NUMERICAL SIMULATION OF SEDIMENTATION IN THE SAND TRAP CHAMBER USING NETNUS APPROACH

Jawad Ahmed[1], Abdul Sattar Shakir[2], Muhammad Masood[3]

[1] Centre of Excellence in Water Resources Engineering, University of Engineering and Technology Lahore, Pakistan. E-mail: jawad_114@yahoo.com

[2] Centre of Excellence in Water Resources Engineering and Dean for faculty Civil Engineering Department, University of Engineering and Technology Lahore, Pakistan. E-mail: director@cewre.edu.pk

[5] Centre of Excellence in Water Resources Engineering, University of Engineering and Technology Lahore, Pakistan. E-mail: masoud@cewre.edu.pk

ABSTRACT: *Sedimentation remains a major problem in reservoirs which not only lessens the useful life of the reservoir but also causes abrasion of turbine units; when the sediment loaded water finds its way into the power house. Sand trap is the major hydraulic structure constructed at the inlet of flow diversion structure in order to trap the sediment to alleviate the abrasion of turbine units. Role of sand trap chambers for small hydropower projects like Golen Gol Hydropower Project to exclude sediment is very significant. To analyze the efficiency of the Sand Trap Chamber in the Golen Gol Hydropower Project; NETNUS Numerical Simulation alongwith MATLAB and AutoCad Softwares was used to assess the effectiveness of the Sand Trap chamber by computing sedimentation load (tons), longitudinal sedimentation thickness (meters) and finally to propose an operational mode of operation for sediment flushing by considering two different scenarios i.e. 1) in which all three chambers in running state and 2) in which only two chambers were operated with varying sediment concentrations i.e. 0.1 kg/m^3, 0.2 kg/m^3,0.3 kg/m^3, 0.4 kg/m^3, 0.5 kg/m^3 and 0.75 kg/m^3 and 1 kg/m^3. Results of Scenario-1 indicates that power units can safely operate for 21 days without any stoppage to flush sedimentation in the sand trap when the diversion flow carries sediment concentration of 0.1 kg/m^3, but the power units have to shutdown in order to flush out the sedimentation from the sand trap chamber just after 3 days in case when the diversion flow carries sediment concentration of 1.0 kg/m^3. Results of Scenario-2 indicates that power units can safely operate for one and a half day when the diversion flow carries sediment concentration of 0.1 kg/m^3, but the power units have to shutdown in order to flush out the sedimentation from the sand trap chamber in less than a day, when the diversion flow carries sediment concentration of 1.0 kg/m^3.*

Key Words: Reservoir Sedimentation; Sediment carrying capacity; Threshold value of sedimentation, Fall velocity, Sediment Deposition Rate.

1. INTRODUCTION

Sediment can be defined as a naturally occurring solid fragmented material originated from the weathering processes of rocks and this sediment later on moved by the action of external forces i.e. water, wind, ice etc, whereas sedimentation in a general sense is a complete process of disintegration, transportation, deposition, erosion and compaction of the sediment.

As river carries a considerable amount of sediment and whenever a barrier in shape of a dam is constructed on a river, flow velocity abruptly decreases that in turn reduce the sediment-carrying capacity of the flow and ultimately sediment settle down in the reservoir and acquire very large area in the reservoir which is termed as sedimentation. Sedimentation imparts negative impact on the storage capacity of the reservoir as it lessens the active and live storages.

Continuous sedimentation in the reservoir causes many negative effects such as reduction in the storage capacity, affects the safe reservoir operation, reduces the life span, causes erosion of turbine blades, clogging of the intake structures, reduces the power generation, affects navigation & canal irrigation supplies but also causes abrasion of turbine units; when the sediment loaded water finds its way into the power house.

