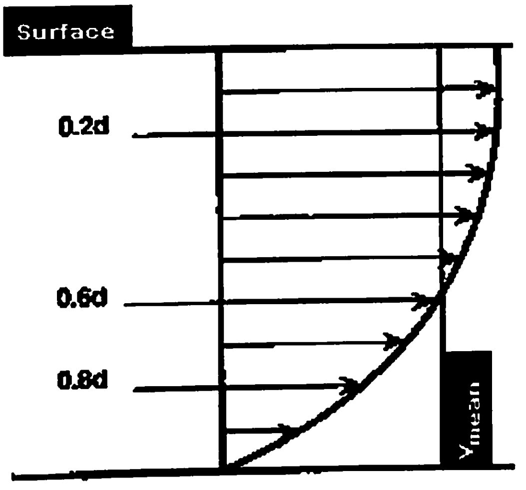


Figure 3.17: Typical River Velocity Profile in the Vertical Plane

Shear stress is an important parameter in habitat rehabilitation design, because all materials, whether manufactured or natural, used for habitat rehabilitation must be able to withstand the expected shear stress at the design discharge (Saldi-Caromile et al. 2004).

On any given bank, the material and vegetation types required to resist erosion may vary with location. Lane's diagram, Figure 3.18, shows theoretical distribution of shear stress on streambed and banks on a straight section of trapezoidal channel. Based on Lane's diagram, materials and plants of greater shear resistance are required lower on the bank, while a lighter-duty treatment may be sufficient near the top of the bank.

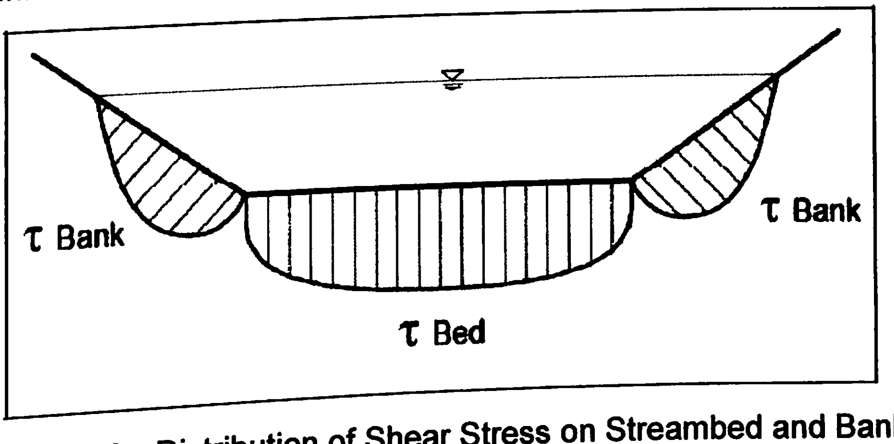


Figure 3.18: Distribution of Shear Stress on Streambed and Banks

A common application of the equation for maximum shear stress in a straight reach will be apply for streambed and bank of the test channel.

For maximum shear stress on the bed is (DID, 2009):

$$\tau_{bed} = \gamma RS = \gamma (A/P)S$$

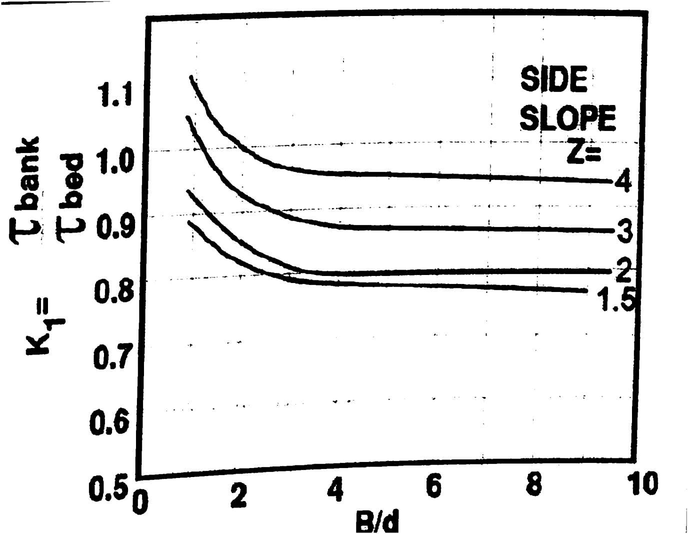
$$\tau_{bed} = 9806\ RS$$

where;

τ_{bed}	=	maximum bed shear stress (N/m^2)
γ	=	the specific weight of water (N/m^3)
R	=	hydraulic radius in m
A	=	flow cross-sectional area (m^2)
P	=	wetted perimeter (m)
S	=	energy slope in m/m

This calculation gives a quantitative measure of the erosive force acting on the bed of the channel.

By approximating the channel cross-section as a trapezoid or rectangular, the maximum bed shear stress can be used to estimate the maximum bank shear stress. This stress acts approximately one-third of the distance up the bank (from the bed) and can be approximated by multiplying the maximum bed shear stress by a factor (see Lane's Diagram, Figure 3.18). This factor, K_1, varies based on channel side slope and the ratio of bottom width to depth as shown in Figure 3.19. This approximation applies only to a relatively straight channel reach.



SIDE
SLOPE
Z=
4
3
2
1.5
$K_1 = \frac{\tau_{bank}}{\tau_{bed}}$
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0
2
4
6
8
10
B/d

For maximum shear stress on the bank is (DID, 2009):

$$\tau_{bank} = K_1 \tau_{bed}$$

where;

τ_{bed} = maximum bed shear stress (N/m^2)

K_1 = ratio from Figure 3.16

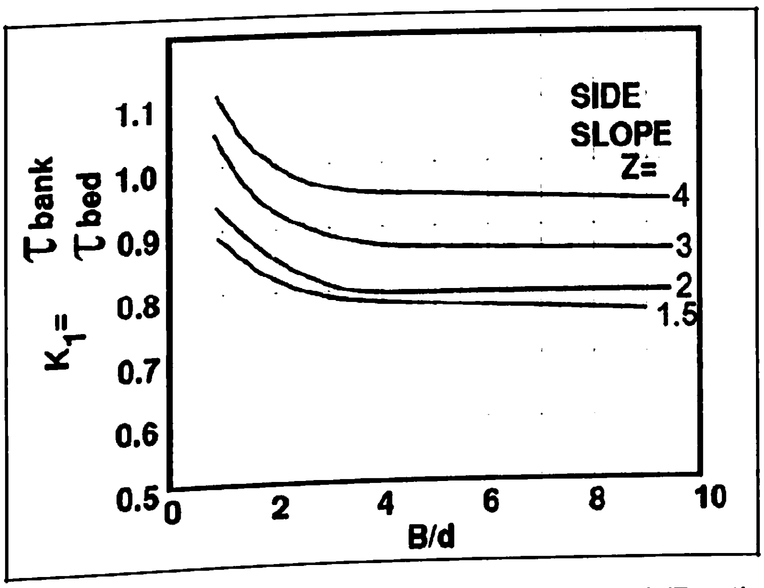


Figure 3.19: Coefficient K_1 vs. Side Slope z, and Width/Depth B/d Ratio

3.1.5 *Identification for Indicators of Possible Failures and Common Failure Modes*

Bioengineering techniques risk failure as do all engineering applications. An exact cause of failure is difficult to assign in a bioengineering techniques channel bank stabilization project because current knowledge of vegetative properties are still limited. The fluvial process interacting with vegetation further complicates the stabilization mechanism of a bioengineering techniques project.

Despite the difficulty of identifying the actual failure cause, the following phenomena, when observed during monitoring, can be indicators of possible failures:

i) erosion at the toe of the underwater slope, leading to failure of the overlying bank;
ii) erosion of the soil along the banks, caused by currents;
iii) sloughing of saturated cohesive banks incapable of free drainage;
iv) flow slides (liquefaction) in saturated silty and sandy soil;
v) erosion of soil by groundwater seepage out of the bank;
vi) erosion of the upper bank or the river bottom due to wave action; and
vii) shrinking and swelling of clays.

Unlike a channel stabilized with traditional techniques, channel banks that show the above symptoms can be economically repaired and further erosion prevented. Coincidentally, an applicable and cost-effective measure used to repair those problems is a bioengineering technique such as live stakes and joint planting.

3.1.6 *Evaluation of Bioengineering Techniques for Channel Bank Stabilization*

The lack of post-project evaluation has been a common problem in channelization projects. The same negligence of post-project evaluations evidenced in channelization projects also holds true for stream restoration and streambank stabilization projects (Kondolf, 1995; Kondolf and Micheli, 1995; Kondolf, 1998). This may be due to the difficulties in measuring variables of the complex stream environment, and unwillingness to fund monitoring activities by most agencies (Kondolf, 1995). If researchers seek to avoid repeating the same mistakes and understand how streams respond to stabilization actions, projects must be monitored after they are completed. Kondolf and Micheli (1995) presented a thorough discussion on the evaluation criteria for different project objectives. For the objective of channel bank stabilization, they suggested collecting the following data to monitor a project:

i) channel cross-sections;
ii) water surface elevations;
iii) channel width-to-depth ratio;
iv) streambank and bed erosion rates;
v) longitudinal profile; and
vi) aerial photo

While it is vegetation that makes bioengineering techniques a viable channel bank stabilization option, it is ironically, working with vegetation that seems to pose the most difficulty on a bioengineering techniques project. Ultimately the stabilization mechanism of bioengineering techniques relies upon the establishment of live materials.

