# EVALUATION OF ANALYTICAL METHODS AND OTHER REGIME THEORIES AS ALTERNATIVE TO LACEY'S THEORY FOR ALLUVIAL CHANNEL DESIGN

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***ABSTRACT:*** *The ideal geometric dimension of alluvial channels has been a topic of fundamental scientific and engineering interest for years. Cross sectional geometry and bed slope of alluvial channels changes with variation in the sediment load transported through them. In Pakistan most of the canals are constructed on regime approach and are facing issues of sedimentation and scouring, so there is need to re-evaluate the design approaches commonly used. This research study is under taken to analyze different approaches of alluvial channel design, calculation of sediment transport rate by various methods of sediment load transportation and recommendations of the most suitable approach for channel design. The results computed by regime theories showed agreement with improved design while the analytical methods show marked variation. Channel design based on Lacey's theory is more acceptable despite its limitation of uncertain sediment contents. Optimal design by combination of Lacey theory with suitable sediment transport methods should be adopted for designing an alluvial channel. Rational methods take into account the sediment entering into a canal, so it seems a feasible alternative to regime theories, but it is discouraged to use for designing such canals where sediment inflow is variable.*

**KEYWORDS:** Alluvial channel, design theories, sediment, design parameters, sediment transport rate theories.

## 1 INTRODUCTION

An alluvial channel is a stable earthen channel with the ability to pass the incoming water born sediment load without significant degradation or aggradations. Ideally in such channels the width, depth, and slope remain constant over time. The phenomenon of sedimentation and erosion has been observed in alluvial channels when heavy silt laden water flows through them. Therefore the design of alluvial channel requires an analysis of channel stability with reference to erosion and sedimentation. The objective of an alluvial channel design is often to produce a channel that has dynamic equilibrium or geomorphic stability. Because maintenance and de-silting of channels often proves to be expensive. Designing a channel involves the selection of channel alignment, size and shape of the channel, longitudinal slope, and the type of lining material. The design usually considers several hydraulically feasible alternatives for the selection of the most effective one among them. An alluvial channel changes its slope and geometry to maximize its transport rate and minimizes its stream power. At a given discharge and slope, the width of a channel changes itself to give a maximum transport rate. The increase in transport rate is equivalent to decrease in slope [1]. The modification in the cross section design of previous mentioned concept was made on the basis of analytical geometry for stable channels [2]. An alluvial channel adjusts its width, depth and slope in such a way that the stream power become minimum considering water discharge and sediment load as the independent variables [3-4]. In equilibrium condition energy dissipation rate in a channel is minimum which vary with its boundary conditions [5-6]. Basic flow relationships of continuity, resistance, and sediment transport can be used to demonstrate the mechanism of a channel self-adjustments. Principle of least action can physically explain extremal hypothesis [7]. Combining the principle of maximum entropy and minimum energy dissipation rate hydraulic geometry relationships were derived [8].

Design of alluvial irrigation canals has usually been achieved using the regime methods. The regime methods mostly depend on regression equations that are used to determine the dependent variables (width, depth). The independent variables of discharge and sediment concentration are single-valued functions and, therefore, are applicable to cases where the discharge is relatively uniform with time. The regime methods are more appropriate for low-energy systems with low sediment transport.

Different concepts of the regime for designing of alluvial channels and modification in the regime concepts for deriving hydraulic geometry relationships were given in past. The regime is defined as the dimensions of width, depth and slope of a channel to transport allocated supply of water along with a given sediment that were all fixed by nature[9]. The relationship between mean velocity and depth of flow was developed [10]. Regime equations for wetted perimeter, hydraulic mean depth, and hydraulic gradient in relation to mean channel discharge and Lacey's silt factor were derived [11]. Hydraulic geometry relationships which were comparable to those of Lacey's were derived but these differentiated between the impact of bed alluvium and bank material where these were unlike. [12-13]. Later on, the analysis of regime theory for sand bed and banks, sand bed and cohesive banks, cohesive bed and banks, coarse non-cohesive material and sand bed and cohesive banks with heavy sediment load of 2000-8000 ppm was made [14-15].After regime theory a concept based on the application of the principle of a limiting tractive force for a boundary of any given material under non scouring conditions was introduced [16-17].

