# Effect of dense streambank vegetation with steep sloping riverbanks on Manning's roughness coefficient of 0.11 in hydraulic model studies

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## Abstract

The Manning's Roughness Coefficient (n) is a major hydraulic parameter which extensively affects the estimation of velocities and consequently the water surface elevations along any water conductor system. The assessment of n value involves many uncertainties, as its estimation is based on literature, judgement and most importantly the slope of the water conductor system. Project reach is characterized with the highly vegetated steep sloping banks of the river. The riverbanks are mainly rainforests, densely vegetated with high trees and bushes. Riverbed is consisting of gravels, rocks and large boulders. The river slope is around 1 in 100 at the river reach under consideration. The daunting task as per the contract was to calibrate the hydraulic model of the river by reproducing the 'n' value of 0.11 (Prototype) for riverbank rainforests. Various alternatives were carried out to match these high friction values in the 3D comprehensive hydraulic as well as 2D mathematical model. The 'n' value in hydraulic model was then arrived based on the results of calibration. It was observed that, these high friction values do not affect much on the composite Manning's 'n' value of the river reach, especially due to the steep slope of the river. This paper represents the results of these studies and recommendations for steep river flows.

***Keywords -*** *Manning's roughness, streambank vegetation, River model calibration, steep sloping rivers*

## 1. Introduction

Principal of conservation of energy of flow as stated by Bernoulli considers the frictionless and incompressible fluid, in which the sum of the potential head, the pressure head and the kinetic head is the same for all points. Based on this, later Chazy derived the formula for calculating flow velocity, considering the resistance of the channels. He assumed a constant frictional value, due to limited data availability. Later investigations showed that frictional value is not constant but depends on the characteristics of the channel. Further, immense contribution in this regard is provided by many scientists namely; Kutter, Manning, Bazin, Kennedy, Lindley, Lacey, etc. Manning's formula is most popular due to its simplicity and applicability in most cases. Manning considered the frictional value to be dependent upon roughness and hydraulic radius, thereby simplifying the computations. Manning's formula is used extensively to predict the velocities and water surface elevations for various flood scenarios. Choice of the correct roughness coefficient, remains a subjective and most challenging task during the analysis of any water conductor system. The project reach under consideration is characterized with densely vegetated and wide river banks having steep side slopes. The river is also having steep gradient. Very sparse literature is available in this regard and choice of Manning's roughness coefficient becomes a factor which induces uncertainty in the predicted behaviors of the floods. Assuming the correct roughness coefficient and reproducing it in the laboratory on a scale model was the challenging task which need to be tackled in the current project. The problem was tackled by implementing a scientific approach by calibrating the river model. Both mathematical and physical models were built and the friction was analyzed in both the models. This paper discussed the procedure and the results obtained from the studies.

## 2. Manning's Roughness coefficient

One the most commonly used equations governing Open Channel Flow is known as the Manning's Equation. It was introduced by the Irish Engineer Robert Manning in 1889 as an alternative to the Chezy

Equation. The Manning's equation is an empirical equation that applies to uniform flow in open channels and is a function of the channel velocity, flow area and channel slope. Frictional resistance to the stream discharges is dependent upon flow-impending characteristics of stream channel and stream banks. Collective effect of these roughness characteristics retards the flow and is represented by a Manning's roughness coefficient in Manning's equation.

The procedure for estimating Manning's roughness coefficient (n value) is generally subjective, and the accuracy is largely dependent on a hydrologist's or engineer's experience in estimating these values over a wide range of hydraulic conditions. Even experienced hydrologists sometimes have difficulty in assessing accurately all the factors that contribute to flow resistance [Coon]. Manning's roughness coefficient is a major factor which affects the velocity and water surface calculations in any river reaches, and at the same time involves lot of uncertainty. In the following sections, few methods are discussed briefly, which are available to estimate the roughness values.

## *2.1. Estimation of Roughness values*

A lot of field data is required to confirm the selected values. In the absence of field data, the traditional approach is to predict the roughness value based on either of the following methods, which are subjective in nature. The various methods available and assumptions are discussed below.