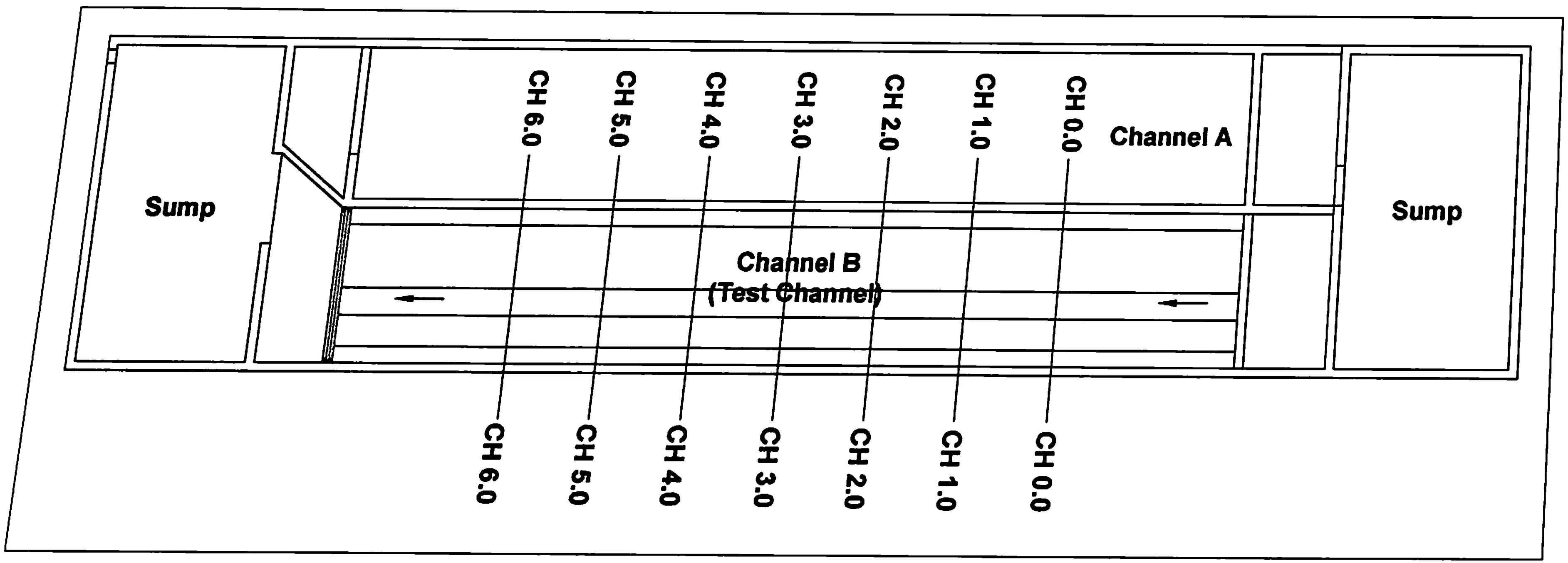


Figure 4.2: Plan View of Test Channel

Table 4.1: Cross Section Profile of Test channel

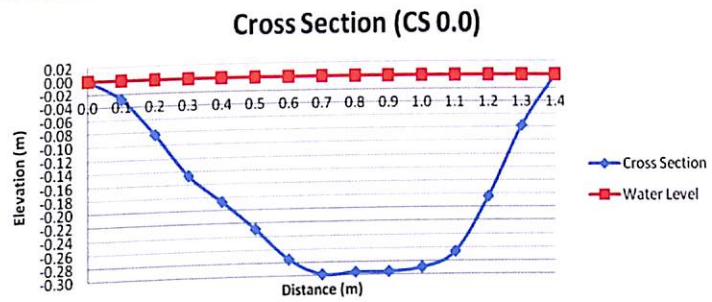
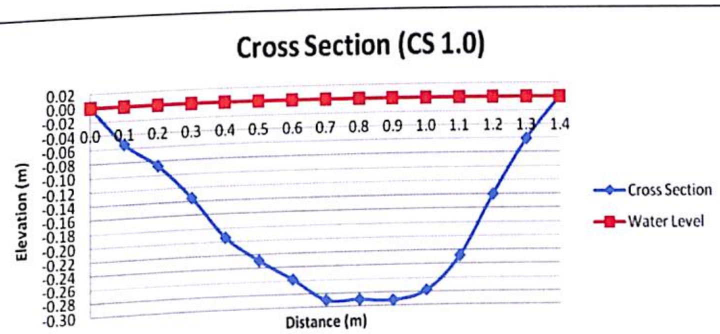
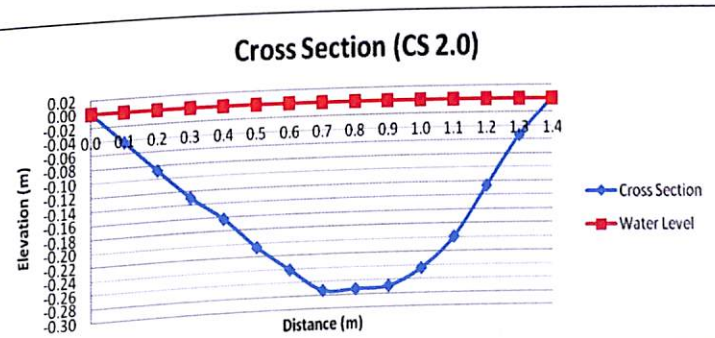
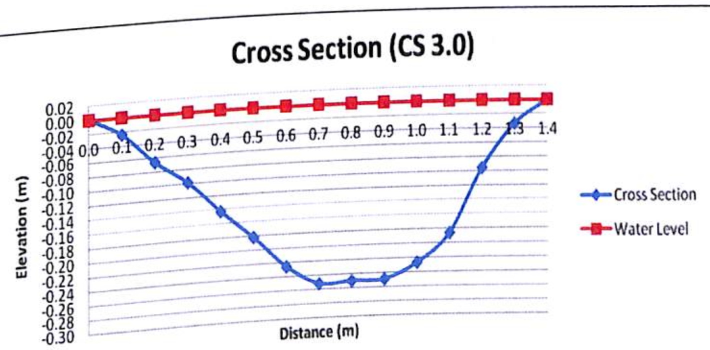
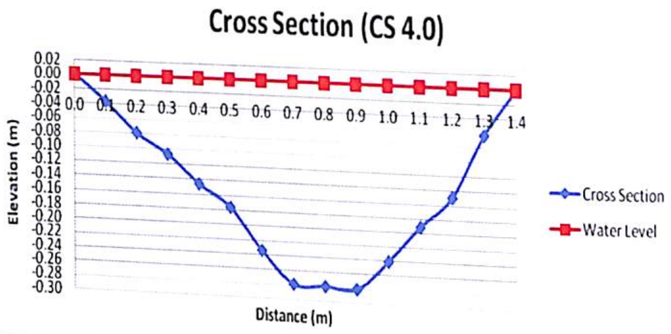
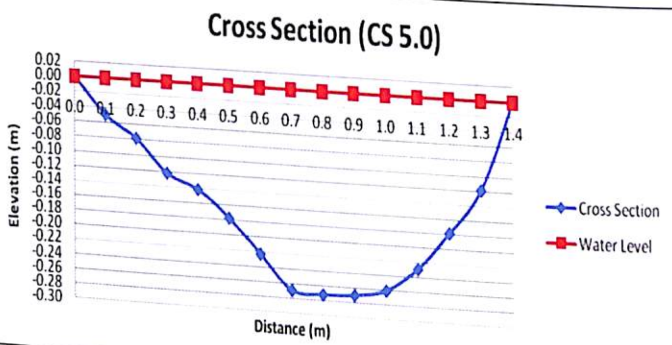
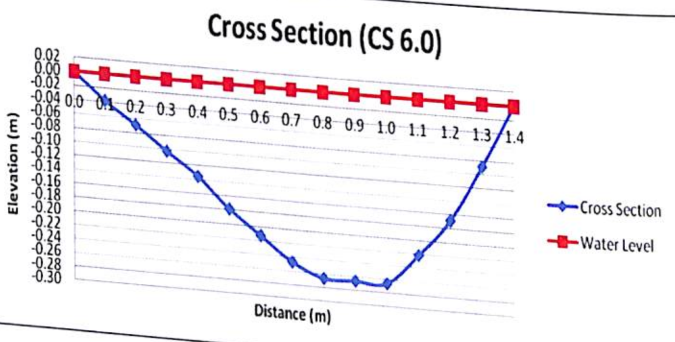
Cross Section (m)	Cross Section Profile
CH 0.0	
CH 1.0	
CH 2.0	
CH 3.0	

Table 4.1: Cross Section Profile of Test channel (Continued)

Cross Section (m)	Cross Section Profile
CH 4.0	
CH 5.0	
CH 6.0	

Linear graph for test channel bed slope are been plotted with depth at center line of each cross section versus longitudinal distance. Figure 4.3 show the linear graph of test channel bed slope.

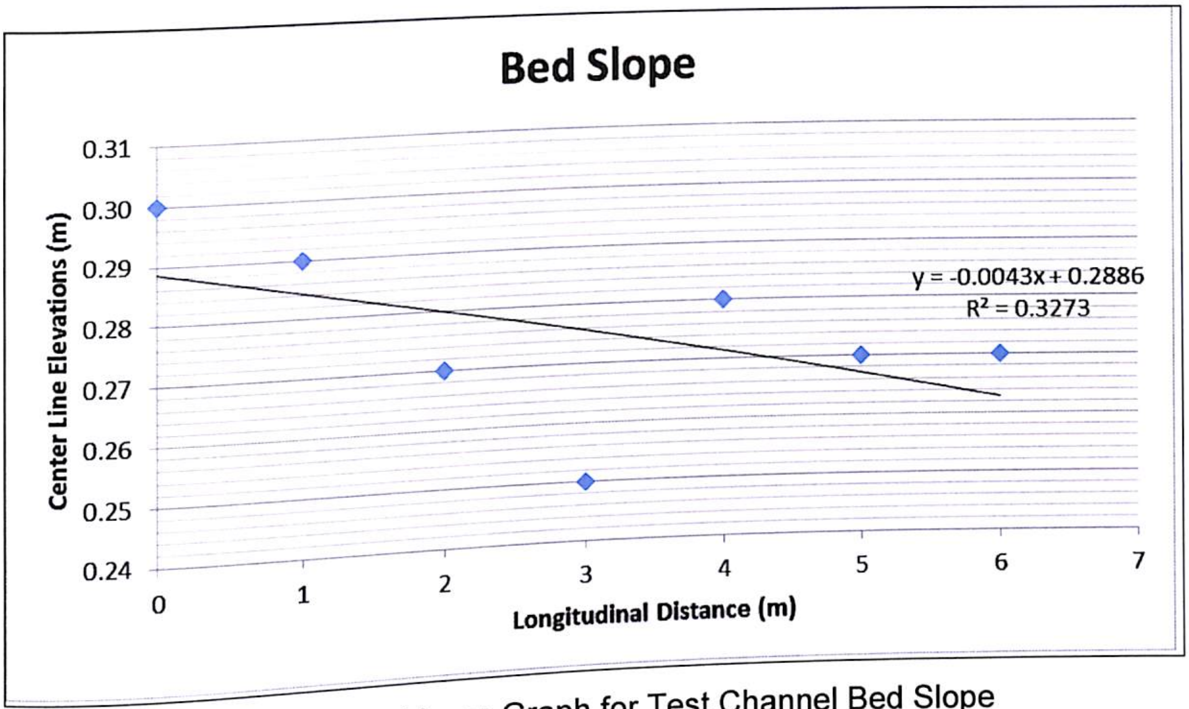


Figure 4.3: Linear Graph for Test Channel Bed Slope

4.1 Flow Measurement

The selected lining material of TRM and ECB were installed over a topsoil and exposed to 1½ hours flow generating escalating levels of hydraulic force/shear stress. The research was designed to simulate field conditions only for unvegetated reinforced vegetated channel lining. There are three (3) different of depth measured from the test channel bed used in the experiment. The depth are 5cm, 10cm and 15cm. Three (3) readings for vertical velocity were recorded by using flow or current meter and then it divided to get the average value for each cross section. Starting with TRM test channel, the average vertical velocity for 10cm depth recorded is in between 0.6m/s to 1.2m/s. The average vertical velocity for 10cm depth recorded is in between 1.6m/s to 1.9m/s. While the average vertical velocity for 15cm depth recorded is in between 3.1m/s to 3.5m/s. The experiment was continued for ECB test channel, the average vertical velocity for 5cm depth recorded is in between 0.7m/s to 1.4m/s. The total average vertical velocity for 10cm depth recorded is in 1.5m/s to 2.7m/s. While the average vertical velocity for 15cm depth recorded is in between 3.2m/s to 4.1m/s. Based on recorded average vertical velocity from different three (3) depths, show that the deeper measurement point the higher vertical velocity.

The formula which is equal to area of flow times the velocity of flow was used to get the volumetric flow rate of each cross section. Based on recorded total value of flow rate for both lining material from different three (3) depths, show that the deeper measurement point the higher flow rate. Table 4.2 and Table 4.3 show the results summary of total average vertical velocity and flow for both lining material used in this research.

Table 4.2: Total Average Vertical Velocity and Flow for TRM Test Channel

Lining Material	Depth (cm)	Cross Section (CH m)	Flow, Q (m^3/s)		Vertical Velocity, v (m/s)	Manning's n
TRM	5.0	0.00	0.0050		0.772	0.025
		1.00	0.0033		0.647	0.039
		2.00	0.0040		0.760	0.037
		3.00	0.0049		0.920	0.019
		4.00	0.0062		1.172	0.015
		Total	**0.0234**	**Ave.**	**0.854**	**0.027**
	10.0	0.00	0.0206		1.840	0.018
		1.00	0.0183		1.823	0.020
		2.00	0.0173		1.893	0.021
		3.00	0.0157		1.693	0.024
		4.00	0.0179		1.697	0.028
		Total	**0.0898**	**Ave.**	**1.789**	**0.022**
	15.0	0.00	0.0451		3.160	0.014
		1.00	0.0436		3.470	0.013
		2.00	0.0453		3.400	0.014
		3.00	0.0439		3.857	0.014
		4.00	0.0458		3.453	0.013
		Total	**0.2237**	**Ave.**	**3.468**	**0.014**

Table 4.3: Total Average Vertical Velocity and Flow for ECB Test Channel

Lining Material	Depth (cm)	Cross Section (CH m)	Flow, Q (m^3/s)		Vertical Velocity, v (m/s)	Manning's n
ECB	5.0	0.00	0.0059		0.783	0.033
		1.00	0.0051		1.007	0.024
		2.00	0.0031		0.780	0.033
		3.00	0.0032		0.782	0.028
		4.00	0.0061		1.347	0.014
		Total	**0.0234**	**Ave.**	**0.940**	**0.026**
	10.0	0.00	0.0179		1.533	0.024
		1.00	0.0117		1.360	0.026
		2.00	0.0130		1.893	0.018
		3.00	0.0121		2.107	0.018
		4.00	0.0164		2.677	0.012
		Total	**0.0711**	**Ave.**	**1.914**	**0.019**
	15.0	0.00	0.0683		4.090	0.013
		1.00	0.0479		3.283	0.017
		2.00	0.0526		3.670	0.013
		3.00	0.0471		3.597	0.015
		4.00	0.0515		3.990	0.012
		Total	**0.2673**	**Ave.**	**3.726**	**0.014**

All the n values presented (Table 4.2 and Figure 4.3) are determined from lab experiment data. The relationship of Manning's n plotted as a function of flow depth for each cross section in tested channel are shown in Figure 4.4 and Figure 4.5. The R^2 value of linear graph for both selected lining material show 0.3581 for TRM and 0.3184 for ECB. The detail calculation for flow discharge of each cross section can be referred to Appendix A and Appendix D.