Recently the artificial neural network models (ANNs) were used to estimate the main design parameters such as wetted perimeter, hydraulic radius and slope which are used in the design of stable alluvial channels [18] and study of regime theory for unlined canals in alluvial soils showed that there is a need to improve the Lacey's final regime concept [19]. Bank stability must be considered in deriving an optimal channel design using rational regime models otherwise it would under predict the channel width [20]. The review and assessment of the stable alluvial channel design showed that the prediction of channel geometry from based on the principle of maximum entropy and minimum energy dissipation is better than other approaches [21]. A new approach for the design of alluvial canal system in Pakistan was given by modification of the Lacey's regime equations and comparison with commonly used design procedures [22]. Comparison of sediment transport approaches and tractive force method with regime theory as alternative design approach for the canals in the Punjab was made .it was concluded that the tractive force method does not effectively deal with sedimentation problem in these canals. It is not a reliable alternative for design and there is need for improvement of design equations of the regime theory [23].

In Pakistan the design of the existing irrigation system is commonly based on the regime theory given by Lacey. Some canals designed on the basis of this theory have not been functioning satisfactorily; where silting and scouring were common problems. The major reasons of these problems could be the scanty data and knowledge about sediment theories. Such deficiencies when coupled with issues such as sediment discharge imbalance, hydraulic bottlenecks, inadequate operational practice and low standard of maintenance, caused serious degradation and deterioration at some sections of irrigation canals. Therefore, there is a need to re- evaluate the existing canals considering other design methods as alternative of Lacey's regime theory and selection of the best suited approach for re designing. In this research study sediment transport rate was estimated using the selected approaches, selected alluvial canal design was re-evaluated and appropriate method was recommended.

## 2 STUDY AREA

The present research study was conducted on Lower Bari Doab Canal (LBDC).It originates from the Balloki Headwork's on the left bank of Ravi River (Figure. 1). Irrigated agriculture in the area is sustained through surface supplies in the LBDC and pumped groundwater. The gross command area (GCA) of the canal is 0.80 million hectare (Mha) and is managed under 13 administrative sub divisions. It is constructed in 1911-13; the system was designed for 67% cropping intensity (CI). The full supply discharge capacity of LBDC in records is 278.9m$^3$/s including 28.35m$^3$/s for Sahiwal Pakpattan (SP) link. Originally LBDC canal was designed to carry a discharge of 191.33m$^3$/s in 1912. After that a series of additions were made into the command of LBDC, the latest of these are increase in cultivable command area (CCA) of 3200ha, 9800 ha and 4300 ha in 1963, 1975 and 1984 respectively. First remodeling of the LBDC system took place in 1940's, the design discharge was increased to215.4m$^3$/s at its head. Whereas, second remodeling was done in 1964-65 and the capacity was enhanced to 245.18m$^3$/s. The third remodeling was done in 1984 to a design discharge of 278m$^3$/s, however this could not be completed and now the same is underway under Lower Bari Doab Canal Improvement Project (LBDCIP). The cropping intensity over the years has risen to about 160%. Due to deferred maintenance resulting insufficient capacity of the canal and structures, the maximum operational discharge is currently limited to 244m$^3$/s. The selected reach of LBDC for this study is from RD 0 to 8993.90 m.

$$P = B + 2\sqrt{1+z^2} \quad (4)$$

$$R = A/P \quad (5)$$

$$V = \frac{1}{n} R^{2/3} S^{1/2} \quad (6)$$

Where,

K= Reduction factor for shear stress

$\tau_o$ = Unit tractive force (N/m$^2$)

$S_o$ = Bed slope

$\theta$= Side slope angle

φ = Angle of repose

$\tau_s$ and $\tau_b$= shear stress at sides and bed (N/m$^2$)

A= Cross sectional area (m$^2$)

B= Bed width (m)

P = Wetted perimeter (m)

V = Velocity (m/sec)

S = Water surface slope

R = hydraulic radius (m)

n =Manning's roughness factor

y=depth of flow (m),

z = Side slope of channel

**a. Rational methods**

The rational methods were further categories as (i) White, Paris and Bettes method(ii) Chang method (iii) Rational canal design method in combination of Lacey's width, friction and transport by Ackers, White, Paris and Bettes(iv) Rational method using Lacey's width friction by Van Rijn and transport by Engelund-Hansen(v) Rational canal design method in combination of Chang's width, friction and transport by Ackers, White, Paris and Bettes (vi) Rational method using Chang's width, friction by Van Rijn and transport by Engelund-Hansen. The analysis for rational methods was carried out with the help of Design of Regime Canal (DORC) computer software.