### *2.1.1. Calibrated Photographs*

In this approach the Engineer uses calibrated photographs of the river reaches of known or measured 'n' values to associate hydraulic roughness values with conditions observed and anticipated in the Project reach. Chow (1959), Barnes (1967) and Aldridge & Garrett (1973) are the dominant sources of calibrated photographs. They represented photographs and cross-section of typical river and creeks and their representative 'n' values.

### *2.1.2. Acrement and Schneider (1989)*

They have summarized the procedure in "Guide for selecting Manning's Roughness coefficient for natural channels and flood plains". The most important factors that affect the selection of channel 'n' value are; a) The type and size of material that compose the bed and banks of the channel and b) The slope of the channel. Cowan (1956) developed a procedure for estimating the effects of these factors for determining the value of 'n' for a channel. The value of 'n' may be computed as follows.

$$N = (n_b+n_1+n_2+n_3+n_4)\, m$$

where;

$n_b$ = Base value of n for a straight, uniform, smooth channel in natural materials.
$n_1$ = Degree of irregularity
$n_2$ = Variation in Channel cross-section
$n_3$ = Effect of Obstructions
$n_4$ = Amount of Vegetation
m = meandering ratio (upto 1.2)

The modifying values for the various factors were developed from the analysis of 40 to 50 small and medium size channels, with top width less than 60 feet. Therefore, use of these adjustment values, is questionable for large channels, in which the hydraulic radius exceeds 15 ft, and large adjustments are required generally for narrow channels. As vegetation adjustment values are for vegetation that is uniformly distributed and not limited to streambank alone.

## *2.2. Factors affecting roughness*

'William F Coon', have published a report on the "Estimates of Roughness Coefficients for selected natural stream channels with vegetated banks in New York". This report is prepared by U.S. Geological

Survey in 1995. The following paragraph discuss the important aspects of this report pertaining to project study area. Roughness value has a good correlation with Hydraulic Radius R, Slope Sf, Streambed particle size and Relative smoothness, (R/d50). Other good correlated pairs are; Energy gradient and water surface slope, Stream top width and wetted perimeter, hydraulic radius and mean depth. The various relationships are discussed below in brief.

### *2.2.1. Relation between n and R*

Channels with low relative smoothness (R/d50 < 5), generally are in mountain streams with high gradients and large median bed particle size. The n value decreases rapidly for such streams with increasing depth and approach an asymptotic value as bank-full flow is approached, as shown by Sargent (1979) and Jarrett (1984). At higher depth flexible vegetation seem to bend and thus provides less resistance. On narrow (top width < 60 ft), low gradient channels (S<0.002) with less streambank vegetation, the n value is expected to increase with increasing depth, at least to the point of vegetation submergence.

### *2.2.2. Relation between n and Energy Gradient*

Hydraulic roughness increases with the increase in slope gradient, in general. Further, slope could be more reliable estimator of n value than size of bed material. In high gradient channels slope can exert a controlling effect on the n value, that can obscure the effect of streambank vegetation.

### *2.2.3. Streambank Particle size and Relative Smoothness*

Benson and Dalrymple (1967) have shown that, wide channels (top width > 100 ft) with R/d50 < 5 and bank-full stages as well as narrow channels with little or no streambank vegetation, following relation exists. All other factors, remaining constant, the hydraulic roughness of a channel will increase with an increase in bed particle size.