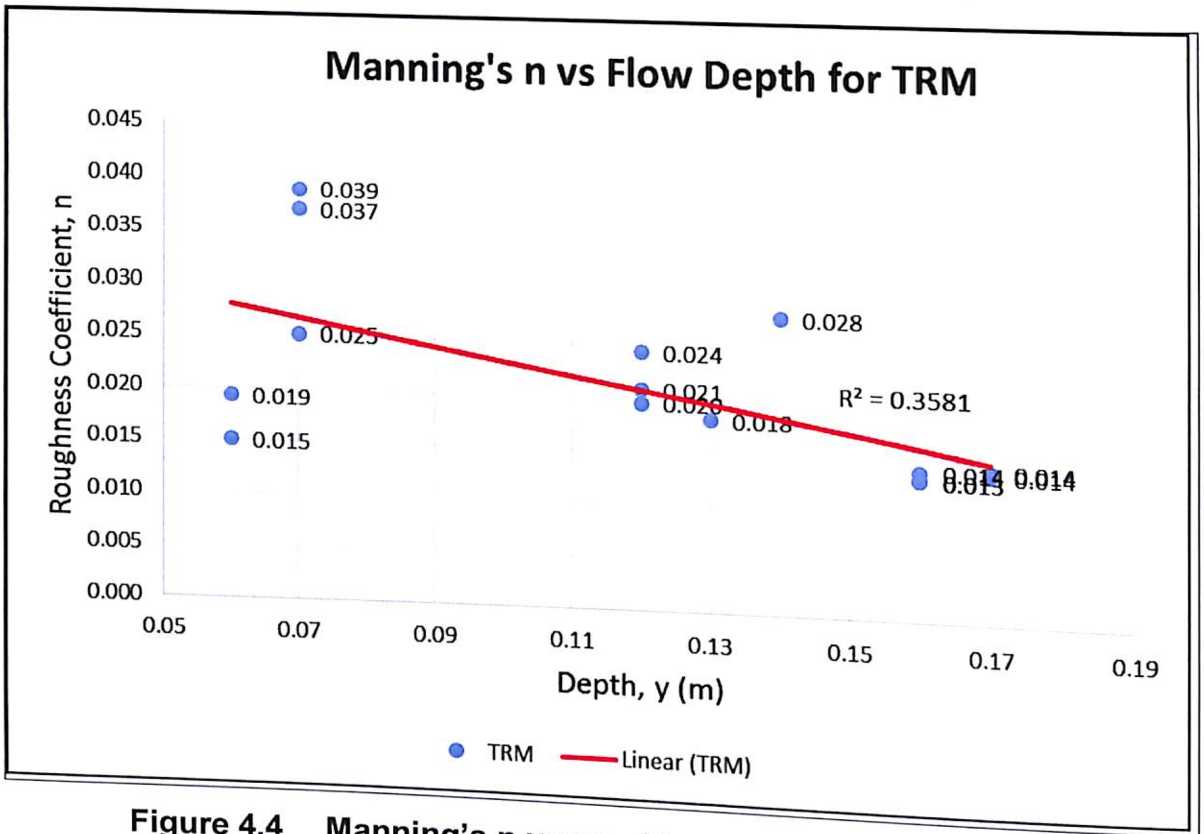


Figure 4.4 Manning's n versus Flow Depth Graph for TRM

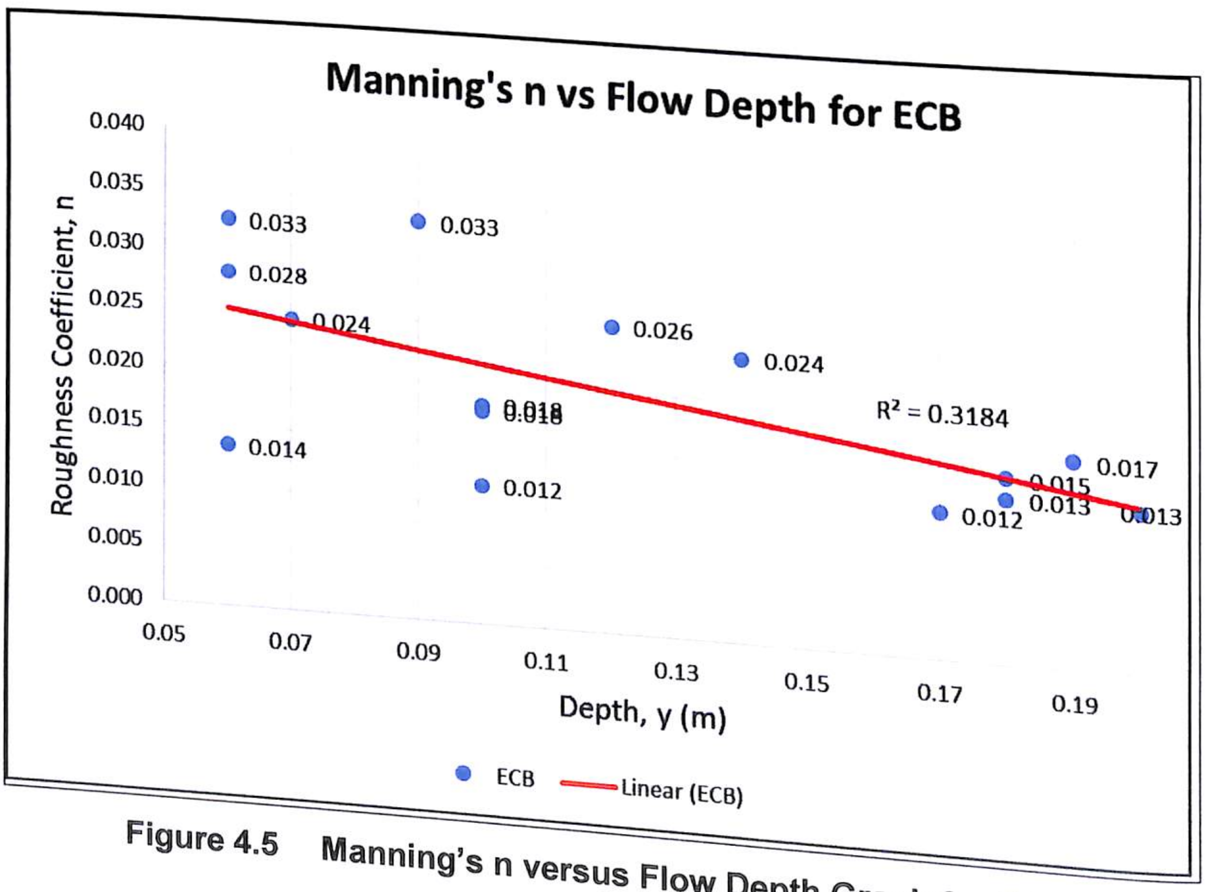


Figure 4.5 Manning's n versus Flow Depth Graph for ECB

4.2 Estimating Shear Stress for Channel Lining Materials

Allowable velocity and allowable shear stress values for a number of different "man-made" channel lining materials are presented in Table 4.4. Data in the table were compiled from many sources. Ranges of allowable velocities and shear stresses, therefore, are presented in the table. For manufactured products, the designer should consult the manufacturer's guidelines to determine thresholds for a specific product (DID, 2009). Table 4.5 show other references for general performance of allowable velocity and shear stress for the TRM and ECB compared to other erosion control products prepared by Greenfix company.

The values in Table 4.4 relate to cross-sectional averaged values. The data typically come from flumes where the flow is uniform and does not exhibit the same level of turbulence as natural channels. The recommended values are empirically derived. The designer should consider modifying tabular values based on site-specific conditions such as duration of flow, soils, temperature, debris in the stream, and plant species, as well as channel shape and planform (Hoag and Fripp 2002).

Table 4.4: Allowable Velocity and Shear Stress for Selected Lining Materials

Boundary Category	Boundary Type	Allowable Velocity (m/s)	Allowable Shear Stress (N/m^2)
Temporary degradable reinforced erosion control products (RECP)	Jute net	0.3-0.8	21
	Straw with net	0.3-0.9	72-79
	Coconut fiber with net	0.9-1.2	107
	Fiberglass roving	0.8-2.1	96
Non-degradable RECP	Unvegetated	1.5-2.1	144
	Partially established	2.3-4.6	192-287
	Fully vegetated	2.4-6.4	383

Table 4.5: Allowable Velocity and Shear Stress for TRM and ECB Compared with Other Erosion Control Products by Greenfix Company

Types of Erosion Control Product	Allowable Velocity (m/s)	Allowable Shear Stress (N/m^2)
Mechanical/Hydro Seeding	N/A	<0.5
Mechanical Mulching	2.0	<0.5
Meshes and Nets	N/A	0.5 – 4.5
Erosion Control Blankets	2.0 – 6.0	1.5 – 2.2
Sod	2.5 – 6.8	0.35 – 3.7
Turf Reinforcement Mat	8.0 – 20.0	2.0 – 10.0
GeoCell Confinement	6.0 – 9.0	4.0 – 8.0
Fabric Formed Revetments	N/A	2.0 – 24.0
Rip Rap (6”to 18”thick)	N/A	2.0 - 5.0
Interlocking Block Mats	15.0 – 26.0	4.4 – 25.0

The allowable velocity and allowable shear stress for two (2) types of temporary degradable RECP from Table 4.4 are been referred and compared. The types of lining material are straw with net for RECP Turf Reinforcement Mat (TRM) and coconut fiber with net for RECP Erosion Control Blanket (ECB). The estimating shear stress for both lining materials in this experiment are typically developed from studies using short durations. The estimate bed and bank shear stress in this experiment are using shear formula which equal to the specific weight of water times hydraulic radius and energy slope. Thus the value for bank shear stress is equal to coefficient K1 (versus side slope and width/depth ratio) times estimate bed shear stress as shown in Figure 3.18 (Chapter 3).

The depth for the bed of 15 cm give the highest values of estimate shear stress for both lining materials. The experiment conducted for TRM lining material gives 0.975 N/m^3 for bed and 1.069 N/m^3 for bank of test channel. While for ECB lining material gives 1.069 N/m^3 for bed and 0.861 N/m^3 for bank of test channel. The

Lining Material	Para				
	Depth from Bed (cm)	Flow, Q (m^3/s)	Vertical Velocity, v (m/s)	Allowable Velocity, v (m/s) (DID, 2012)	B/y (Ave.)
TRM	5	0.023	0.854	0.3 – 0.9	8.071
	10	0.090	1.789		6.096
	15	0.224	3.468		4.861
ECB	5	0.023	0.940	0.9 – 1.2	7.525
	10	0.071	1.914		5.113
	15	0.267	3.726		4.467

depth for the bed of 15cm gives the lowest values of estimate shear stress for both lining materials. Lining material of TRM gives the values 0.486 N/m^3 for bed and 0.385 N/m^3 for bank of test channel. While lining material of ECB gives the values 0.479 N/m^3 for bed and 0.383 N/m^3 for bank of test channel. Based on recorded calculated estimating shear stress from different three (3) depths, show that the deeper measurement point the higher estimate shear stress. Table 4.4 that the summary of estimating of average shear stress for test channel bed show the summary of estimating of average shear stress for test channel bed and bank. The graph in Figure 4.6 to Figure 4.7 shows the average shear stress for both tested material.

Table 4.4: Average Shear Stress for Test Channel Bed and Bank

Lining Material	Parameters							
	Depth from Bed (cm)	Flow, Q (m³/s)	Vertical Velocity, v (m/s)	Allowable Velocity, v (m/s) (DID, 2012)	B/y (Ave.)	Bed Shear Stress, τ_b (N/m²)	Bank Shear Stress, τ_s (N/m²)	Allowable Shear Stress (N/m²) (DID, 2012)
TRM	5	0.023	0.854	0.3 – 0.9	8.071	0.486	0.385	72 - 79
	10	0.090	1.789		6.096	0.784	0.631	
	15	0.224	3.468		4.861	0.975	0.787	
ECB	5	0.023	0.940	0.9 – 1.2	7.525	0.479	0.383	107
	10	0.071	1.914		5.113	0.709	0.569	
	15	0.267	3.726		4.467	1.069	0.861	

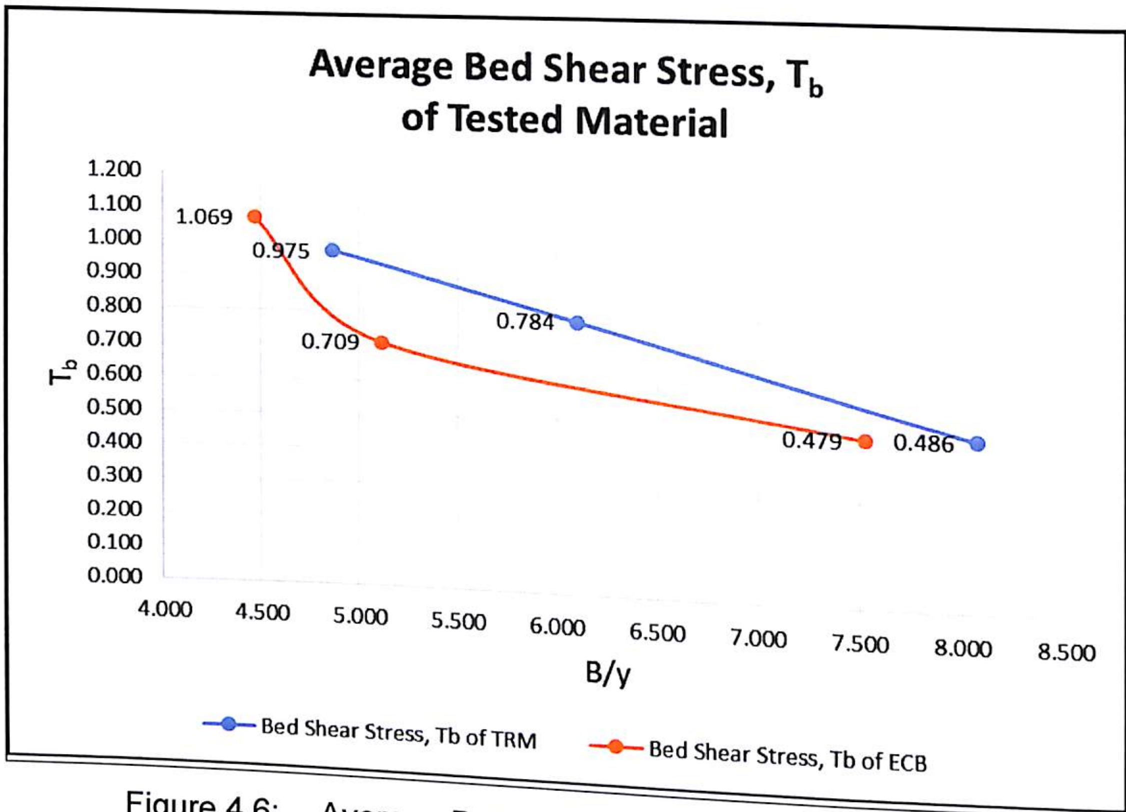


Figure 4.6: Average Bed Shear Stress for Tested Material

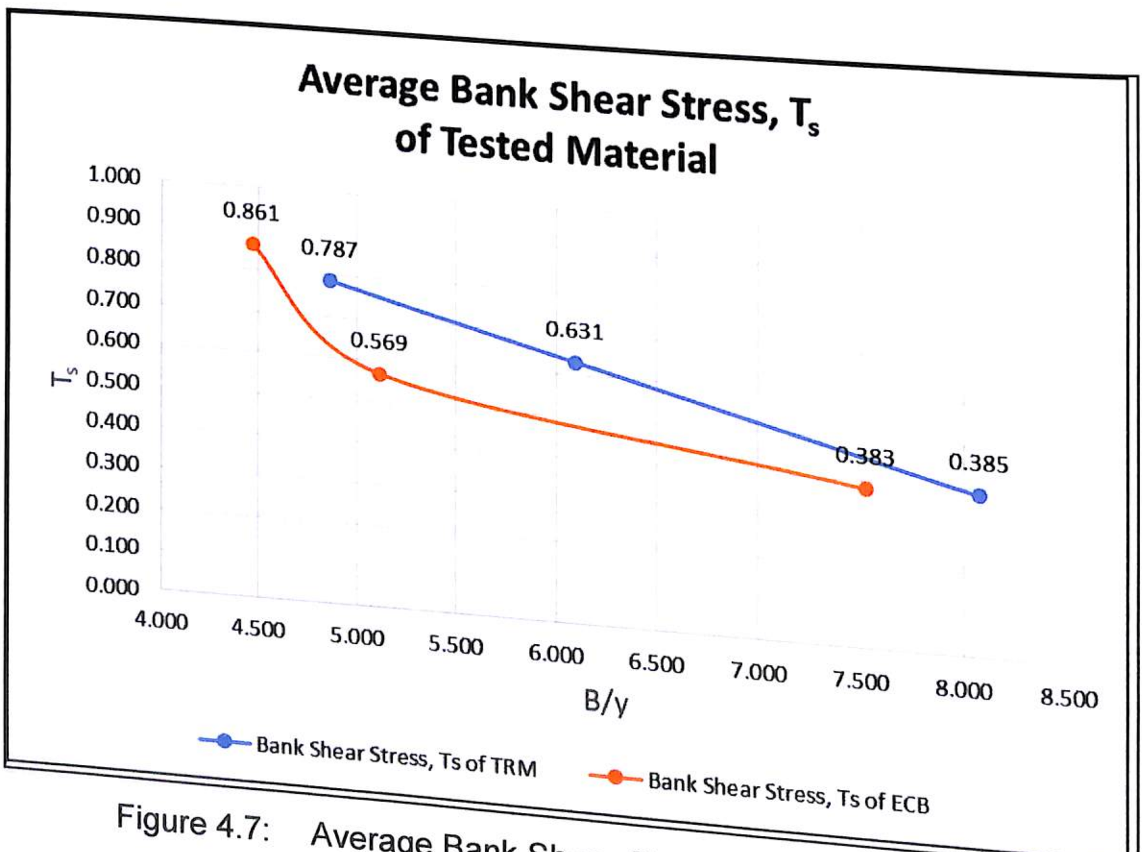


Figure 4.7: Average Bank Shear Stress for Tested Material

The experimental works in the laboratory for unvegetated testing for both tested lining materials, were exposed to flows generating incrementally greater shear stresses from 0.486 N/m^2 up to 0.975 N/m^2 at the channel bed and 0.385 N/m^2 up to 0.787 N/m^2 at the channel bank for lining material of TRM. Same goes to lining material of ECB, were exposed to flows generating incrementally greater shear stresses from 0.479 N/m^2 up to 1.069 N/m^2 at the channel bed and 0.383 N/m^2 up to 0.861 N/m^2 at the channel bank. After each 1½ hours flow, the channel's soil profile was surveyed for soil loss and the matting structure was assessed for physical damage and fiber loss.