### 3.1.2 Regime methods

In the regime methods the stable channel is designated as 'regime channel'. Alluvial channel adjust its dimensions in response to the variation in the size and amount of sediments carried by it. Theselected regime methods were (i)Lacey'stheory (ii) Blench Theory, and (iii) Simons and Albertson.

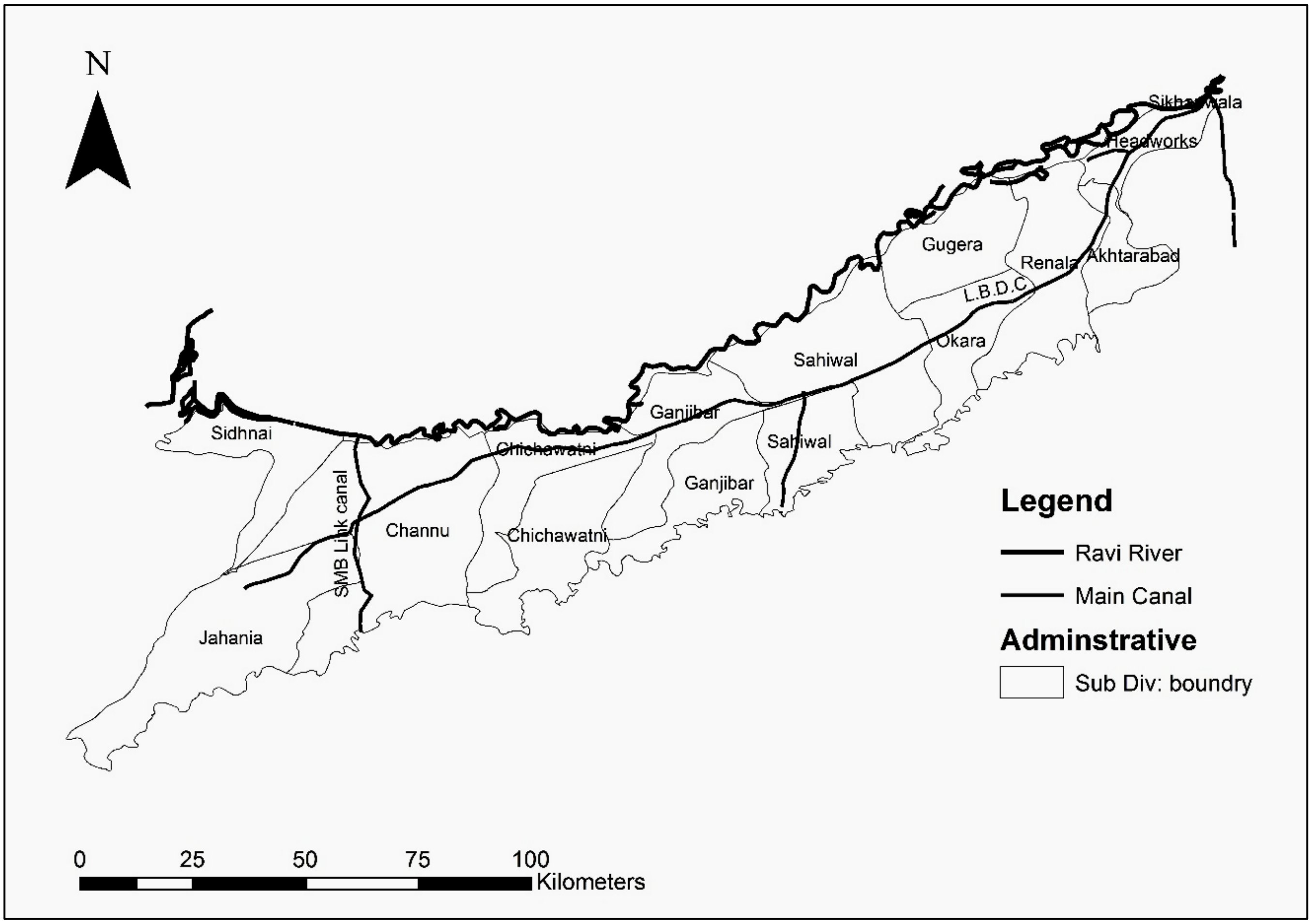



**Figure 1. Map of the study area**

**a. Lacey Theory**

Lacey gave the following set of equations for channel design

$$P = 4.75\sqrt{Q} \quad (7)$$

$$f_s = 1.76d^{\frac{1}{2}} \quad (8)$$

$$R = 0.47(\frac{Q}{f_s})^{1/3} \quad (9)$$

$$S = 0.00003 {f_s}^{5/3} Q^{1/6} \quad (10)$$

Where,

Q = Discharge ($m^3/s$)

D = Diameter of sediment (mm)

$f_s$ = Lacey's silt factor, and

P, R, S are as defined earlier

**b. Blench Theory**

The following regression equation developed by Blench was used for sand beds and cohesive to non-cohesive banks

$$d = (F_S Q/{F_B}^2)^{1/3} \quad (11)$$

$$W = (F_B Q/F_S)^{0.5} \quad (12)$$

$$F_B = 1.9\sqrt{D_{50}} \quad (13)$$

$$S = \frac{F_B^{0.875}}{3.63g/\sqrt{0.25}} W^{0.25} d^{0.125}\left(1 + \frac{C}{2330}\right) \quad (14)$$

Where,

d =Channel depth (m)

W = Channel width (m)

$F_B$ = Channel bed factor

$F_S$ = Channel side factor

Q=Discharge ($m^3/s$)

$d_{50}$= Median grain size of bed material (mm)

C = Sediment concentration (ppm)

**c. Simon and Albertson theory**

Simon and Albertson extends the analysis of regime theory for Sand bed and banks, Sand bed and cohesive banks, Cohesive bed and banks, Coarse non-cohesive material and Sand bed and cohesive banks with heavy sediment load of 2000-8000 ppm. Simon and Albertson regime analysis consist of the following set of equations