### *2.2.4. Streambank Vegetation*

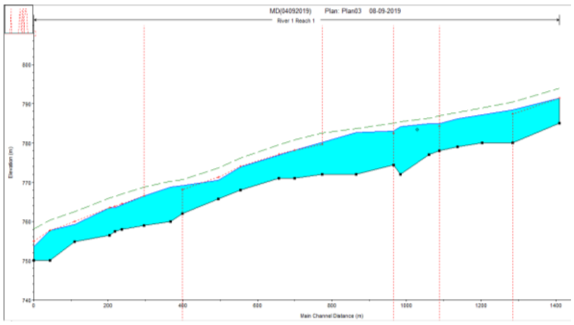
The narrow channels, normally less than 100 ft wide, require larger adjustments in n values for vegetation. Wide channels with no substantial channel bottom vegetation would require negligible adjustments, if any. The graphs of n against R values presented in "Station descriptions, hydraulic data and channel photographs for the 21 study sites" indicate that, bank vegetation has no measurable effect on the roughness coefficient of streams, that are wider than 100 ft and that have wetted perimeter less than 25% vegetated. At study sites where stream widths are less than 63 ft, vegetation that covers are more than 25% of the wetted perimeter causes the roughness coefficient to increase by as much as 0.005 during non-growing (vegetation) season and additional 0.002 to 0.012 during the growing (vegetation) season. The values for streambank vegetation adjustment for one site (East Branch Ausable River at Au Sable Forks), where the top width is about 200 ft and wetted perimeter is more than 30% vegetated, appears to range from 0.005 to 0.009. The n value computed is in the range of 0.055 to 0.057. The higher roughness coefficient values are generally adopted for the overbanks and floodplains with dense vegetation. The n values can vary from range of 0.1 to 0.4. These values are related with flatter slopes of overbanks / floodplains, with high degree of resistance to flow by vegetation.

### *2.2.5. Scale effects and Roughness*

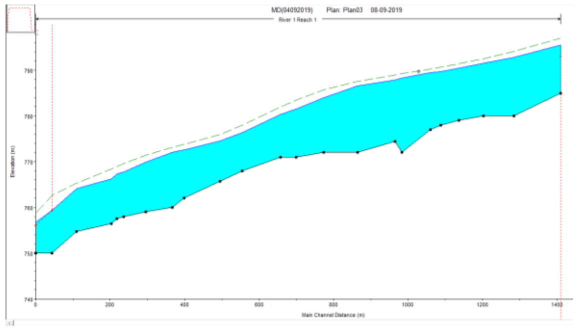
In the physical model, scale effects increase with reduction in scale. The scale effects normally have a damping effect, resulting in a higher frictional effects. Thus, sometimes reducing the roughness by ignoring geometric roughness similarity can result in an identical friction coefficient in both the model and real-world prototype, despite different Reynold number, resulting in a compensation of scale effects. (Heller, et al, 2011).

### *2.3. Effects of n value on water surface profiles*

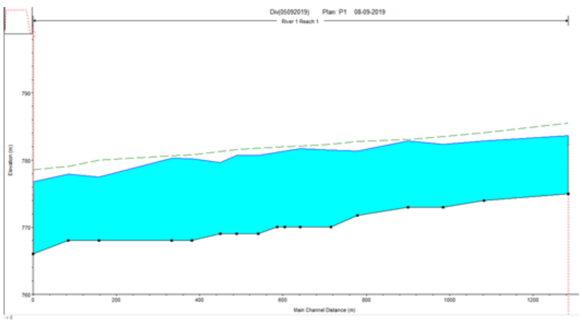
Following comparison shows the water surface profiles predicted for the different n values assumed, for different river slopes. It is clearly evident that higher n values will result in lower velocities and higher water surface elevations. Depending on the flow depths and velocities, the predicted flow regime can vary from super-critical to sub-critical, for higher n values. Hence, the correct assumption of n value is very important.



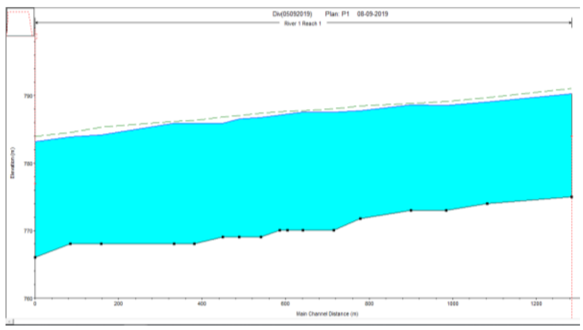
i-a) n value = 0.06



i-b) n value = 0.1



ii-a) n value = 0.04



ii-b) n value = 0.08

Figure 1 – Water surface profiles obtained in Hec-RAS model for different n values

## 3. Project reach

The project is located in tropical rainforest in mountainous terrain. The highest flood discharge estimated for 1 in 2 year return period is 1000 cumec and that of 1 in 500 year flood frequency is around 3100 cumec. The yearly average discharge is around 15 cumec. Powerhouse is envisaged to be operated for a design discharge of 20 cumec. The longitudinal slope of the river bed is around 1 in 100 at the project reach. The water depth of the 1 in 200 year flood is around 8 to 12 m and stream width of around 50 to 70 m. The river has wide banks with highly vegetated forest cover.