Refer to Appendix B and Appendix C for detail calculation of estimate shear stress for TRM test channel bed and bank. While Appendix E and Appendix F will show the detail calculation of estimate shear stress for ECB test channel bed and bank.

CHAPTER5
CONCLUSION

Rolled Erosion Control Product (RECPs) such as Turf Reinforcement Mats (TRM) and Erosion Control Blanket (ECB) has become an acceptable, performance proven, cost effective and environmentally friendly alternative to rock riprap, rock mattresses and other forms of non-vegetative lining materials. There are several design parameters need to take into account include hydraulic data such as shears tress and flow velocity, geometry, slope, vegetation type and product specification/properties. While design shear stress, design velocity, roughness, resiliency, tensile strength, light penetration and UV resistance are the important product properties need to be considered.

Flow generating of shear stress with an average allowable velocity over unvegetated tested materials resulted in no physical damage to the matting. This testing, in conjunction with past research, better quantifies the erosion control and vegetation reinforcement capabilities of the selected lining material and provides further substantiation for the design values of both selected lining material.

The Manning's n value or the roughness coefficient indicates to what extent the surface or the channel will resist flow and is critical in its sizing. The coefficient varies with the type of lining material and the flow depth. The n value for tested lining material obtained from the experimental works was close to the estimated n value from the product manufacturer.

There is a further research study regarding on hydraulic assessment of bioengineering techniques for stable stormwater drainage system. This study will investigate the flow distribution along channel bank in order to assess the channel stability for different bioengineering materials. The result from the assessment then will recommend the suitable bank stability techniques for application in Malaysia. Benefits of the study can be used as guidance in order to ensure the effectiveness and applicability of the techniques for bank stability and protection against erosion especially for urban environment condition.

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APPENDIX A: Calculation of Flow Discharge for TRM

Date: 03/06/2015 (Wednesday) Time: 3.00 pm Location: Physical Modeling Laboratory Cross Section: CH0.00 Depth: 5cm

1	2	3	4	5	6	7			8	9	10	11	12	13	14	15
Distance from Left Bank (m)	Vertical Depth, D (m)	Method of Reading			Vertical Velocity (m/s)						Average Vertical Velocity (m/s)	Section Width (m)	Average Vertical Depth (m)	Section Area (m^2)	Flow, Q (m^3/s)	Remarks
		0.2D	0.6D	0.8D	0.2D	0.6D			0.8D	Average						
0.00	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.50	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.05	0.00	0.000	0.0000	
0.55	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.05	0.00	0.000	0.0000	
0.60	0.03	-	0.018	-	-	0.01	0.01	0.01	-	0.01						
											0.037	0.10	0.05	0.005	0.0002	
0.70	0.06	-	0.036	-	-	0.06	0.06	0.07	-	0.06						
											0.242	0.10	0.07	0.007	0.0016	
0.80	0.07	-	0.042	-	-	0.42	0.43	0.41	-	0.42						
											0.325	0.10	0.07	0.007	0.0023	
0.90	0.07	-	0.042	-	-	0.23	0.23	0.23	-	0.23						
											0.142	0.10	0.07	0.007	0.0009	
1.00	0.06	-	0.036	-	-	0.06	0.05	0.05	-	0.05						
											0.027	0.08	0.03	0.002	0.0001	
1.08	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.02	0.00	0.000	0.0000	
1.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.40	0.00	-	0.00	-	-	0.00	0.00	0.00	-	0.00						
										TOTAL	0.772				0.0050	

Date: 03/06/2015 (Wednesday) Time: 3.15 pm Location: Physical Modeling Laboratory Cross Section: CH1.00 Depth: 5cm

1	2	3	4	5	6	7			8	9	10	11	12	13	14	15
Distance from Left Bank (m)	Vertical Depth, D (m)	Method of Reading			Vertical Velocity (m/s)						Average Vertical Velocity (m/s)	Section Width (m)	Average Vertical Depth (m)	Section Area (m^2)	Flow, Q (m^3/s)	Remarks
		0.2D	0.6D	0.8D	0.2D	0.6D			0.8D	Average						
0.00	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.50	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.02	0.00	0.000	0.0000	
0.52	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.08	0.00	0.000	0.0000	
0.60	0.02	-	0.012	-	-	0.00	0.00	0.00	-	0.00						
											0.075	0.10	0.03	0.003	0.0002	
0.70	0.04	-	0.024	-	-	0.16	0.15	0.14	-	0.15						
											0.193	0.10	0.06	0.006	0.0011	
0.80	0.07	-	0.042	-	-	0.25	0.22	0.24	-	0.24						
											0.188	0.10	0.07	0.007	0.0013	
0.90	0.07	-	0.042	-	-	0.13	0.14	0.15	-	0.14						
											0.130	0.10	0.05	0.005	0.0007	
1.00	0.03	-	0.018	-	-	0.13	0.11	0.12	-	0.12						
											0.060	0.08	0.02	0.001	0.0001	
1.08	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.02	0.00	0.000	0.0000	
1.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.40	0.00	-	0.00	-	-	0.00	0.00	0.00	-	0.00						
										TOTAL	0.647				0.0033	

1	2	3	4	5	6	7			8	9	10	11				15
Distance from Left Bank (m)	Vertical Depth, D (m)	Method of Reading			Vertical Velocity (m/s)						Average Vertical Velocity (m/s)	Section Width (m)	Average Vertical Depth (m)	Section Area (m^2)	Flow, Q (m^3/s)	Remarks
		0.2D	0.6D	0.8D	0.2D	0.6D			0.8D	Average						
0.00	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00	0.000	0.10	0.00	0.000	0.0000	
0.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00	0.000	0.10	0.00	0.000	0.0000	
0.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00	0.000	0.10	0.00	0.000	0.0000	
0.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00	0.000	0.10	0.00	0.000	0.0000	
0.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00	0.000	0.10	0.00	0.000	0.0000	
0.50	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00	0.000	0.10	0.01	0.001	0.0000	
0.60	0.02	-	0.012	-	-	0.00	0.00	0.00	-	0.00	0.087	0.10	0.04	0.004	0.0003	
0.70	0.05	-	0.030	-	-	0.17	0.17	0.18	-	0.17	0.250	0.10	0.06	0.006	0.0015	
0.80	0.07	-	0.042	-	-	0.32	0.34	0.32	-	0.33	0.293	0.10	0.06	0.006	0.0018	
0.90	0.05	-	0.030	-	-	0.25	0.26	0.27	-	0.26	0.130	0.10	0.03	0.003	0.0004	
[illegible]	0.01	-	0.006	-	-	0.00	0.00	0.00	-	0.00	0.000	0.08	0.01	0.000	0.0000	

Date: 03/06/2015 (Wednesday) Time: 3.30 pm Location: Physical Modeling Laboratory Cross Section: CH2.00 Depth: 5cm

1	2	3	4	5	6	7			8	9	10	11	12	13	14	15
Distance from Left Bank (m)	Vertical Depth, D (m)	Method of Reading			Vertical Velocity (m/s)						Average Vertical Velocity (m/s)	Section Width (m)	Average Vertical Depth (m)	Section Area (m^2)	Flow, Q (m^3/s)	Remarks
		0.2D	0.6D	0.8D	0.2D	0.6D			0.8D	Average						
0.00	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.50	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.01	0.001	0.0000	
0.60	0.02	-	0.012	-	-	0.00	0.00	0.00	-	0.00						
											0.087	0.10	0.04	0.004	0.0003	
0.70	0.05	-	0.030	-	-	0.17	0.17	0.18	-	0.17						
											0.250	0.10	0.06	0.006	0.0015	
0.80	0.07	-	0.042	-	-	0.32	0.34	0.32	-	0.33						
											0.293	0.10	0.06	0.006	0.0018	
0.90	0.05	-	0.030	-	-	0.25	0.26	0.27	-	0.26						
											0.130	0.10	0.03	0.003	0.0004	
1.00	0.01	-	0.006	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.08	0.01	0.000	0.0000	
1.08	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.02	0.00	0.000	0.0000	
1.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.40	0.00	-	0.00	-	-	0.00	0.00	0.00	-	0.00						
										TOTAL	0.760				0.0040	

Date: 03/06/2015 (Wednesday) Time: 3.45 pm Location: Physical Modeling Laboratory Cross Section: CH3.00 Depth: 5cm

1	2	3	4	5	6	7			8	9	10	11	12	13	14	15
Distance from Left Bank (m)	Vertical Depth, D (m)	Method of Reading			Vertical Velocity						Average Vertical Velocity (m/s)	Section Width (m)	Average Vertical Depth (m)	Section Area (m^2)	Flow, Q (m^3/s)	Remarks
		0.2D	0.6D	0.8D	0.2D	0.6D			0.8D	Average						
0.00	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.50	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.04	0.00	0.000	0.0000	
0.54	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.06	0.00	0.000	0.0000	
0.60	0.01	-	0.006	-	-	0.00	0.00	0.00	-	0.00						
											0.138	0.10	0.04	0.004	0.0005	
0.70	0.06	-	0.036	-	-	0.28	0.28	0.27	-	0.28						
											0.295	0.10	0.06	0.006	0.0018	
0.80	0.06	-	0.036	-	-	0.31	0.31	0.32	-	0.31						
											0.322	0.10	0.06	0.006	0.0019	
0.90	0.06	-	0.036	-	-	0.34	0.33	0.32	-	0.33						
											0.165	0.10	0.05	0.005	0.0007	
1.00	0.03	-	0.018	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.04	0.02	0.001	0.0000	
1.04	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.06	0.00	0.000	0.0000	
1.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.40	0.00	-	0.00	-	-	0.00	0.00	0.00	-	0.00						
										TOTAL	0.920				0.0049	

Date: 03/06/2015 (Wednesday) Time: 4.00 pm Location: Physical Modeling Laboratory Cross Section: CH4.00 Depth: 5cm

1	2	3	4	5	6	7			8	9	10	11	12	13	14	15
Distance from Left Bank (m)	Vertical Depth, D (m)	Method of Reading			Vertical Velocity						Average Vertical Velocity	Section Width (m)	Average Vertical Depth	Section Area (m^2)	Flow, Q (m^3/s)	Remarks
		0.2D	0.6D	0.8D	0.2D	0.6D			0.8D	Average						
0.00	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.50	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.05	0.00	0.000	0.0000	
0.55	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.05	0.00	0.000	0.0000	
0.60	0.02	-	0.012	-	-	0.22	0.22	0.21	-	0.22						
											0.293	0.10	0.04	0.004	0.0012	
0.70	0.06	-	0.036	-	-	0.36	0.37	0.38	-	0.37						
											0.393	0.10	0.06	0.006	0.0024	
0.80	0.06	-	0.036	-	-	0.42	0.40	0.43	-	0.42						
											0.347	0.10	0.06	0.006	0.0021	
0.90	0.06	-	0.036	-	-	0.27	0.28	0.28	-	0.28						
											0.138	0.10	0.05	0.005	0.0006	
1.00	0.03	-	0.018	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.04	0.02	0.001	0.0000	
1.04	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.06	0.00	0.000	0.0000	
1.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.40	0.00	-	0.00	-	-	0.00	0.00	0.00	-	0.00						
										TOTAL	1.172				0.0062	

Date: 28/05/2015 (Thursday) Time: 10.00 am Location: Physical Modeling Laboratory Cross Section: CH0.00 Depth: 10cm

1	2	3	4	5	6	7			8	9	10	11	12	13	14	15
Distance from Left Bank (m)	Vertical Depth, D (m)	Method of Reading			Vertical Velocity (m/s)						Average Vertical Velocity (m/s)	Section Width (m)	Average Vertical Depth (m)	Section Area (m^2)	Flow, Q (m^3/s)	Remarks
		0.2D	0.6D	0.8D	0.2D	0.6D			0.8D	Average						
0.00	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.04	0.02	0.001	0.0000	
0.44	0.04	-	0.024	-	-	0.00	0.00	0.00	-	0.00						
											0.015	0.06	0.06	0.004	0.0001	
0.50	0.08	-	0.048	-	-	0.03	0.02	0.04	-	0.03						
											0.112	0.10	0.10	0.010	0.0011	
0.60	0.11	-	0.066	-	-	0.21	0.19	0.18	-	0.19						
											0.382	0.10	0.12	0.012	0.0046	
0.70	0.13	-	0.078	-	-	0.58	0.56	0.57	-	0.57						
											0.560	0.10	0.13	0.013	0.0073	
0.80	0.13	-	0.078	-	-	0.54	0.55	0.56	-	0.55						
											0.523	0.10	0.12	0.012	0.0063	
0.90	0.11	-	0.066	-	-	0.48	0.50	0.51	-	0.50						
											0.248	0.10	0.06	0.006	0.0014	
1.00	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.40	0.00	-	0.00	-	-	0.00	0.00	0.00	-	0.00						
														TOTAL	0.0206	

Date: 28/05/2015 (Thursday) Time: 10.15 am Location: Physical Modeling Laboratory Cross Section: CH1.00 Depth: 10cm

1	2	3	4	5	6	7			8	9	10	11	12	13	14	15
Distance from Left Bank (m)	Vertical Depth, D (m)	Method of Reading			Vertical Velocity (m/s)						Average Vertical Velocity (m/s)	Section Width (m)	Average Vertical Depth (m)	Section Area (m^2)	Flow, Q (m^3/s)	Remarks
		0.2D	0.6D	0.8D	0.2D	0.6D			0.8D	Average						
0.00	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.073	0.10	0.04	0.004	0.0003	
0.50	0.07	-	0.042	-	-	0.16	0.13	0.15	-	0.15						
											0.225	0.10	0.09	0.009	0.0019	
0.60	0.10	-	0.060	-	-	0.30	0.31	0.30	-	0.30						
											0.375	0.10	0.11	0.011	0.0041	
0.70	0.12	-	0.072	-	-	0.43	0.45	0.46	-	0.45						
											0.463	0.10	0.12	0.012	0.0056	
0.80	0.12	-	0.072	-	-	0.47	0.49	0.48	-	0.48						
											0.463	0.10	0.11	0.011	0.0051	
0.90	0.10	-	0.060	-	-	0.43	0.45	0.46	-	0.45						
											0.223	0.10	0.06	0.006	0.0013	
1.00	0.02	-	0.012	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.01	0.001	0.0000	
1.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.04	0.00	0.000	0.0000	
1.14	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.06	0.00	0.000	0.0000	
1.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.40	0.00	-	0.00	-	-	0.00	0.00	0.00	-	0.00						
														TOTAL	0.0183	