Sand trap is the major hydraulic structure constructed at the inlet of flow diversion structure in order to trap the sediment to alleviate the abrasion of turbine units. Chief intention of the sand trap structure is to eliminate the sediment from entering into the power house. Sand trap is usually funnel like shape which is divided into mainly three parts i.e. upstream transition; in which inlet channel is constructed with constant cross-sectional area to reduce turbulence effect, secondly, sand trap chamber; in which cross-sectional area is increased so that velocity could be reduced for the settlement of sediment and last one is the downstream transition where cross-sectional area then increase and is connected with the flushing channel. (Daneshvari Milad et al, 2012)

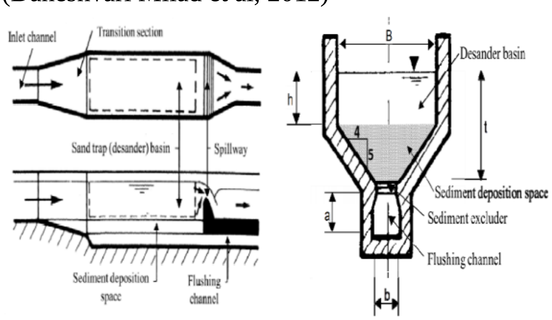


Figure 1: Sand Trap Layout

Investigation of sediment transport and flow properties that is involved during the operation of sand trap chambers is very important in order to finds out that whether components of vertical and horizontal velocities in the settling chamber is lower than critical velocity or otherwise. Design of the sand trap should also be checked with respect to dimensioning of three sand trap transitions i.e. upstream, down-stream and settling basin to guarantee that lesser velocities will be maintained all over the settling chamber for the safe retention of the sediments in the settling basin and removal of desired sediment particle sizes to check the removal efficiency. (Mustafa et al, 2013)

Investigation on the removal efficiency of the sand traps by analyzing concentration of sediments and its particle size distributions is of greater significance for not only the overall safe operation of sand trap itself but also for the safety of the turbine units against the possible abrasion of the turbine blades. In order to propose mode of sediment flushing, computations of percentage of sedimentation in the sand trap chamber and deposited sediment particle sizes should be precisely carried out, so that against the removal efficiency of the sand trap, flushing mode / period may be proposed under the prevailing sediment concentrations. (Paulos et al, 2006)

1.1. Golen Gol Hydropower Project (HPP)

Preferred area for research is Sand Trap Chamber of Golen Gol HPP which is located in Khyber Pakhtunkhwa about 22 km north of Chitral town at the junction of Golen Gol River with Mastuj River. Principal goal of the Project is to supply cheap hydel power generation of about 106 MW at a designed discharge of 29.15 m^3/s against gross head of 435 m that would produce energy of 436 GWh per year.

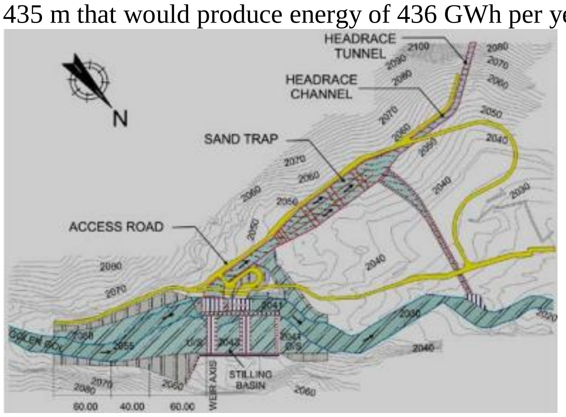


Figure 2: Layout details of Sand trap

Total length of Sand trap in Golen Gol HPP is 148.46 m which is divided into three transitions namely, upstream transition of 27.80 m, sand trap chamber of 71.40 m and downstream transition having length of 49.26 m. Isometric view of the sand trap is shown below:

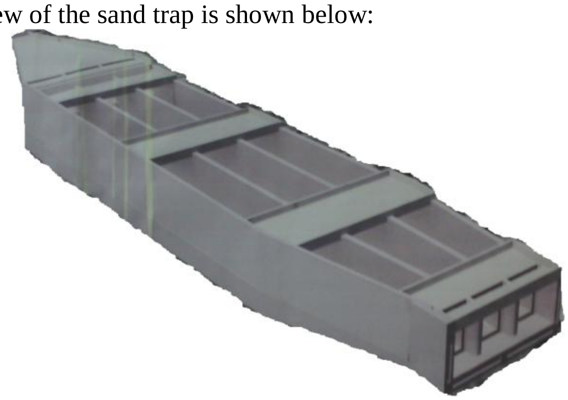


Figure 3: Isometric view of Sand trap chamber

1.2. NETNUS Approach

Role of sand trap chambers for small hydropower projects like Golen Gol HPP to exclude sediment is very significant. To analyze the efficiency of the Sand Trap Chamber, Non-Equilibrium Transportation of the Non-Uniform Sediment (NETNUS) Approach used, which is based upon the theory of Mr. Han Qiwei, Chinese Academician. NETNUS Technique is basically a 1-D Mathematical Model which has a strong theoretical foundation, comprehensive factors considered in the equations, fruitful result oriented and also proved practically in various projects. Basic Governing equations used in NETNUS Approach are as under:

Flow continuity;

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}-q_x=0$$

Flow momentum;

$$\frac{1}{gA}\frac{\partial Q}{\partial t}+\frac{\partial H}{\partial x}+\frac{1}{2g}\frac{\partial}{\partial x}\left(\frac{Q}{A}\right)^2+\frac{1}{g}\frac{Q}{A^2}q_x+\frac{n^2Q|Q|}{A^2R^{4/3}}=0$$

$$H_i=H_{i+1}+\frac{\Delta x_i n^2}{2}\left(\frac{B_i^{4/3}Q_i^2}{A_i^{10/3}}+\frac{B_{i+1}^{4/3}Q_{i+1}^2}{A_{i+1}^{10/3}}\right)+\frac{1}{2g}\left(\frac{Q_{i+1}^2}{A_{i+1}^2}-\frac{Q_i^2}{A_i^2}\right)$$

Sediment continuity;

$$\frac{\partial (AS)}{\partial t}+\frac{\partial (QS)}{\partial x}-s_x q_x+\alpha\omega B(S-S_*)=0$$

$$S_{i+1,j}=S^*_{i+1,j}+(S_{i,j}-S^*_{i,j})e^{-\frac{\alpha\omega_j\Delta x_i}{q_i}}+(S^*_{i,j}-S^*_{i+1,j})\frac{q_i}{\alpha\omega_j\Delta x_i}\left(1-e^{-\frac{\alpha\omega_j\Delta x_i}{q_i}}\right)$$

$$S_{i+1}=S^*_{i+1}+(S_i-S^*_i)\sum_{j=1}^{L}P_{i,j}e^{-\frac{\alpha\omega_j\Delta x_i}{q_i}}+(S^*_i-S^*_{i+1})\sum_{j=1}^{L}P_{i+1,j}\frac{q_i}{\alpha\omega_j\Delta x_i}\left(1-e^{-\frac{\alpha\omega_j\Delta x_i}{q_i}}\right)$$

2. METHODOLOGY

2.1. Data collection

Data in shape of river discharges, suspended and bed load sediment, suspended sediment gradation curves, drawings of sand trap chamber i.e. layout and cross-sectional areas collected. River discharges and Suspended Sediment Data from 1964 to 2010 obtained. Design discharge selected in the sand trap chamber is 29.15 m^3/s which includes flushing discharge of about 0.15 m^3/s. Suspended sediment concentration data at Golen Bridge from year 1964 to 2006 showing yearly 10 daily discharges and suspended sediment concentrations was obtained from PES which is depicted in the Tabel-1 below:

Table 1: Suspended sediment concentrations

Month	1st 10-Daily (kg/m^3)	2nd 10-Daily (kg/m^3)	3rd 10-Daily (kg/m^3)
January	0.28	0.28	0.28
February	0.27	0.27	0.27
March	0.27	0.27	0.27
April	0.27	0.28	0.29
May	0.30	0.32	0.35
June	0.39	0.42	0.47
July	0.49	0.50	0.50
August	0.50	0.48	0.46

September	0.42	0.39	0.36
October	0.34	0.32	0.31
November	0.30	0.30	0.29
December	0.29	0.29	0.28

2.2. Data processing

Sand trap chamber having length of 71.40 m divided into 18 equal sized cross-sections having length of 'Δx' i.e. 0.12 m each from inlet to the outlet to simulate the sediment transport phenomenon as under:

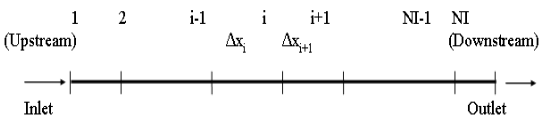


Figure-4: Cross-sections

2.3. Treatment of Non-uniform Sediment

Due to continuously exchanging of bed and suspended load in the river, sediment transport phenomenon turn into more complex and the characteristics of sediment changes from uniform to non-uniform. In order to resolve this dilemma, NETNUS Numerical Simulation Approach split the non-uniform sediment in different groups according to size and fall velocities in which they are considered to be uniform so, theories for uniform sediment can be applied to non-uniform sediment in examining the sediment transport phenomenon as shown in figure-5.