$$B = 0.9\,P \quad (15)$$

$$B = 0.92\,B_T - 2.0 \quad (16)$$

$$D = 1.21\,R \qquad \text{For } R \leq 2.13 \text{ m} \quad (17)$$

$$D = 2 + 0.93\,R \qquad \text{For } R > 2.13, \text{ and } R < 3.66 \text{ m} \quad (18)$$

$$P = K_1 Q^{1/2} \quad (19)$$

$$R = K_2 Q^{0.36} \quad (20)$$

$$V = K_3 (R^2 S)^m \quad (21)$$

$$\frac{C^2}{g} = \frac{V^2}{2DS} = K_4\left(\frac{V_b}{V}\right)^{0.37} \quad (22)$$

Where,

B= Average bed width of channel (m)
$B_T$= Top width of channel (m)
D = Average depth of channel (m)
V = Velocity (m/s)
$V_b$= Velocity at bed (m/s)
g =Acceleration due to gravity ($m/s^2$)
$K_1$, $K_2$, $K_3$, k4 and m are coefficients.
P, R, S and Q are as defined earlier

**3.2 Methods selected for sediment transport rate**

The rate of sediment transport in the selected reach of the LBDC was assessed using Lacey, Blench and Simon and Albertson regime theories in combination with five methods for bed material transport i.e. (i)Engelund-Hansen(ii) Ackers-White (iii) Ackers and White revised method (iv) Brownlie method, and (v) Yang Method. The suspended silt transport rate was assessed using two methods: (i)Westrich and Jurashek method (ii) Arora,Raju and Grade method in combination of the aforementioned regime theories. The sediment transport was analyzed for the average and design discharge scenarios and is categorized as bed material transport and the suspended silt transport.