Date: 28/05/2015 (Thursday) Time: 10.30 am Location: Physical Modeling Laboratory Cross Section: CH2.00 Depth: 10cm

1	2	3	4	5	6	7			8	9	10	11	12	13	14	15
Distance from Left Bank (m)	Vertical Depth, D (m)	Method of Reading			Vertical Velocity (m/s)						Average Vertical Velocity (m/s)	Section Width (m)	Average Vertical Depth (m)	Section Area (m^2)	Flow, Q (m^3/s)	Remarks
		0.2D	0.6D	0.8D	0.2D	0.6D			0.8D	Average						
0.00	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.075	0.06	0.02	0.001	0.0001	
0.46	0.04	-	0.024	-	-	0.14	0.15	0.16	-	0.15						
											0.227	0.04	0.06	0.002	0.0005	
0.50	0.08	-	0.048	-	-	0.30	0.31	0.30	-	0.30						
											0.333	0.10	0.10	0.010	0.0033	
0.60	0.12	-	0.072	-	-	0.37	0.36	0.36	-	0.36						
											0.398	0.10	0.12	0.012	0.0048	
0.70	0.12	-	0.072	-	-	0.42	0.44	0.44	-	0.43						
											0.430	0.10	0.12	0.012	0.0049	
0.80	0.11	-	0.066	-	-	0.43	0.41	0.44	-	0.43						
											0.322	0.10	0.10	0.010	0.0031	
0.90	0.08	-	0.048	-	-	0.21	0.22	0.22	-	0.22						
											0.108	0.10	0.05	0.005	0.0005	
1.00	0.02	-	0.012	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.01	0.001	0.0000	
1.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.05	0.00	0.000	0.0000	
1.15	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.05	0.00	0.000	0.0000	
1.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.40	0.00	-	0.00	-	-	0.00	0.00	0.00	-	0.00						
														TOTAL	0.0173	

Date: 28/05/2015 (Thursday) Time: 10.45 am Location: Physical Modeling Laboratory Cross Section: CH3.00 Depth: 10cm

1	2	3	4	5	6	7			8	9	10	11	12	13	14	15
Distance from Left Bank (m)	Vertical Depth, D (m)	Method of Reading			Vertical Velocity						Average Vertical Velocity (m/s)	Section Width (m)	Average Vertical Depth (m)	Section Area (m^2)	Flow, Q (m^3/s)	Remarks
		0.2D	0.6D	0.8D	0.2D	0.6D			0.8D	Average						
0.00	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.102	0.10	0.02	0.002	0.0002	
0.40	0.04	-	0.024	-	-	0.21	0.20	0.20	-	0.20						
											0.237	0.10	0.06	0.006	0.0014	
0.50	0.08	-	0.048	-	-	0.26	0.27	0.28	-	0.27						
											0.283	0.10	0.10	0.010	0.0027	
0.60	0.11	-	0.066	-	-	0.30	0.29	0.30	-	0.30						
											0.302	0.10	0.12	0.012	0.0035	
0.70	0.12	-	0.072	-	-	0.31	0.31	0.30	-	0.31						
											0.333	0.10	0.12	0.012	0.0040	
0.80	0.12	-	0.072	-	-	0.36	0.36	0.36	-	0.36						
											0.308	0.10	0.11	0.011	0.0032	
0.90	0.09	-	0.054	-	-	0.25	0.25	0.27	-	0.26						
											0.128	0.10	0.06	0.006	0.0007	
1.00	0.02	-	0.012	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.01	0.001	0.0000	
1.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.03	0.00	0.000	0.0000	
1.13	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.07	0.00	0.000	0.0000	
1.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.40	0.00	-	0.00	-	-	0.00	0.00	0.00	-	0.00						
														TOTAL	0.0157	

Date: 28/05/2015 (Thursday) Time: 11.00 am Location: Physical Modeling Laboratory Cross Section: CH4.00 Depth: 10cm

1	2	3	4	5	6	7			8	9	10	11	12	13	14	15
Distance from Left Bank (m)	Vertical Depth, D (m)	Method of Reading			Vertical Velocity						Average Vertical Velocity (m/s)	Section Width (m)	Average Vertical Depth (m)	Section Area (m^2)	Flow, Q (m^3/s)	Remarks
		0.2D	0.6D	0.8D	0.2D	0.6D			0.8D	Average						
0.00	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.025	0.10	0.02	0.002	0.0000	
0.40	0.03	-	0.018	-	-	0.05	0.05	0.05	-	0.05						
											0.087	0.10	0.06	0.006	0.0005	
0.50	0.08	-	0.048	-	-	0.12	0.14	0.11	-	0.12						
											0.202	0.10	0.11	0.011	0.0021	
0.60	0.13	-	0.078	-	-	0.29	0.27	0.28	-	0.28						
											0.320	0.10	0.14	0.014	0.0043	
0.70	0.14	-	0.084	-	-	0.37	0.35	0.36	-	0.36						
											0.383	0.10	0.14	0.014	0.0052	
0.80	0.13	-	0.078	-	-	0.40	0.40	0.42	-	0.41						
											0.353	0.10	0.12	0.012	0.0041	
0.90	0.10	-	0.060	-	-	0.29	0.30	0.31	-	0.30						
											0.238	0.10	0.07	0.007	0.0015	
1.00	0.03	-	0.018	-	-	0.17	0.18	0.18	-	0.18						
											0.088	0.10	0.02	0.002	0.0001	
1.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.05	0.00	0.000	0.0000	
1.15	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.05	0.00	0.000	0.0000	
1.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.40	0.00	-	0.00	-	-	0.00	0.00	0.00	-	0.00						
														TOTAL	0.0179	

Date: 11/06/2015 (Friday) Time: 10.00 am Location: Physical Modeling Laboratory Cross Section: CH0.00 Depth: 15cm

1	2	3	4	5	6	7			8	9	10	11	12	13	14	15
Distance from Left Bank (m)	Vertical Depth, D (m)	Method of Reading			Vertical Velocity (m/s)						Average Vertical Velocity (m/s)	Section Width (m)	Average Vertical Depth (m)	Section Area (m^2)	Flow, Q (m^3/s)	Remarks
		0.2D	0.6D	0.8D	0.2D	0.6D			0.8D	Average						
0.00	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.05	0.00	0.000	0.0000	
0.35	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.05	0.01	0.001	0.0000	
0.40	0.02	-	0.012	-	-	0.00	0.00	0.00	-	0.00						
											0.010	0.10	0.04	0.004	0.0000	
0.50	0.06	-	0.036	-	-	0.01	0.02	0.03	-	0.02						
											0.022	0.10	0.09	0.009	0.0002	
0.60	0.11	-	0.066	-	-	0.02	0.02	0.03	-	0.02						
											0.162	0.10	0.11	0.011	0.0018	
0.70	0.11	-	0.066	-	-	0.32	0.29	0.29	-	0.30						
											0.560	0.10	0.14	0.014	0.0078	
0.80	0.17	-	0.102	-	-	0.79	0.84	0.83	-	0.82						
											0.795	0.10	0.17	0.017	0.0135	
0.90	0.17	-	0.102	-	-	0.78	0.77	0.76	-	0.77						
											0.815	0.10	0.17	0.017	0.0134	
1.00	0.16	-	0.096	-	-	0.86	0.88	0.84	-	0.86						
											0.613	0.10	0.13	0.013	0.0080	
1.10	0.10	-	0.060	-	-	0.37	0.35	0.38	-	0.37						
											0.183	0.04	0.05	0.002	0.0004	
1.14	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.06	0.00	0.000	0.0000	
1.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
										TOTAL	3.160				0.0451	

Date: 11/06/2015 (Friday) Time: 10.15 am Location: Physical Modeling Laboratory Cross Section: CH1.00 Depth: 15cm

1	2	3	4	5	6	7			8	9	10	11	12	13	14	15
Distance from Left Bank (m)	Vertical Depth, D (m)	Method of Reading			Vertical Velocity (m/s)						Average Vertical Velocity (m/s)	Section Width (m)	Average Vertical Depth (m)	Section Area (m^2)	Flow, Q (m^3/s)	Remarks
		0.2D	0.6D	0.8D	0.2D	0.6D			0.8D	Average						
0.00	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.07	0.00	0.000	0.0000	
0.37	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.03	0.01	0.000	0.0000	
0.40	0.02	-	0.012	-	-	0.00	0.00	0.00	-	0.00						
											0.043	0.10	0.04	0.004	0.0002	
0.50	0.05	-	0.030	-	-	0.06	0.11	0.09	-	0.09						
											0.182	0.10	0.08	0.008	0.0015	
0.60	0.11	-	0.066	-	-	0.27	0.28	0.28	-	0.28						
											0.383	0.10	0.12	0.012	0.0046	
0.70	0.13	-	0.078	-	-	0.49	0.49	0.49	-	0.49						
											0.583	0.10	0.14	0.014	0.0082	
0.80	0.15	-	0.090	-	-	0.68	0.67	0.68	-	0.68						
											0.747	0.10	0.16	0.016	0.0116	
0.90	0.16	-	0.096	-	-	0.83	0.81	0.81	-	0.82						
											0.790	0.10	0.15	0.015	0.0119	
1.00	0.14	-	0.084	-	-	0.76	0.77	0.76	-	0.76						
											0.562	0.10	0.10	0.010	0.0056	
1.10	0.06	-	0.036	-	-	0.36	0.37	0.35	-	0.36						
											0.180	0.04	0.03	0.001	0.0002	
1.14	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.06	0.00	0.000	0.0000	
1.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
										TOTAL	3.470				0.0436	

Date: 11/06/2015 (Friday) Time: 10.30 am Location: Physical Modeling Laboratory Cross Section: CH2.00 Depth: 15cm

1	2	3	4	5	6	7			8	9	10	11	12	13	14	15
Distance from Left Bank (m)	Vertical Depth, D (m)	Method of Reading			Vertical Velocity (m/s)						Average Vertical Velocity (m/s)	Section Width (m)	Average Vertical Depth (m)	Section Area (m^2)	Flow, Q (m^3/s)	Remarks
		0.2D	0.6D	0.8D	0.2D	0.6D			0.8D	Average						
0.00	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.040	0.10	0.02	0.002	0.0001	
0.40	0.03	-	0.018	-	-	0.08	0.07	0.09	-	0.08						
											0.147	0.10	0.05	0.005	0.0007	
0.50	0.07	-	0.042	-	-	0.21	0.20	0.23	-	0.21						
											0.352	0.10	0.10	0.010	0.0033	
0.60	0.12	-	0.072	-	-	0.50	0.49	0.48	-	0.49						
											0.560	0.10	0.14	0.014	0.0078	
0.70	0.16	-	0.096	-	-	0.64	0.63	0.62	-	0.63						
											0.670	0.10	0.17	0.017	0.0111	
0.80	0.17	-	0.102	-	-	0.70	0.73	0.70	-	0.71						
											0.715	0.10	0.17	0.017	0.0122	
0.90	0.17	-	0.102	-	-	0.70	0.73	0.73	-	0.72						
											0.508	0.10	0.15	0.015	0.0074	
1.00	0.12	-	0.072	-	-	0.30	0.29	0.30	-	0.30						
											0.278	0.10	0.09	0.009	0.0025	
1.10	0.06	-	0.036	-	-	0.26	0.27	0.25	-	0.26						
											0.130	0.06	0.03	0.002	0.0002	
1.16	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.04	0.00	0.000	0.0000	
1.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
										TOTAL	3.400				0.0453	

Date: 11/06/2015 (Friday) Time: 10.45 am Location: Physical Modeling Laboratory Cross Section: CH3.00 Depth: 15cm

1	2	3	4	5	6	7			8	9	10	11	12	13	14	15
Distance from Left Bank (m)	Vertical Depth, D (m)	Method of Reading			Vertical Velocity						Average Vertical Velocity (m/s)	Section Width (m)	Average Vertical Depth (m)	Section Area (m^2)	Flow, Q (m^3/s)	Remarks
		0.2D	0.6D	0.8D	0.2D	0.6D			0.8D	Average						
0.00	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.04	0.00	0.000	0.0000	
0.34	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.130	0.06	0.01	0.001	0.0001	
0.40	0.02	-	0.012	-	-	0.27	0.26	0.25	-	0.26						
											0.283	0.10	0.05	0.005	0.0013	
0.50	0.07	-	0.042	-	-	0.30	0.31	0.31	-	0.31						
											0.415	0.10	0.08	0.008	0.0033	
0.60	0.09	-	0.054	-	-	0.51	0.53	0.53	-	0.52						
											0.528	0.10	0.12	0.012	0.0061	
0.70	0.14	-	0.084	-	-	0.55	0.53	0.52	-	0.53						
											0.583	0.10	0.15	0.015	0.0088	
0.80	0.16	-	0.096	-	-	0.60	0.65	0.65	-	0.63						
											0.657	0.10	0.16	0.016	0.0105	
0.90	0.16	-	0.096	-	-	0.68	0.67	0.69	-	0.68						
											0.625	0.10	0.15	0.015	0.0091	
1.00	0.13	-	0.078	-	-	0.58	0.57	0.56	-	0.57						
											0.460	0.10	0.10	0.010	0.0044	
1.10	0.06	-	0.036	-	-	0.36	0.33	0.36	-	0.35						
											0.175	0.08	0.03	0.002	0.0004	
1.18	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.02	0.00	0.000	0.0000	
1.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
										TOTAL	3.857				0.0439	

Date: 11/06/2015 (Friday) Time: 11.00 am Location: Physical Modeling Laboratory Cross Section: CH4.00 Depth: 15cm