### *3.1. Riverbed*

The riverbed consists of gravel, rock and boulders with a diameter up to 5 m, however most boulders are of less than 1 m in diameter. The riverbanks are lined with rock (steep slopes), boulders, trees and bushes. Size and shape of the cross sections vary occasionally. Dredged channels, considerable bed roughness and moderately sloughed side slopes can be identified. Almost no vegetation is observed inside the riverbed. The typical condition can be seen in the Figure 1 below. The partial roughness coefficients derived from these descriptions (according to Arcement and Schneider 1989) yield an overall roughness coefficient of 0.05, which was adopted by project authorities for the river channel bed which is in good conformity with Barnes (1967) and Chow (1959).

### *3.2. Streambanks*

Floodplains are typically characterized with the steep slopes covering tall trees of more than 15 to 20m height, which are very densely vegetated. The vegetation of the floodplains mostly consists of medium to large trees. Firm soil with slight surface irregularities can be found. Few obstructions such as downed trees and flood debris are present. Ground cover consists of weeds and small undergrowth. The typical streambank can be seen in the Figure 2 below. This leads to an estimated roughness coefficient of 0.11 by the project authorities. There are some patches of the mountains covered by medium size weeds and bushes. For the areas of the flood plains with a dominating characteristic of smaller vegetation, such as growing bushes, a roughness coefficient of 0.06 was estimated by project authorities, which is in good conformity with Barnes (1967).

**Figure 2 -** Riverbed channel showing large boulders


**Figure 3 –** Densely vegetated steep sloping riverbanks

Conclusively the project domains was divided into three different types of landscapes with their characteristic Manning coefficients;

- Bushlands: 0.06
- Rainforest: 0.11
- Riverbed: 0.05

## 4. Model studies

A comprehensive, geometrically similar, three-dimensional model on Froudian similitude for a scale of 1:40, for assessing the performance of proposed Dam Spillway was constructed. A river reach of 900 m upstream and 500 m downstream of dam axis was reproduced in the model. As per the contract the requirement was first to construct the river portion in the reach and calibrate it for the given discharges and water levels. The pre-defined water levels were established in the physical model by adjusting the friction. The various alternatives were tested to reproduce the high friction values in the model. In the second step the spillway structure would be fixed inside the calibrated river model to assess its impact and hydraulic behavior.

### *4.1. Mathematical model*

LiDAR survey was carried out for entire project area and contours were obtained. Bathymetry survey of the project area was carried out. The bathymetry survey was used for the river bed whereas LiDAR survey prevailed for the streambanks. Cross sections were worked out from these surveys using GIS software. The horizontal extend for the project domain was selected to be about 4 km of the river length. The dam structure was placed roughly in the middle of the respective domain. For the finalization of the horizontal extend, requirements for the inlet and outlet boundary condition had to be met. For the inlet boundary condition, a river section with a relatively flat slope was chosen, so as to assures subcritical inlet boundary conditions. The river section for the outlet was chosen by a relatively steep slope in the area in order to assure supercritical outlet boundary conditions in the simulation. In order to take into account, the different landscapes and therefore different Manning coefficients, an analysis of satellite recordings was carried out. By this analysis the surrounding area of the river could be divided into regions with bushland and areas with growing trees. Manning coefficients of 0.06 for bushlands and 0.11 for forest areas were applied. For the riverbed itself a value of 0.05 was selected for the corresponding Manning coefficient.