## 4 DATA COLLECTION

Regime methods require less input data as compared to rational methods. The required input data includes the canal discharge, sediment inflow, and sediment size and soil type. The required input data to model the selected methods was collected from different Government and Non-Government organizations. Hydraulic, geometric and Sediment data of canal was collected from the project consultant NESPAK, Provisional Irrigation Department (PID) and ACE Consultants. The collected data covered the period 2001 to 2012 on daily frequency. The data was analyzed in excel work sheet to check the trends of canal discharges and sediment inflow in different years and for ease of assessments monthly and yearly averages were computed from daily data.

**4.1 Formulation of models**

Equations of tractive force method and regime theories were used to develop excel worksheet model, while DORC computer software was used for modeling the rational methods. Channel design parameters i.e. width, depth, hydraulic radius, wetted perimeter, bed slope, side slope and velocity were determined using the selected approaches. Comparison of calculated design parameters was made under the average (169.5 $m^3/s$) and design (279 $m^3/s$) discharge scenarios with improved design values given by LBDC improvement project consultants. These improvements in the design of canal prism were proposed on basis of Manning's equation after complete simulation of LBDC and economic analysis. Using the designed channel dimensions; calculation of sediment-transport rate was made in the selected reach. Then the comparison of calculated transport rate and field data collected sediment was made.

## 5 RESULTS

The design of the proposed canal was evaluated primarily based upon the analytical approach and the regime theories. Figure 2 shows the canal design evaluation framework. The design parameters were simulated against the annual average and design discharge of 169.5 and 279.0 $m^3/s$ respectively. The results of design bed width, flow depth, mean flow velocity, bed slope, sediment transport rate and bed material transport rate are furthers discussed in the following sections.

**5.1 Bed width**

Comparison of the bed width calculated by the regime approaches R2, R3 and analytical approaches A4 and A5 shows agreement with Lacey's regime approach R1. On the other scenario bed width computed by A4 and A5 under the average discharge has resulted in the most valid design which varies by 0.01% from the improved design value. All other selected analytical approaches resulted in wide variation of the bed width as shown in Figure.3.

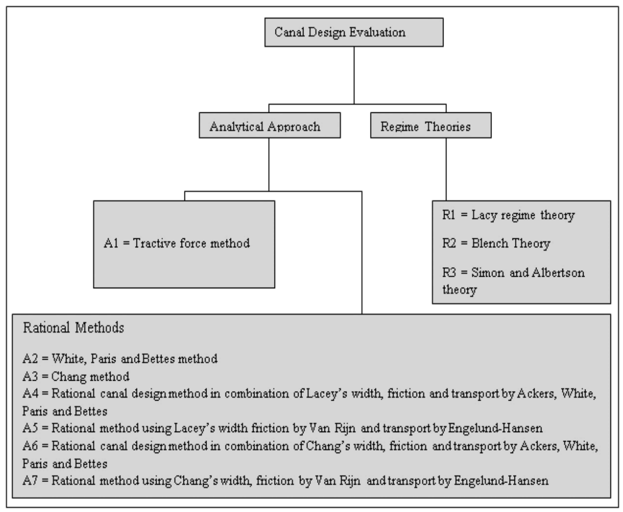



**Figure 2. Canal design evaluation framework**

On the other hand the comparison of bed width as calculated by selected regime theories under the average discharge varies with in 10% with Lacey's regime theory being the lowest (0.01%) and Blench theory being the highest (9.48%). The comparative bed width values under the design discharge scenarios are proportionally higher.

5.2 Flow depths5.4 Bed Slope

The LBDC canal traverse through an area of mild slope varies from 1 in 4000 to 1 in 10000. Comparison of computed results by A1, R2 and R3 shows agreement with the Lacey's regime. On the other hand computed results under the average and design discharge scenarios by analytical methods other than A1 resulted in bed slope which are much higher than the practicable limits in the area as shown in Figure 6.