1	2	3	4	5	6	7			8	9	10	11	12	13	14	15
Distance from Left Bank (m)	Vertical Depth, D (m)	Method of Reading			Vertical Velocity						Average Vertical Velocity	Section Width (m)	Average Vertical Depth	Section Area (m^2)	Flow, Q (m^3/s)	Remarks
		0.2D	0.6D	0.8D	0.2D	0.6D			0.8D	Average						
0.00	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.06	0.00	0.000	0.0000	
0.36	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.04	0.01	0.000	0.0000	
0.40	0.01	-	0.006	-	-	0.00	0.00	0.00	-	0.00						
											0.165	0.10	0.04	0.004	0.0006	
0.50	0.06	-	0.036	-	-	0.34	0.33	0.32	-	0.33						
											0.372	0.10	0.10	0.010	0.0037	
0.60	0.14	-	0.084	-	-	0.43	0.40	0.41	-	0.41						
											0.467	0.10	0.15	0.015	0.0070	
0.70	0.16	-	0.096	-	-	0.52	0.51	0.53	-	0.52						
											0.573	0.10	0.16	0.016	0.0092	
0.80	0.16	-	0.096	-	-	0.63	0.64	0.61	-	0.63						
											0.657	0.10	0.16	0.016	0.0105	
0.90	0.16	-	0.096	-	-	0.69	0.68	0.69	-	0.69						
											0.637	0.10	0.16	0.016	0.0099	
1.00	0.15	-	0.090	-	-	0.59	0.58	0.59	-	0.59						
											0.438	0.10	0.11	0.011	0.0046	
1.10	0.06	-	0.036	-	-	0.29	0.27	0.31	-	0.29						
											0.145	0.08	0.03	0.002	0.0003	
1.18	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.02	0.00	0.000	0.0000	
1.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
										TOTAL	3.453				0.0458	

APPENDIX B: Calculation of Bed Shear Stress for TRM

Bed Shear Stress, τ_b (N/m^2)_5cm - 03/06/15

Station	Top Width, B_{top} (m)	Bottom Width, B_{bottom} (m)	Depth, y (m)	Area, A (m^2)	x_1 (m)	y_1 (m)	x_2 (m)	y_2 (m)	Wetted Perimeter, P (m)	Hydraulic Radius, R (m)
0	0.53	0.3	0.07	0.029	0.15	0.07	0.08	0.07	0.572	0.051
1	0.56	0.3	0.07	0.030	0.18	0.07	0.08	0.07	0.599	0.050
2	0.58	0.3	0.07	0.031	0.10	0.07	0.08	0.07	0.528	0.058
3	0.50	0.3	0.06	0.024	0.16	0.06	0.04	0.06	0.543	0.044
4	0.49	0.3	0.06	0.024	0.15	0.06	0.04	0.06	0.534	0.044

Continued

Kinematic Viscosity, v (m^2/s)	Discharge, Q (m^3/s)	Velocity, V (m/s)	Manning's n	Reynold Number, Re	Specific Weight of Water, λ_D (N/m^2)	Energy Slope, S (m/m)	Bed Shear Stress, τ_b (N/m^3)
0.000001	0.0050	0.772	0.025	156876	9806	0.001	0.498
0.000001	0.0033	0.647	0.039	129954	9806	0.001	0.492
0.000001	0.0040	0.760	0.037	177210	9806	0.001	0.572
0.000001	0.0049	0.920	0.019	162655	9806	0.001	0.433
0.000001	0.0062	1.172	0.015	208193	9806	0.001	0.435

Bed Shear Stress, τ_b (N/m^2)_10cm - 28/05/15

Station	Top Width, B_{top} (m)	Bottom Width, B_{bottom} (m)	Depth, y (m)	Area, A (m^2)	x_1 (m)	y_1 (m)	x_2 (m)	y_2 (m)	Wetted Perimeter, P (m)	Hydraulic Radius, R (m)
0	0.66	0.3	0.13	0.062	0.26	0.13	0.10	0.13	0.755	0.083
1	0.74	0.3	0.12	0.062	0.30	0.12	0.14	0.12	0.808	0.077
2	0.75	0.3	0.12	0.063	0.30	0.12	0.15	0.12	0.815	0.077
3	0.83	0.3	0.12	0.068	0.40	0.12	0.13	0.12	0.895	0.076
4	0.85	0.3	0.14	0.081	0.40	0.14	0.15	0.14	0.929	0.087

Continued

Kinematic Viscosity, v (m^2/s)	Discharge, Q (m^3/s)	Velocity, V (m/s)	Manning's n	Reynold Number, Re	Specific Weight of Water, λ_D (N/m^2)	Energy Slope, S (m/m)	Bed Shear Stress, τ_b (N/m^3)
0.000001	0.0206	0.772	0.014	255321	9806	0.001	0.811
0.000001	0.0183	0.647	0.013	199989	9806	0.001	0.758
0.000001	0.0173	0.760	0.014	234935	9806	0.001	0.758
0.000001	0.0157	0.920	0.014	278922	9806	0.001	0.743
0.000001	0.0179	1.172	0.013	406237	9806	0.001	0.850

Bed Shear Stress, τ_b (N/m^2)_15cm - 11/06/15

Station	Top Width, B_{top} (m)	Bottom Width, B_{bottom} (m)	Depth, y (m)	Area, A (m^2)	x_1 (m)	y_1 (m)	x_2 (m)	y_2 (m)	Wetted Perimeter, P (m)	Hydraulic Radius, R (m)
0	0.79	0.3	0.17	0.093	0.35	0.17	0.14	0.17	0.909	0.102
1	0.77	0.3	0.16	0.086	0.33	0.16	0.14	0.16	0.879	0.097
2	0.76	0.3	0.17	0.090	0.30	0.17	0.16	0.17	0.878	0.103
3	0.84	0.3	0.16	0.091	0.36	0.16	0.18	0.16	0.935	0.098
4	0.82	0.3	0.16	0.090	0.34	0.16	0.18	0.16	0.917	0.098

Continued

Kinematic Viscosity, v (m^2/s)	Discharge, Q (m^3/s)	Velocity, V (m/s)	Manning's n	Reynold Number, Re	Specific Weight of Water, λ_D (N/m^2)	Energy Slope, S (m/m)	Bed Shear Stress, τ_b (N/m^3)
0.000001	0.0451	0.772	0.014	314631	9806	0.001	0.999
0.000001	0.0436	0.647	0.013	251929	9806	0.001	0.955
0.000001	0.0453	0.760	0.014	311867	9806	0.001	1.006
0.000001	0.0439	0.920	0.014	359030	9806	0.001	0.957
0.000001	0.0458	1.172	0.013	458265	9806	0.001	0.959

APPENDIX C: Calculation of Bank Shear Stress for TRM

Bank Shear Stress, τ_s (N/m^2)_5cm - Turf Reinforcement Mat (TRM)(03/06/15)

Station	Top Width, B (m)	Depth, y (m)	B/y	Side Slope, z_1	Side Slope, z_2	MSMA Chapter 3 - Table 3.5			Bed Shear Stress, τ_b (N/m^3)	Bank Shear Stress, τ_s (N/m^3)
						Coefficient, K for z_1	Coefficient, K for z_2	Average K		
0	0.53	0.07	7.571	1	2	0.780	0.810	0.795	0.498	0.396
1	0.56	0.07	8.000	1	2	0.770	0.810	0.790	0.492	0.389
2	0.58	0.07	8.286	1	2	0.770	0.810	0.790	0.572	0.452
3	0.50	0.06	8.333	1	2	0.770	0.810	0.790	0.433	0.342
4	0.49	0.06	8.167	1	2	0.770	0.810	0.790	0.435	0.344
	Average		8.071			Average			0.486	0.385

* K < 1.0

Bank Shear Stress, τ_s (N/m^2)_10cm - Turf Reinforcement Mat (TRM)(28/05/15)

Station	Top Width, B (m)	Depth, y (m)	B/y	Side Slope, z_1	Side Slope, z_2	MSMA Chapter 3 - Table 3.5			Bed Shear Stress, τ_b (N/m^3)	Bank Shear Stress, τ_s (N/m^3)
						Coefficient, K for z_1	Coefficient, K for z_2	Average K		
0	0.66	0.13	5.077	1	2	0.800	0.820	0.810	0.811	0.657
1	0.74	0.12	6.167	1	2	0.790	0.820	0.805	0.758	0.610
2	0.75	0.12	6.250	1	2	0.780	0.820	0.800	0.758	0.606
3	0.83	0.12	6.917	1	2	0.775	0.820	0.798	0.743	0.593
4	0.85	0.14	6.071	1	2	0.800	0.820	0.810	0.850	0.688
	Average		6.096			Average			0.784	0.631

* K < 1.0

Bank Shear Stress, τ_s (N/m^2)_15cm - Turf Reinforcement Mat (TRM)(11/06/15)

Station	Top Width, B (m)	Depth, y (m)	B/y	Side Slope, z_1	Side Slope, z_2	MSMA Chapter 3 - Table 3.5			Bed Shear Stress, τ_b (N/m^3)	Bank Shear Stress, τ_s (N/m^3)
						Coefficient, K for z_1	Coefficient, K for z_2	Average K		
0	0.79	0.17	4.647	1	2	0.800	0.825	0.813	0.999	0.812
1	0.77	0.16	4.813	1	2	0.790	0.825	0.808	0.955	0.771
2	0.76	0.17	4.471	1	2	0.800	0.825	0.813	1.006	0.817
3	0.84	0.16	5.250	1	2	0.780	0.825	0.803	0.957	0.768
4	0.82	0.16	5.125	1	2	0.780	0.825	0.803	0.959	0.769
	Average		4.861			Average			0.975	0.787

* K < 1.0

APPENDIX D: Calculation of Flow Discharge for ECB

Date: 18/06/2015 (Thursday) Time: 11.30 am Location: Physical Modeling Laboratory Cross Section: CH0.00 Depth: 5cm

1	2	3	4	5	6	7			8	9	10	11	12	13	14	15
Distance from Left Bank (m)	Vertical Depth, D (m)	Method of Reading			Vertical Velocity (m/s)						Average Vertical Velocity (m/s)	Section Width (m)	Average Vertical Depth (m)	Section Area (m^2)	Flow, Q (m^3/s)	Remarks
		0.2D	0.6D	0.8D	0.2D	0.6D			0.8D	Average						
0.00	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.50	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.03	0.003	0.0000	
0.60	0.05	-	0.030	-	-	0.00	0.00	0.00	-	0.00						
											0.010	0.10	0.06	0.006	0.0001	
0.70	0.06	-	0.036	-	-	0.02	0.01	0.03	-	0.02						
											0.107	0.10	0.07	0.007	0.0007	
0.80	0.08	-	0.048	-	-	0.19	0.19	0.20	-	0.19						
											0.338	0.10	0.09	0.009	0.0029	
0.90	0.09	-	0.054	-	-	0.48	0.48	0.49	-	0.48						
											0.285	0.10	0.08	0.008	0.0021	
1.00	0.06	-	0.036	-	-	0.09	0.09	0.08	-	0.09						
											0.043	0.09	0.03	0.003	0.0001	
1.09	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.03	0.003	0.0000	
1.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.11	0.00	0.000	0.0000	
1.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
										TOTAL	0.783			TOTAL	0.0059	

Date: 18/06/2015 (Thursday) Time: 11.45 am Location: Physical Modeling Laboratory Cross Section: CH1.00 Depth: 5cm

1	2	3	4	5	6	7			8	9	10	11	12	13	14	15
Distance from Left Bank (m)	Vertical Depth, D (m)	Method of Reading			Vertical Velocity (m/s)						Average Vertical Velocity (m/s)	Section Width (m)	Average Vertical Depth (m)	Section Area (m^2)	Flow, Q (m^3/s)	Remarks
		0.2D	0.6D	0.8D	0.2D	0.6D			0.8D	Average						
0.00	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.50	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.02	0.00	0.000	0.0000	
0.52	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.030	0.08	0.02	0.002	0.0000	
0.60	0.04	-	0.024	-	-	0.06	0.06	0.06	-	0.06						
											0.083	0.10	0.05	0.005	0.0004	
0.70	0.06	-	0.036	-	-	0.11	0.11	0.10	-	0.11						
											0.178	0.10	0.07	0.007	0.0012	
0.80	0.07	-	0.042	-	-	0.25	0.25	0.25	-	0.25						
											0.290	0.10	0.07	0.007	0.0019	
0.90	0.06	-	0.036	-	-	0.33	0.33	0.33	-	0.33						
											0.252	0.10	0.05	0.005	0.0013	
1.00	0.04	-	0.024	-	-	0.17	0.18	0.17	-	0.17						
											0.087	0.05	0.04	0.002	0.0002	
1.05	0.04	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.087	0.10	0.02	0.002	0.0002	
1.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
										TOTAL	1.007			TOTAL	0.0051	

Date: 18/06/2015 (Thursday) Time: 12.00 am Location: Physical Modeling Laboratory Cross Section: CH2.00 Depth: 5cm

1	2	3	4	5	6	7			8	9	10	11	12	13	14	15
Distance from Left Bank (m)	Vertical Depth, D (m)	Method of Reading			Vertical Velocity (m/s)						Average Vertical Velocity (m/s)	Section Width (m)	Average Vertical Depth (m)	Section Area (m^2)	Flow, Q (m^3/s)	Remarks
		0.2D	0.6D	0.8D	0.2D	0.6D			0.8D	Average						
0.00	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.50	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.040	0.10	0.02	0.002	0.0001	
0.60	0.04	-	0.024	-	-	0.08	0.08	0.08	-	0.08						
											0.100	0.10	0.05	0.005	0.0005	
0.70	0.05	-	0.030	-	-	0.12	0.12	0.12	-	0.12						
											0.155	0.10	0.06	0.006	0.0009	
0.80	0.06	-	0.036	-	-	0.19	0.19	0.19	-	0.19						
											0.210	0.10	0.05	0.005	0.0011	
0.90	0.04	-	0.024	-	-	0.23	0.23	0.23	-	0.23						
											0.195	0.10	0.03	0.003	0.0006	
1.00	0.02	-	0.012	-	-	0.16	0.16	0.16	-	0.16						
											0.080	0.05	0.01	0.001	0.0000	
1.05	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.05	0.00	0.000	0.0000	
1.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
										TOTAL	0.780			TOTAL	0.0031	

Date: 18/06/2015 (Thursday) Time: 12.15 am Location: Physical Modeling Laboratory Cross Section: CH3.00 Depth: 5cm