### *4.2. Procedure for Calibration of the physical river model*

The adopted methodology for the calibration of the physical model was as follows;

- The physical models was calibrated based on the results of the mathematical models. This calibration was carried out without structures in the riverbed in order to ensure that the impact of the structures on the rivers is properly assessed.
- The calibration consisted of various trials which were carried out by using various materials such as coarse sand, sandpaper, gravels, pebbles, acrylic teeth, etc. or any other suitable material, to increase the friction of the river bed and banks. During the trials, the roughness values applied in different areas of the mathematical model were recreated in the same areas in the physical models.
- It was pointed out that shallow obstacles, commonly used to reproduce high roughness values in physical models, will lose their impact with increasing water depth to the contrary of trees as stream bank vegetation, which obstruct water flows all the way up to their crown. It was therefore required to employ obstacles in the physical model that capture this effect over the entire water level range. To achieve this, plastic or aluminum rods of up to 40 cm length may be used as obstacles. It was expected that the high friction of rods may distort flow conditions and thus may result in excessive roughness values. To counteract this, the density of rods was varied such as to achieve the desired water levels.
- The upstream and downstream water levels at the start and end of the physical model domains were adopted according to the numerical model results for the different discharges to be calibrated.

- This procedure was carried out in an iterative manner until a satisfactory similarity between the physical and mathematical models was achieved. The similarity was proven by comparing the Manning roughness coefficients' as per numerical and physical models as well as by comparing water levels in control sections.
- The calibration was done sequentially for the 10-years return flood (1500 cum/sec), the 200-years return flood (2500 cum/sec), corresponding to the design flood, and the 500-years return flood (3000 cum/sec), corresponding to the safety flood. The riverbeds were calibrated for the 10-years return flood first. Materials used in this first calibration phase to reproduce the riverbed, bushland and trees roughness, and thus to increase friction, were retained for the next calibration phase which was performed for the next higher flow. Additional materials required to increase the friction for the next phase were applied only in areas where they don't impact the water levels calibrated in the previous phase. This procedure was repeated until the highest flood discharge was calibrated.
- After the calibration process of the river beds and banks, the dam models were installed in the river models and further detailed experiments were carried out.

### *4.3. Reproduction of the high friction in physical model*

River channel bed and banks were marked on the river cross sections as per the survey data. The areas of different roughness values were identified and marked on the model. Pebbles and grit were used to reproduce the high friction in the river bed channel. The size and density of the pebbles and grit was varied as per requirement. For the reproduction of model trees, steel rods of 8 mm diameter were installed vertically on river bed, and the plastic leaves were tied to it. This arrangement is removable and fast. Further, spacing of trees could be altered as per requirement very quickly. Even the density of the leaves of the trees can be adjusted vertically, which again adds to the friction. Further at areas where bushlands were to be reproduced on the river banks, again the pebbles and grit were used. Figure 4 shows the roughness raster alongside the photographs of reproduction of high friction in the river model. Various trials were carried out to understand the effect of friction and the desired water levels were successfully achieved in the model. At first the 10-year return flow was calibrated, followed 200-year and 500-year return floods. Spillway and power intake structures were installed after the calibration process was completed, by excavating the river bed and removing the trees in the vicinity. Further hydraulic model studies were conducted for analyzing discharging capacity, energy dissipation at the downstream, gates and power house operations, etc.

## 5. Results and Discussions

Following observations were made from this exercise;

- In the first step trials were made to evaluate the water levels in the river model without any friction applied. When the inlet and outlet boundary conditions are maintained, it was observed that, the water levels in-between drop below the expected levels by large extent. The flow shoots up at curves and bends of river and the main controlling factor is longitudinal slope of the river. The high velocity flow is being concentrated along the center line of the river. The water levels observed at the banks are well below the expected levels.
- Various trails were carried out, by changing the density of trees and changing the plaster roughness on riverbed, for finding the best match for all three discharges. The current arrangement as shown in photographs in Figure 4, shows a good match for all three discharges. It is noted that, very high-density trees are required at some places, to reproduce the desired water levels.
- Considerably higher water levels are observed at near the banks after reproducing high friction. Without friction the flow in the river is observed to be concentrated at some locations. Friction has helped in avoiding these flow concentrations, and the flow is observed to be streamlined. The difference in the flow conditions can be observed in the Figure 5.
- Water levels were compared from mathematical and physical model for all the cross sections. The examples are shown in Figure 6 for various cross sections along the length of the river. It can be seen from the comparison of graphs, that the water surface profiles are matching quite very well. Further it was observed that, water surface patterns at cross-sections are getting exaggerated in the physical model, especially at curves and bends, due to scale effects.