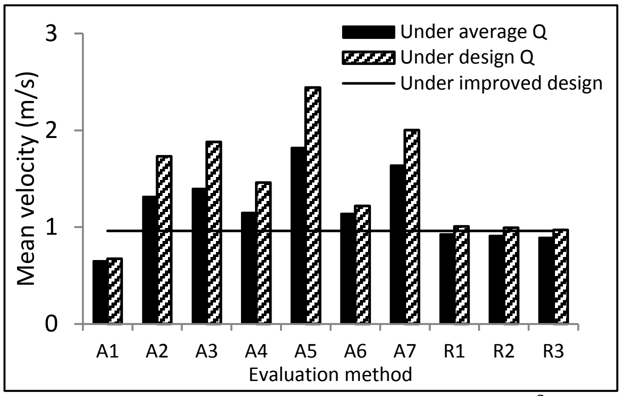



**Figure 3. Canal bed width under average (169.5 $m^3$/s) and design discharge (279.0 $m^3$/s) conditions**

However, the bed slopes calculated from different regime theories are consistent and lies in the permissible limit of 1 in 10000. The slopes computed by the rational methods are due to the fact that steeper slopes favor easy flushing of the sediment loads.

Comparison of flow depth computed by R2 and R3 shows close agreement with R1 while analytical approaches showed marked variation. Flow depth under the average

and design discharge scenarios shows that this parameter is remarkably varied under all analytical approaches with A2 being on the higher side of the improved design depth of flow while the remaining analytical approaches underestimated the flow depth as shown in Figure 4. Contrarily the flow depths calculated by the regime theories are comparatively in close agreement with the improved design depth of flow under both average and design discharge conditions. The variation in depth of flow calculated by the regime theories ranges from 8 to 19% and -9 to 6% under the average and design discharge conditions, respectively.

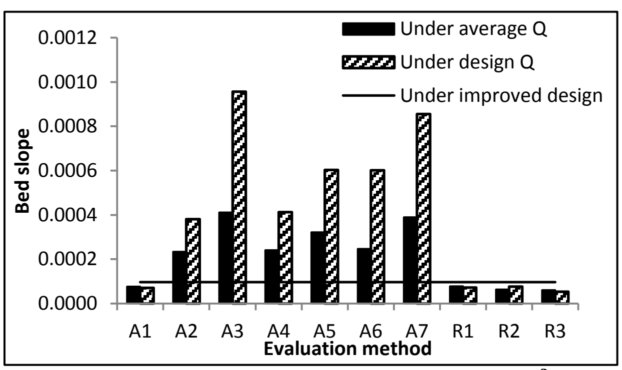
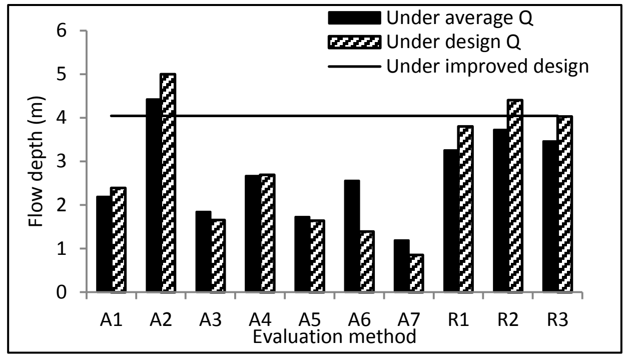



**Figure 4. Canal flow depth under average (169.5 $m^3$/s) and design discharge (279.0 $m^3$/s) conditions**

### 5.3 Mean flow velocity

Comparison of the computed average mean flow velocity by regime approaches R2 and R3 shows agreement with R1 but analytical approaches shows marked variation with R1.The average flow velocity computed under the average and design discharge conditions are varying under all analytical approaches as shown in Figure 5. A1 being the only analytical method which underestimate the flow velocity under both discharges, while the remaining of the analytical methods overestimated the flow velocity. On the other hand the regime theories resulted in comparatively good agreement of the calculated flow velocities with a variation of only 3 to 7% under the average discharge scenario and -1 to -5% under the design discharge scenario.