1	2	3	4	5	6	7			8	9	10	11	12	13	14	15
Distance from Left Bank (m)	Vertical Depth, D (m)	Method of Reading			Vertical Velocity						Average Vertical Velocity (m/s)	Section Width (m)	Average Vertical Depth (m)	Section Area (m^2)	Flow, Q (m^3/s)	Remarks
		0.2D	0.6D	0.8D	0.2D	0.6D			0.8D	Average						
0.00	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.50	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.07	0.00	0.000	0.0000	
0.57	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.03	0.01	0.000	0.0000	
0.60	0.01	-	0.006	-	-	0.00	0.00	0.00	-	0.00						
											0.070	0.10	0.03	0.003	0.0002	
0.70	0.05	-	0.030	-	-	0.14	0.14	0.14	-	0.14						
											0.182	0.10	0.06	0.006	0.0010	
0.80	0.06	-	0.036	-	-	0.22	0.22	0.23	-	0.22						
											0.238	0.10	0.06	0.006	0.0013	
0.90	0.05	-	0.030	-	-	0.26	0.25	0.25	-	0.25						
											0.182	0.10	0.04	0.004	0.0006	
1.00	0.02	-	0.012	-	-	0.11	0.11	0.11	-	0.11						
											0.055	0.03	0.01	0.000	0.0000	
1.03	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.055	0.10	0.01	0.001	0.0001	
1.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
										TOTAL	0.782			TOTAL	0.0032	

Date: 18/06/2015 (Thursday) Time: 12.30 am Location: Physical Modeling Laboratory Cross Section: CH4.00 Depth: 5cm

1	2	3	4	5	6	7			8	9	10	11	12	13	14	15
Distance from Left Bank (m)	Vertical Depth, D (m)	Method of Reading			Vertical Velocity						Average Vertical Velocity	Section Width (m)	Average Vertical Depth	Section Area (m^2)	Flow, Q (m^3/s)	Remarks
		0.2D	0.6D	0.8D	0.2D	0.6D			0.8D	Average						
0.00	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.50	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.60	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.180	0.10	0.03	0.003	0.0005	
0.70	0.05	-	0.030	-	-	0.09	0.09	0.90	-	0.36						
											0.418	0.10	0.06	0.006	0.0023	
0.80	0.06	-	0.036	-	-	0.48	0.48	0.47	-	0.48						
											0.493	0.10	0.06	0.006	0.0027	
0.90	0.05	-	0.030	-	-	0.51	0.51	0.51	-	0.51						
											0.255	0.10	0.03	0.003	0.0006	
1.00	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.02	0.00	0.000	0.0000	
1.02	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.08	0.00	0.000	0.0000	
1.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
										TOTAL	1.347			TOTAL	0.0061	

Date: 18/06/2015 (Thursday) Time: 10.00 am Location: Physical Modeling Laboratory Cross Section: CH0.00 Depth: 10cm

1	2	3	4	5	6	7			8	9	10	11	12	13	14	15
Distance from Left Bank (m)	Vertical Depth, D (m)	Method of Reading			Vertical Velocity (m/s)						Average Vertical Velocity (m/s)	Section Width (m)	Average Vertical Depth (m)	Section Area (m^2)	Flow, Q (m^3/s)	Remarks
		0.2D	0.6D	0.8D	0.2D	0.6D			0.8D	Average						
0.00	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.06	0.00	0.000	0.0000	
0.46	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.025	0.04	0.02	0.001	0.0000	
0.50	0.04	-	0.024	-	-	0.05	0.05	0.05	-	0.05						
											0.047	0.10	0.06	0.006	0.0003	
0.60	0.07	-	0.042	-	-	0.06	0.05	0.02	-	0.04						
											0.135	0.10	0.10	0.010	0.0014	
0.70	0.13	-	0.078	-	-	0.23	0.21	0.24	-	0.23						
											0.287	0.10	0.14	0.014	0.0039	
0.80	0.14	-	0.084	-	-	0.35	0.35	0.34	-	0.35						
											0.465	0.10	0.14	0.014	0.0065	
0.90	0.14	-	0.084	-	-	0.60	0.58	0.57	-	0.58						
											0.403	0.10	0.13	0.013	0.0050	
1.00	0.11	-	0.066	-	-	0.20	0.22	0.25	-	0.22						
											0.142	0.10	0.06	0.006	0.0009	
1.10	0.01	-	0.006	-	-	0.06	0.07	0.05	-	0.06						
											0.030	0.02	0.01	0.000	0.0000	
1.12	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.08	0.00	0.000	0.0000	
1.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
										TOTAL	1.533			TOTAL	0.0179	

Date: 18/06/2015 (Thursday) Time: 10.15 am Location: Physical Modeling Laboratory Cross Section: CH1.00 Depth: 10cm

1	2	3	4	5	6	7			8	9	10	11	12	13	14	15
Distance from Left Bank (m)	Vertical Depth, D (m)	Method of Reading			Vertical Velocity (m/s)						Average Vertical Velocity (m/s)	Section Width (m)	Average Vertical Depth (m)	Section Area (m^2)	Flow, Q (m^3/s)	Remarks
		0.2D	0.6D	0.8D	0.2D	0.6D			0.8D	Average						
0.00	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.50	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.048	0.10	0.03	0.003	0.0001	
0.60	0.05	-	0.030	-	-	0.10	0.09	0.10	-	0.10						
											0.178	0.10	0.07	0.007	0.0012	
0.70	0.08	-	0.048	-	-	0.26	0.26	0.26	-	0.26						
											0.290	0.10	0.09	0.009	0.0026	
0.80	0.10	-	0.060	-	-	0.32	0.31	0.33	-	0.32						
											0.368	0.10	0.11	0.011	0.0041	
0.90	0.12	-	0.072	-	-	0.43	0.42	0.40	-	0.42						
											0.342	0.10	0.10	0.010	0.0034	
1.00	0.08	-	0.048	-	-	0.27	0.27	0.26	-	0.27						
											0.133	0.07	0.04	0.003	0.0004	
1.07	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.03	0.04	0.001	0.0000	
1.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
										TOTAL	1.360			TOTAL	0.0117	

Date: 18/06/2015 (Thursday) Time: 10.30 am Location: Physical Modeling Laboratory Cross Section: CH2.00 Depth: 10cm

1	2	3	4	5	6	7			8	9	10	11	12	13	14	15
Distance from Left Bank (m)	Vertical Depth, D (m)	Method of Reading			Vertical Velocity (m/s)						Average Vertical Velocity (m/s)	Section Width (m)	Average Vertical Depth (m)	Section Area (m^2)	Flow, Q (m^3/s)	Remarks
		0.2D	0.6D	0.8D	0.2D	0.6D			0.8D	Average						
0.00	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.013	0.10	0.03	0.003	0.0000	
0.40	0.06	-	0.036	-	-	0.03	0.02	0.03	-	0.03						
											0.013	0.08	0.03	0.002	0.0000	
0.48	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.02	0.04	0.001	0.0000	
0.50	0.01	-	0.006	-	-	0.00	0.00	0.00	-	0.00						
											0.103	0.10	0.03	0.003	0.0003	
0.60	0.05	-	0.030	-	-	0.21	0.20	0.21	-	0.21						
											0.210	0.10	0.07	0.007	0.0015	
0.70	0.09	-	0.054	-	-	0.22	0.20	0.22	-	0.21						
											0.375	0.10	0.10	0.010	0.0036	
0.80	0.10	-	0.060	-	-	0.53	0.55	0.53	-	0.54						
											0.480	0.10	0.10	0.010	0.0046	
0.90	0.09	-	0.054	-	-	0.43	0.43	0.41	-	0.42						
											0.317	0.10	0.07	0.007	0.0022	
1.00	0.05	-	0.030	-	-	0.21	0.21	0.21	-	0.21						
											0.105	0.07	0.03	0.002	0.0002	
1.07	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.138	0.03	0.06	0.002	0.0002	
1.10	0.06	-	0.036	-	-	0.29	0.28	0.26	-	0.28						
											0.138	0.10	0.03	0.003	0.0004	
1.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
										TOTAL	1.893			TOTAL	0.0130	

Date: 18/06/2015 (Thursday) Time: 10.45 am Location: Physical Modeling Laboratory Cross Section: CH3.00 Depth: 10cm

1	2	3	4	5	6	7			8	9	10	11	12	13	14	15
Distance from Left Bank (m)	Vertical Depth, D (m)	Method of Reading			Vertical Velocity						Average Vertical Velocity (m/s)	Section Width (m)	Average Vertical Depth (m)	Section Area (m^2)	Flow, Q (m^3/s)	Remarks
		0.2D	0.6D	0.8D	0.2D	0.6D			0.8D	Average						
0.00	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.153	0.10	0.03	0.003	0.0005	
0.50	0.06	-	0.036	-	-	0.30	0.31	0.31	-	0.31						
											0.153	0.04	0.03	0.001	0.0002	
0.54	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.100	0.06	0.05	0.003	0.0003	
0.60	0.04	-	0.024	-	-	0.20	0.20	0.20	-	0.20						
											0.237	0.10	0.06	0.006	0.0014	
0.70	0.08	-	0.048	-	-	0.27	0.28	0.27	-	0.27						
											0.342	0.10	0.09	0.009	0.0031	
0.80	0.10	-	0.060	-	-	0.42	0.41	0.40	-	0.41						
											0.373	0.10	0.10	0.010	0.0035	
0.90	0.09	-	0.054	-	-	0.34	0.33	0.34	-	0.34						
											0.283	0.10	0.08	0.008	0.0021	
1.00	0.06	-	0.036	-	-	0.24	0.24	0.21	-	0.23						
											0.115	0.08	0.03	0.002	0.0003	
1.08	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.175	0.02	0.06	0.001	0.0002	
1.10	0.06	-	0.036	-	-	0.36	0.33	0.36	-	0.35						
											0.175	0.10	0.03	0.003	0.0005	
1.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
										TOTAL	2.107			TOTAL	0.0121	

Date: 18/06/2015 (Thursday) | Time: 11.00 am | Location: Physical Modeling Laboratory | Cross Section: CH4.00 | Depth: 10cm

1	2	3	4	5	6	7			8	9	10	11	12	13	14	15
Distance from Left Bank (m)	Vertical Depth, D (m)	Method of Reading			Vertical Velocity						Average Vertical Velocity	Section Width (m)	Average Vertical Depth	Section Area (m^2)	Flow, Q (m^3/s)	Remarks
		0.2D	0.6D	0.8D	0.2D	0.6D			0.8D	Average						
0.00	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.153	0.10	0.03	0.003	0.0005	
0.50	0.06	-	0.036	-	-	0.30	0.31	0.31	-	0.31						
											0.153	0.06	0.03	0.002	0.0003	
0.56	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.030	0.04	0.05	0.002	0.0001	
0.60	0.04	-	0.024	-	-	0.06	0.06	0.06	-	0.06						
											0.178	0.10	0.06	0.006	0.0011	
0.70	0.08	-	0.048	-	-	0.30	0.30	0.29	-	0.30						
											0.492	0.10	0.09	0.009	0.0044	
0.80	0.10	-	0.060	-	-	0.69	0.69	0.68	-	0.69						
											0.672	0.10	0.10	0.010	0.0064	
0.90	0.09	-	0.054	-	-	0.66	0.65	0.66	-	0.66						
											0.488	0.10	0.06	0.006	0.0027	
1.00	0.02	-	0.012	-	-	0.32	0.32	0.32	-	0.32						
											0.160	0.04	0.01	0.000	0.0001	
1.04	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.175	0.06	0.04	0.002	0.0004	
1.10	0.06	-	0.036	-	-	0.36	0.33	0.36	-	0.35						
											0.175	0.10	0.03	0.003	0.0005	
1.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
										TOTAL	2.677			TOTAL	0.0164	

Date: 17/06/2015 (Tuesday) Time: 4.00 am Location: Physical Modeling Laboratory Cross Section: CH0.00 Depth: 15cm

1	2	3	4	5	6	7			8	9	10	11	12	13	14	15
Distance from Left Bank (m)	Vertical Depth, D (m)	Method of Reading			Vertical Velocity (m/s)						Average Vertical Velocity (m/s)	Section Width (m)	Average Vertical Depth (m)	Section Area (m^2)	Flow, Q (m^3/s)	Remarks
		0.2D	0.6D	0.8D	0.2D	0.6D			0.8D	Average						
0.00	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.012	0.10	0.03	0.003	0.0000	
0.40	0.05	-	0.030	-	-	0.02	0.04	0.01	-	0.02						
											0.182	0.10	0.08	0.008	0.0014	
0.50	0.10	-	0.060	-	-	0.37	0.34	0.31	-	0.34						
											0.513	0.10	0.13	0.013	0.0064	
0.60	0.15	-	0.090	-	-	0.66	0.72	0.68	-	0.69						
											0.677	0.10	0.17	0.017	0.0112	
0.70	0.18	-	0.108	-	-	0.65	0.68	0.67	-	0.67						
											0.713	0.10	0.19	0.019	0.0136	
0.80	0.20	-	0.120	-	-	0.72	0.81	0.75	-	0.76						
											0.782	0.10	0.20	0.020	0.0156	
0.90	0.20	-	0.120	-	-	0.75	0.81	0.85	-	0.80						
											0.673	0.10	0.19	0.019	0.0128	
1.00	0.18	-	0.108	-	-	0.56	0.57	0.50	-	0.54						
											0.405	0.10	0.16	0.016	0.0065	
1.10	0.14	-	0.084	-	-	0.32	0.25	0.23	-	0.27						
											0.133	0.09	0.07	0.006	0.0008	
1.19	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.01	0.00	0.000	0.0000	
1.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
										TOTAL	4.090			TOTAL	0.0683	

Date: 17/06/2015 (Tuesday) Time: 4.15 pm Location: Physical Modeling Laboratory Cross Section: CH1.00 Depth: 15cm

1	2	3	4	5	6	7			8	9	10	11	12	13	14	15
Distance from Left Bank (m)	Vertical Depth, D (m)	Method of Reading			Vertical Velocity (m/s)						Average Vertical Velocity (m/s)	Section Width (m)	Average Vertical Depth (m)	Section Area (m^2)	Flow, Q (m^3/s)	Remarks
		0.2D	0.6D	0.8D	0.2D	0.6D			0.8D	Average						
0.00	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.02	0.00	0.000	0.0000	
0.32	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.028	0.08	0.03	0.002	0.0001	
0.40	0.06	-	0.036	-	-	0.03	0.05	0.09	-	0.06						
											0.143	0.10	0.08	0.008	0.0011	
0.50	0.09	-	0.054	-	-	0.22	0.24	0.23	-	0.23						
											0.380	0.10	0.12	0.012	0.0044	
0.60	0.14	-	0.084	-	-	0.56	0.49	0.54	-	0.53						
											0.538	0.10	0.16	0.016	0.0083	
0.70	0.17	-	0.102	-	-	0.52	0.55	0.57	-	0.55						
											0.565	0.10	0.17	0.017	0.0096	
0.80	0.17	-	0.102	-	-	0.53	0.59	0.63	-	0.58						
											0.600	0.10	0.18	0.018	0.0108	
0.90	0.19	-	0.114	-	-	0.66	0.58	0.61	-	0.62						
											0.517	0.10	0.18	0.018	0.0090	
1.00	0.16	-	0.096	-	-	0.42	0.39	0.44	-	0.42						
											0.360	0.10	0.12	0.012	0.0041	
1.10	0.07	-	0.042	-	-	0.30	0.32	0.29	-	0.30						
											0.152	0.08	0.04	0.003	0.0004	
1.18	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.02	0.00	0.000	0.0000	
1.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
										TOTAL	3.283			TOTAL	0.0479	