- For the river reach under consideration, the average composite roughness value (Manning's roughness coefficient, n) was estimated to be 0.05 for 10-year return period flood, whereas it was 0.055 for the 200-year and 500-year return period flood.
- The trees on the streambanks have resulted in higher water levels near the banks. There is not much effect on the water levels and velocities in the central portion of the river. The maximum flow is passing through the central portion of the river due to high velocities and large cross-sectional area.
- As the maximum flow is passing through the central portion of the river, the flow velocities do not differ considerably.
- The flow is being controlled mainly due to the higher slope gradient of the river and the vegetation on the banks have very limited effect on the average flow velocities and flow depths except near the banks.
- As such when the spillway structure was installed along with the power intake structure, a good reservoir is formed on the upstream of spillway for the length of around 120 m. The flow conditions are completely governed by the operation of gates. Comprehensive experiments were conducted for the spillway to analyze the overall flow conditions. It was observed that, due to the steep slope of the river, very high momentum of the flow passes through the spillway, generating high velocities.

## 6. Conclusion and Recommendations

From the above experiments and calibration studies, it was concluded that;
- Higher Manning's roughness coefficient (n) values were observed on the flatter gradient, whereas n value decrease with the increase in river slope.
- With the increase in discharge, n values observed to increase marginally for the river reach under consideration.
- Friction has little or negligible effect on the overall flow conditions, especially in the presence of spillway structure. The higher friction has negligible effect on the upstream water levels and these are totally controlled by the gate operations.
- High gradient of the river is the controlling factor in the absence of the spillway structure and friction has limited effect.
- The water levels in the vicinity of the river banks varied considerably due to the frictional effects along the streambank. However, it has very negligible effect on the flow velocities as the maximum flow is passing through the center of the river channel.
- Composite Manning's Roughness Coefficient ('n') value should be restricted to maximum 0.06 for reproduction of the higher friction in the model for the wide and steep sloping banks and steep gradient rivers.

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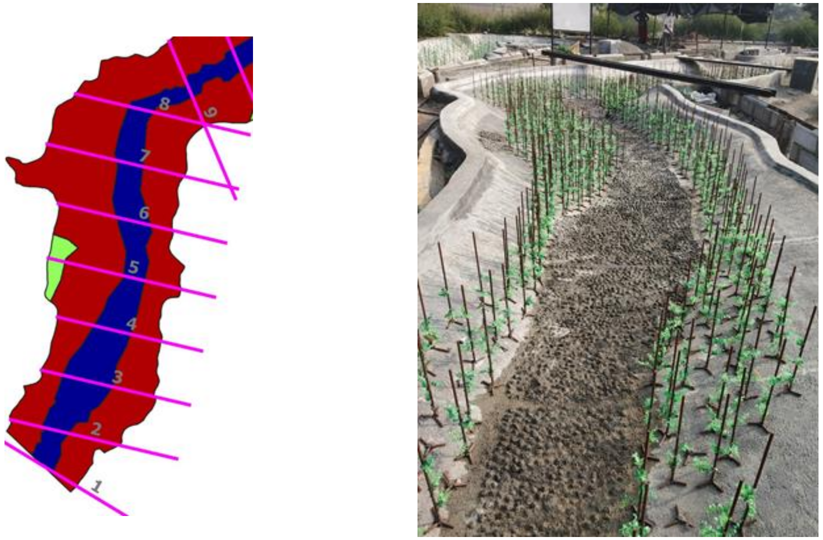
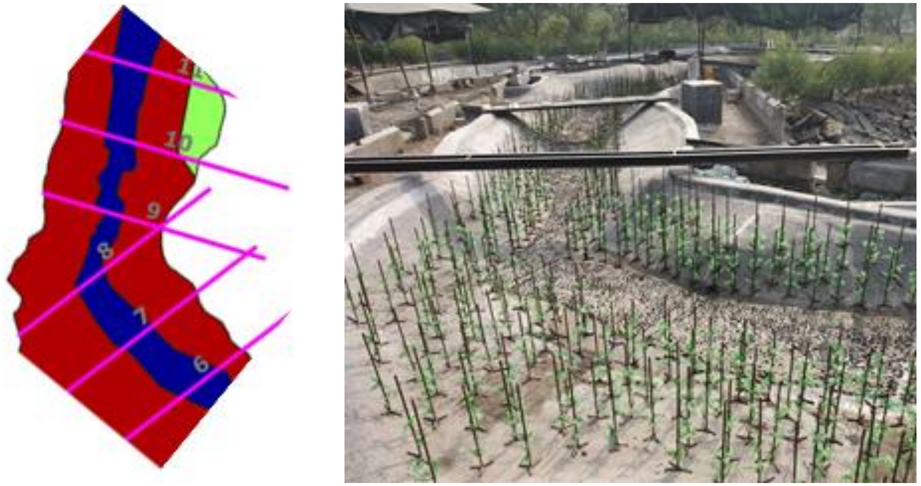
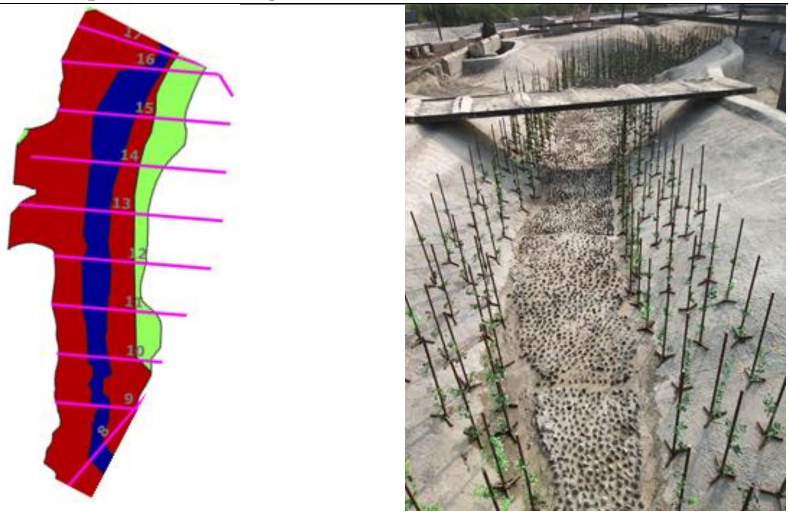