**Figure 5. Mean velocity of flow under average (169.5 $m^3$/s) and**

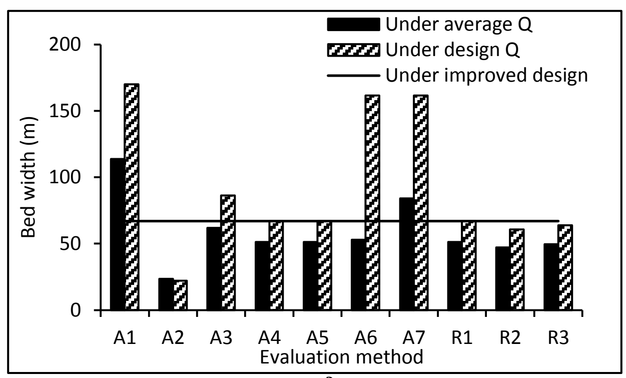



**design discharge (279.0 $m^3$/s) conditions**

### 5.5 Bed material load

The median bed material diameter ($d_{50}$) of the LBDC main canal contains sediments in the range of 0.11 to 0.23mm. The median $d_{50}$ used in this study is 0.18 mm. Comparisons of the computed sediment transport rate using the selected methods and the field data is presented in Table 1. Results shows that the Engelund and Hansen, Ackers and White and Brownlie methods give comparable results with field computed values.

**Figure 6.Canal bed slope under average (169.5 $m^3$/s) and design**




**discharge (279.0 $m^3$/s) conditions**

Sediment transport rate computed under Simon and Albertson regime theory underestimate the transport

rate and Blench theory overestimate the transport rate.

### 5.6 Suspended material load

The suspended material of LBDC consist of well graded silt with an average settling velocity of 0.24 m/s and $d_{50}$ is 0.016mm.The comparison of two methods of suspended sediment transport capacity are shown in Table 2. The results show that the Westrich and Jurashek method under estimate the suspended sediment transport capacity and

**Table 1. Comparison of Bed material transport rate**

| | Bed material sediment concentration (ppm) | | | | | | |
|---|---|---|---|---|---|---|---|
| Theory | Lacey | | Blench | | Simon & Albertson | | Observed (average) |
| Discharge | Design | Average | Design | Average | Design | Average | |
| Engelund & Hansen | 102 | 100 | 121 | 76 | 67 | 67 | 105 |
| Ackers & White (1973) | 172 | 152 | 197 | 110 | 105 | 93 | 105 |
| Ackers & White Revised | 127 | 115 | 140 | 85 | 82 | 74 | 105 |
| Yang | 37 | 36 | 44 | 25 | 22 | 22 | 105 |
| Brownlie | 135 | 125 | 133 | 98 | 100 | 93 | 105 |

**Table 2. Comparison of suspended sediments transport rate**

| | Bed material sediment concentration (ppm) | | | | | | |
|---|---|---|---|---|---|---|---|
| Theory | Lacey | | Blench | | Simon and Albertson | | Observed(average) |
| Discharge | Design | Average | Design | Average | Design | Average | |
| Westrich & Jurashek | 862 | 697 | 920 | 690 | 632 | 601 | 1244 |
| Arora,Raju & Garde | 2442 | 1123 | 1056 | 485 | 1445 | 740 | 1244 |

Arora, Raju and Grade method gives better results as compared to field observed data.

which would limit the silt carrying capacity of the channel as compared to Lacey's theory. The results further suggest that the channel design based on Lacey's theory is more acceptable despite its limitation of uncertain sediment contents. However, this deficiency could be made up by incorporating the silt carrying capacity model by Arora, Raju and Grade. Similarly the Lacey's model in combination of Engelund-Hansen or Ackers and White methods performed better in predicting the bed material transport.

Rational methods of canal design are efficient than the regime methods as they used minimum stream power concept and sediment inflow. But these methods are generally applicable where the sediment inflow is constant or has very small variation. In the LBDC canal system the sediment concentration varies with the river discharge i.e. higher sediment concentration during the summer season (June-September) and vice versa. Another other limitation of the rational methods in cases like LBDC canal is that it's predicted steep slope and high velocity to carry the sediment load in areas with naturally mild slope is impractical.

## 7 RECOMMENDATION

As concluded the tractive force method and the Blench theory is not recommended for the design of LBDC due to its exceptional channel design parameters and over estimation of sediment transport respectively. It is discouraged to use the rational methods of canal design as these methods are not capable of handling the varying silt load. The optimum design technique using the Lacey's regime theory should be used for the design of alluvial canals. Design procedures should be developed by combination of regime theories and sediment transport model while keeping in view the natural surface slope of the proposed area.

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