Date: 17/06/2015 (Tuesday) Time: 4.30 pm Location: Physical Modeling Laboratory Cross Section: CH2.00 Depth: 15cm

1	2	3	4	5	6	7			8	9	10	11	12	13	14	15
Distance from Left Bank (m)	Vertical Depth, D (m)	Method of Reading			Vertical Velocity (m/s)						Average Vertical Velocity (m/s)	Section Width (m)	Average Vertical Depth (m)	Section Area (m^2)	Flow, Q (m^3/s)	Remarks
		0.2D	0.6D	0.8D	0.2D	0.6D			0.8D	Average						
0.00	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.08	0.00	0.000	0.0000	
0.38	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.013	0.02	0.03	0.001	0.0000	
0.40	0.06	-	0.036	-	-	0.03	0.02	0.03	-	0.03						
											0.175	0.10	0.08	0.008	0.0014	
0.50	0.10	-	0.060	-	-	0.32	0.33	0.32	-	0.32						
											0.470	0.10	0.12	0.012	0.0056	
0.60	0.14	-	0.084	-	-	0.62	0.63	0.60	-	0.62						
											0.597	0.10	0.15	0.015	0.0090	
0.70	0.16	-	0.096	-	-	0.60	0.58	0.55	-	0.58						
											0.627	0.10	0.17	0.017	0.0107	
0.80	0.18	-	0.108	-	-	0.66	0.72	0.65	-	0.68						
											0.702	0.10	0.18	0.018	0.0126	
0.90	0.18	-	0.108	-	-	0.73	0.70	0.75	-	0.73						
											0.587	0.10	0.16	0.016	0.0094	
1.00	0.14	-	0.084	-	-	0.45	0.47	0.42	-	0.45						
											0.362	0.10	0.10	0.010	0.0036	
1.10	0.06	-	0.036	-	-	0.29	0.28	0.26	-	0.28						
											0.138	0.08	0.03	0.002	0.0003	
1.18	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.02	0.00	0.000	0.0000	
1.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
										TOTAL	3.670			TOTAL	0.0526	

Date: 17/06/2015 (Tuesday) Time: 4.45 pm Location: Physical Modeling Laboratory Cross Section: CH3.00 Depth: 15cm

1	2	3	4	5	6	7			8	9	10	11	12	13	14	15
Distance from Left Bank (m)	Vertical Depth, D (m)	Method of Reading			Vertical Velocity						Average Vertical Velocity (m/s)	Section Width (m)	Average Vertical Depth (m)	Section Area (m^2)	Flow, Q (m^3/s)	Remarks
		0.2D	0.6D	0.8D	0.2D	0.6D			0.8D	Average						
0.00	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.07	0.00	0.000	0.0000	
0.37	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.03	0.00	0.000	0.0000	
0.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.153	0.10	0.03	0.003	0.0005	
0.50	0.06	-	0.036	-	-	0.30	0.31	0.31	-	0.31						
											0.415	0.10	0.10	0.010	0.0039	
0.60	0.13	-	0.078	-	-	0.51	0.53	0.53	-	0.52						
											0.528	0.10	0.14	0.014	0.0071	
0.70	0.14	-	0.084	-	-	0.55	0.53	0.52	-	0.53						
											0.583	0.10	0.16	0.016	0.0093	
0.80	0.18	-	0.108	-	-	0.60	0.65	0.65	-	0.63						
											0.657	0.10	0.18	0.018	0.0115	
0.90	0.17	-	0.102	-	-	0.68	0.67	0.69	-	0.68						
											0.625	0.10	0.16	0.016	0.0097	
1.00	0.14	-	0.084	-	-	0.58	0.57	0.56	-	0.57						
											0.460	0.10	0.10	0.010	0.0046	
1.10	0.06	-	0.036	-	-	0.36	0.33	0.36	-	0.35						
											0.175	0.08	0.03	0.002	0.0004	
1.18	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.02	0.00	0.000	0.0000	
1.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
										TOTAL	3.597			TOTAL	0.0471	

Date: 17/06/2015 (Tuesday) Time: 5.00 pm Location: Physical Modeling Laboratory Cross Section: CH4.00 Depth: 15cm

1	2	3	4	5	6	7			8	9	10	11	12	13	14	15
Distance from Left Bank (m)	Vertical Depth, D (m)	Method of Reading			Vertical Velocity						Average Vertical Velocity (m/s)	Section Width (m)	Average Vertical Depth (m)	Section Area (m^2)	Flow, Q (m^3/s)	Remarks
		0.2D	0.6D	0.8D	0.2D	0.6D			0.8D	Average						
0.00	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.10	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
0.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.085	0.10	0.03	0.003	0.0002	
0.50	0.05	-	0.030	-	-	0.17	0.19	0.15	-	0.17						
											0.285	0.10	0.09	0.009	0.0026	
0.60	0.13	-	0.078	-	-	0.38	0.40	0.42	-	0.40						
											0.438	0.10	0.14	0.014	0.0061	
0.70	0.15	-	0.090	-	-	0.47	0.46	0.50	-	0.48						
											0.660	0.10	0.16	0.016	0.0106	
0.80	0.17	-	0.102	-	-	0.86	0.84	0.83	-	0.84						
											0.868	0.10	0.17	0.017	0.0148	
0.90	0.17	-	0.102	-	-	0.91	0.89	0.88	-	0.89						
											0.815	0.10	0.15	0.015	0.0118	
1.00	0.12	-	0.072	-	-	0.71	0.77	0.73	-	0.74						
											0.603	0.10	0.09	0.009	0.0051	
1.10	0.05	-	0.030	-	-	0.50	0.45	0.46	-	0.47						
											0.235	0.05	0.03	0.001	0.0003	
1.15	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.05	0.00	0.000	0.0000	
1.20	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.30	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
											0.000	0.10	0.00	0.000	0.0000	
1.40	0.00	-	0.000	-	-	0.00	0.00	0.00	-	0.00						
										TOTAL	3.990			TOTAL	0.0515	

APPENDIX E: Calculation of Bed Shear Stress for ECB

Bed Shear Stress, τ_b (N/m^2)_5cm - 18/06/15

Station	Top Width, B_{top} (m)	Bottom Width, B_{bottom} (m)	Depth, y (m)	Area, A (m^2)	x_1 (m)	y_1 (m)	x_2 (m)	y_2 (m)	Wetted Perimeter, P (m)	Hydraulic Radius, R (m)
0	0.59	0.3	0.09	0.040	0.20	0.09	0.09	0.09	0.647	0.062
1	0.53	0.3	0.07	0.029	0.18	0.07	0.05	0.07	0.579	0.050
2	0.55	0.3	0.06	0.026	0.20	0.06	0.05	0.06	0.587	0.043
3	0.46	0.3	0.06	0.023	0.13	0.06	0.03	0.06	0.510	0.045
4	0.40	0.3	0.06	0.021	0.10	0.06	0.02	0.06	0.480	0.044

Continued

Kinematic Viscosity, v (m^2/s)	Discharge, Q (m^3/s)	Velocity, V (m/s)	Manning's n	Reynold Number, Re	Specific Weight of Water, λ_D (N/m^2)	Energy Slope, S (m/m)	Bed Shear Stress, τ_b (N/m^3)
0.000001	0.0059	0.783	0.033	191270	9806	0.001	0.607
0.000001	0.0051	1.007	0.024	129812	9806	0.001	0.492
0.000001	0.0031	0.780	0.033	132082	9806	0.001	0.426
0.000001	0.0032	0.782	0.028	164434	9806	0.001	0.438
0.000001	0.0061	1.347	0.014	205158	9806	0.001	0.429

Bed Shear Stress, τ_b (N/m^2)_10cm - 18/06/15

Station	Top Width, B_{top} (m)	Bottom Width, B_{bottom} (m)	Depth, y (m)	Area, A (m^2)	x_1 (m)	y_1 (m)	x_2 (m)	y_2 (m)	Wetted Perimeter, P (m)	Hydraulic Radius, R (m)
0	0.66	0.3	0.14	0.067	0.24	0.14	0.12	0.14	0.762	0.088
1	0.57	0.3	0.12	0.052	0.20	0.12	0.07	0.12	0.672	0.078
2	0.59	0.3	0.10	0.045	0.22	0.10	0.07	0.10	0.664	0.067
3	0.54	0.3	0.10	0.042	0.16	0.10	0.08	0.10	0.617	0.068
4	0.48	0.3	0.10	0.039	0.14	0.10	0.14	0.10	0.644	0.061

Continued

Kinematic Viscosity, v (m^2/s)	Discharge, Q (m^3/s)	Velocity, V (m/s)	Manning's n	Reynold Number, Re	Specific Weight of Water, λ_D (N/m^2)	Energy Slope, S (m/m)	Bed Shear Stress, τ_b (N/m^3)
0.000001	0.0179	1.533	0.024	272242	9806	0.001	0.865
0.000001	0.0117	1.360	0.026	200984	9806	0.001	0.762
0.000001	0.0130	1.893	0.018	203819	9806	0.001	0.657
0.000001	0.0121	2.107	0.018	250607	9806	0.001	0.668
0.000001	0.0164	2.677	0.012	283860	9806	0.001	0.594

Bed Shear Stress, τ_b (N/m^2)_15cm - 17/06/15

Station	Top Width, B_{top} (m)	Bottom Width, B_{bottom} (m)	Depth, y (m)	Area, A (m^2)	x_1 (m)	y_1 (m)	x_2 (m)	y_2 (m)	Wetted Perimeter, P (m)	Hydraulic Radius, R (m)
0	0.89	0.3	0.20	0.119	0.40	0.20	0.19	0.20	1.023	0.116
1	0.86	0.3	0.19	0.110	0.38	0.19	0.18	0.19	0.987	0.112
2	0.80	0.3	0.18	0.099	0.32	0.18	0.18	0.18	0.922	0.107
3	0.81	0.3	0.18	0.100	0.33	0.18	0.18	0.18	0.930	0.107
4	0.75	0.3	0.17	0.089	0.30	0.17	0.15	0.17	0.872	0.102

Continued

Kinematic Viscosity, v (m^2/s)	Discharge, Q (m^3/s)	Velocity, V (m/s)	Manning's n	Reynold Number, Re	Specific Weight of Water, λ_D (N/m^2)	Energy Slope, S (m/m)	Bed Shear Stress, τ_b (N/m^3)
0.000001	0.0683	4.090	0.013	359184	9806	0.001	1.141
0.000001	0.0479	3.283	0.017	289078	9806	0.001	1.095
0.000001	0.0526	3.670	0.013	326524	9806	0.001	1.053
0.000001	0.0471	3.597	0.015	395109	9806	0.001	1.053
0.000001	0.0515	3.990	0.012	480077	9806	0.001	1.004

APPENDIX F: **Calculation of Bank Shear Stress for ECB**

Bank Shear Stress, τ_s (N/m²)_5cm - 18/06/15

Station	Top Width, B (m)	Depth, y (m)	B/y	Side Slope, z_1	Side Slope, z_2	MSMA Chapter 3 - Table 3.5			Bed Shear Stress, τ_b (N/m³)	Bank Shear Stress, τ_s (N/m³)
						Coefficient, K for z_1	Coefficient, K for z_2	Average K		
0	0.59	0.09	6.556	1	2	0.790	0.815	0.803	0.607	0.487
1	0.53	0.07	7.571	1	2	0.790	0.810	0.800	0.492	0.393
2	0.55	0.06	9.167	1	2	0.780	0.810	0.795	0.426	0.339
3	0.46	0.06	7.667	1	2	0.790	0.810	0.800	0.438	0.351
4	0.40	0.06	6.667	1	2	0.790	0.815	0.803	0.429	0.344
	Average		7.525			Average			0.479	0.383

* K < 1.0

Bank Shear Stress, τ_s (N/m²)_10cm - 18/06/15

Station	Top Width, B (m)	Depth, y (m)	B/y	Side Slope, z_1	Side Slope, z_2	MSMA Chapter 3 - Table 3.5			Bed Shear Stress, τ_b (N/m³)	Bank Shear Stress, τ_s (N/m³)
						Coefficient, K for z_1	Coefficient, K for z_2	Average K		
0	0.66	0.14	4.714	1	2	0.800	0.810	0.805	0.865	0.696
1	0.57	0.12	4.750	1	2	0.800	0.810	0.805	0.762	0.613
2	0.59	0.10	5.900	1	2	0.790	0.810	0.800	0.657	0.526
3	0.54	0.10	5.400	1	2	0.790	0.810	0.800	0.668	0.534
4	0.48	0.10	4.800	1	2	0.800	0.810	0.805	0.594	0.478
	Average		5.113			Average			0.709	0.569

* K < 1.0

Bank Shear Stress, τ_s (N/m^2)_15cm - 17/06/15

Station	Top Width, B (m)	Depth, y (m)	B/y	Side Slope, z_1	Side Slope, z_2	MSMA Chapter 3 - Table 3.5			Bed Shear Stress, τ_b (N/m^3)	Bank Shear Stress, τ_s (N/m^3)
						Coefficient, K for z_1	Coefficient, K for z_2	Average K		
0	0.89	0.20	4.450	1	2	0.800	0.810	0.805	1.141	0.918
1	0.86	0.19	4.526	1	2	0.800	0.810	0.805	1.095	0.882
2	0.80	0.18	4.444	1	2	0.800	0.810	0.805	1.053	0.848
3	0.81	0.18	4.500	1	2	0.800	0.810	0.805	1.053	0.848
4	0.75	0.17	4.412	1	2	0.800	0.810	0.805	1.004	0.808
	Average		4.467			Average			1.069	0.861

* K < 1.0