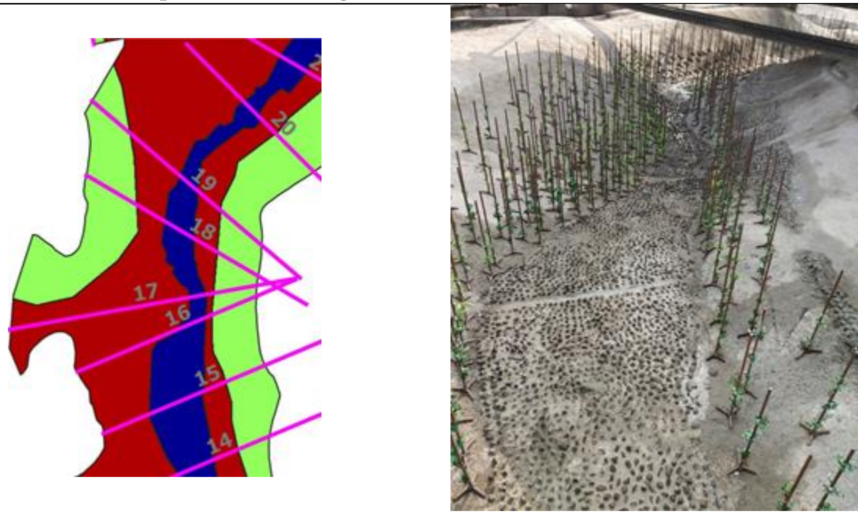

a. River portion showing cross section 1 to 6




b. River portion showing cross section 6 to 8




c. River portion showing cross section 8 to 14




d. River portion showing cross section 14 to 20

Figure 4 – Reproduction of high friction, pebbles and grit was used in the river bed and tress were modelled in the river banks


Figure 5 – Effect on the flow conditions due to high friction (such as tall trees) at the stream banks.


Figure 6 – Graphs showing comparison of water surface profiles obtained from Mathematical and Physical model.