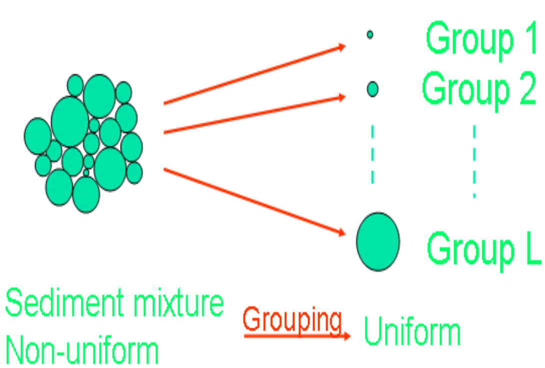


Figure-5: Grouping of non-uniform sediment

Then, particle sorting of suspended sediment will be made according to size and fall velocity 'ω' by using suspended sediment gradation curve and accordingly fall velocity will be computed by using following equation:

$$\omega = \left(\sum_{j=1}^{L} p_j \omega_j^m \right)^{\frac{1}{m}}$$

2.4. Hydraulic Parameters

Determination of the hydraulic parameters i.e. water level (H), bed slope (Zb), velocity (U), hydraulic radius (R), sediment carrying capacity (S*) at each and every cross-section by using flow continuity, flow momentum and sediment momentum equations.

2.5. Boundary conditions

Initial boundary condition i.e. design discharge (Q), sediment concentration (S), water levels (H), geometric dimensions of the sand trap chambers and water level at last cross-section as final boundary condition assigned.

2.6. Computations

All computations and iterations of the NETNUS equations performed on MATLAB Software. Sediment deposition (tons) computed from following equations by considering two different scenarios; one in which all three chamber in running state and second one in which only two chambers operated with varying sediment concentrations i.e. 0.1 kg/m^3, 0.2 kg/m^3, 0.3 kg/m^3, 0.4 kg/m^3, 0.5 kg/m^3 and 0.75 kg/m^3 and 1.0 kg/m^3.

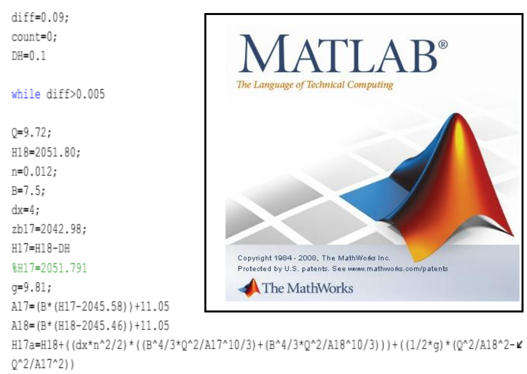


Figure-6: MATLAB computations

3. RESULTS AND DISCUSSIONS

3.1. Water diversion through 3 chambers – Scenario 1

First step in determining the sedimentation amount in sand trap chamber is to compute water levels at closely spaced intervals, for this, 18 No. cross-sections were arranged from inlet to outlet with a 4 m interval space. Water level (H) so computed at each & every cross-section is shown in the following figure:

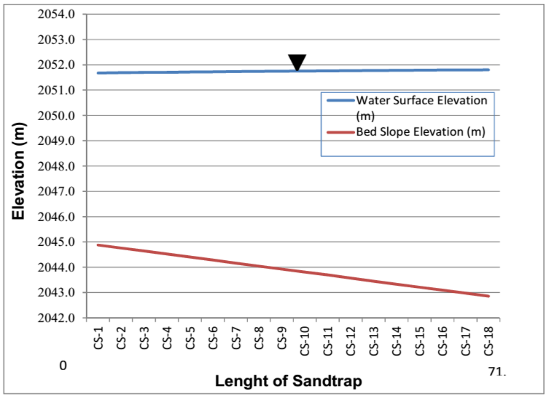


Figure-7: Water Levels at different CS

3.1.1. Diversion flow with sediment concentration 0.1 kg/m^3

After calculating the above said hydraulic parameters, computations were performed on MATLAB Software to find out sediment concentrations from cross-section 2 to 18 with known sediment concentration of 0.1 kg/m^3 at inlet. Results illustrate that sediment concentration at inlet was 0.1 kg/m^3 which is reduced to 0.0633 kg/m^3 at the outlet after 24 hours operation of sand trap chamber which is shown in following figure:

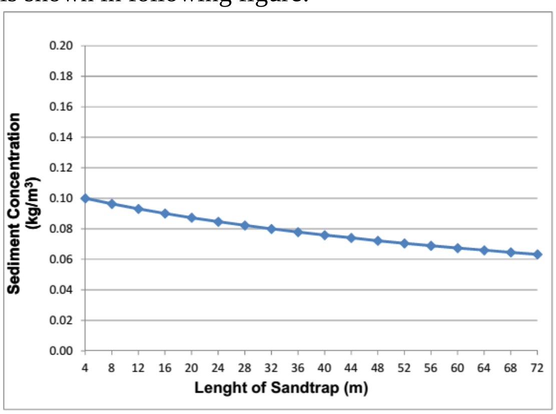


Figure-8: Sediment Concentration

Then computations for sedimentation thickness (m) performed shows that sedimentation thickness of the deposited sediment in the chamber was initially 0.58141 m at the inlet and reduced to 0.20995 m at the outlet as shown in following figure:

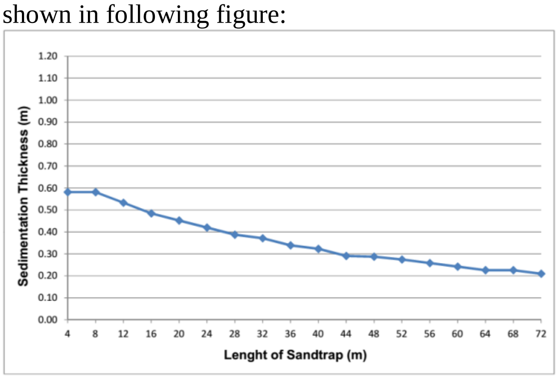


Figure-9: Sediment thickness

After that, accumulative sedimentation rate determined that comes out to be 36.7126 % at the outlet as shown is following figure:

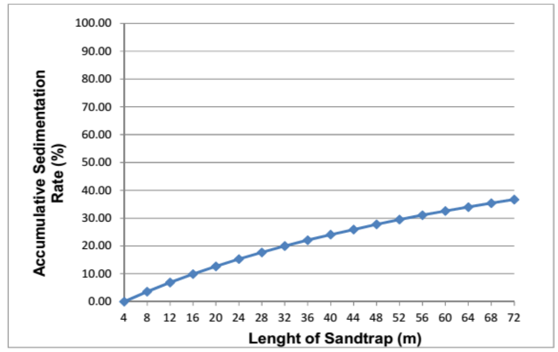


Figure-10: Accumulative Sedimentation Percentage

Finally, a comparison between initial and final bed elevation after sedimentation in the sand trap chamber is made as shown in the following figure:

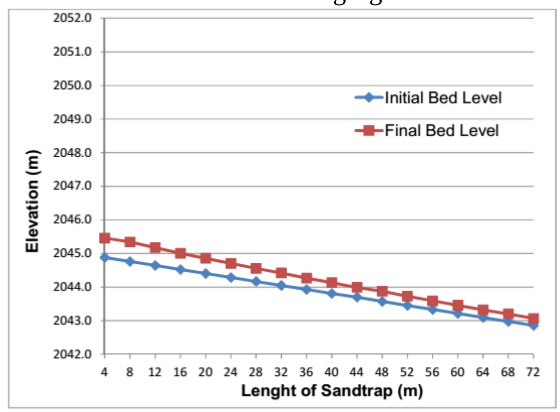


Figure-11: Initial and final bed elevations

Resulted cross-section was then drawn on AutoCad Software as shown in the following figure in order to compute area of sedimentation, so that threshold value of sedimentation can be calculated for the formulation of operational mode of operation:

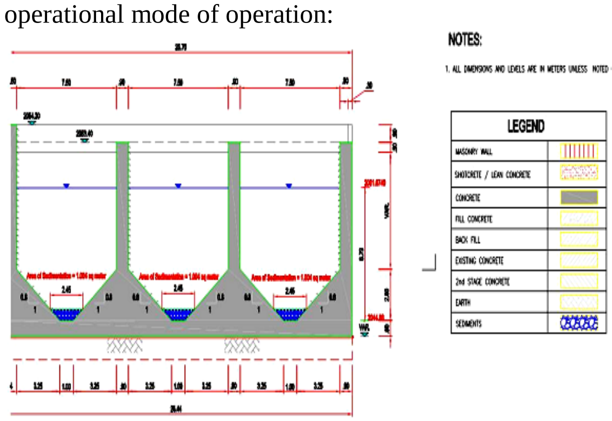


Figure-12: Sedimented cross-section

Hence, it is concluded that during 24 hours operation, 83.952 Tons of suspended sediment load was entered in the chamber and the accumulative sedimentation amount of 30.82 Tons deposited in the single chamber contributing to an accumulative sedimentation rate of 36.71 % and it would take about 21 days for inlet thickness in order to attain the threshold value (when half the chamber is filled up with sediment) when the sediment concentration at inlet is 0.1 kg/m^3.

3.1.2. Diversion flow with sediment concentration 0.2 kg/m^3, 0.3 kg/m^3, 0.4 kg/m^3, 0.5 kg/m^3, 0.75 kg/m^3 and 1.0 kg/m^3 for Scenario-1

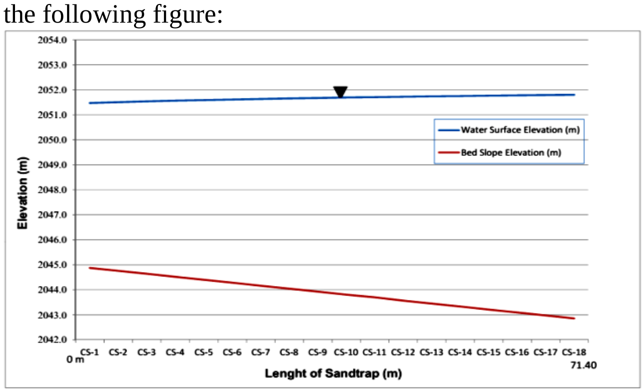
Similar computations were then performed for other sediment concentrations and results so obtained are shown in the following tabular form:

Table-2: Results for Scenario-1

Sediment Concentration at the inlet (kg/m^3)	Sediment Concentration at the outlet (kg/m^3)	Maximum Sedimentation Thickness (m)	Accumulative Sedimentation amount (tons)	Accumulative Sedimentation Rate P $(G_i)_s$ (%)	Threshold value of Sedimentation (days)
0.1	0.0633	0.5814	30.8210	36.7126	21
0.2	0.1468	0.7429	44.6778	26.6091	15
0.3	0.2301	0.9044	58.7026	23.3080	11
0.4	0.3134	1.0821	72.7274	21.6574	8
0.5	0.3967	1.2436	86.7522	20.6671	7
0.75	0.6051	1.6635	121.6882	19.3266	4
1.0	0.8135	2.0834	156.6242	18.6564	3

3.2. Water diversion through 2 chambers – Scenario 2

In scenario 2, diversion flow of 29.15 m^3/s allowed to flow in only two chambers for which the flow passing through single chamber will be 14.75 m^3/s. First step in determining the sedimentation amount in sand trap chamber is to compute water levels at closely spaced intervals, for this, 18 No. cross-sections were arranged from inlet to outlet with a 4 m interval space. Water level (H) so computed at each & every cross-section is shown in the following figure:



3.2.1. Diversion flow with sediment concentration 0.1 kg/m^3

After calculating the above said hydraulic parameters, computations were performed on MATLAB Software to find out sediment concentrations from cross-section 2 to 18 with known sediment concentration of 0.1 kg/m^3 at inlet. Results illustrate that sediment concentration at inlet was 0.1 kg/m^3 which is reduced to 0.009 kg/m^3 at the outlet after 24 hours operation of sand trap chamber which is shown in following figure:

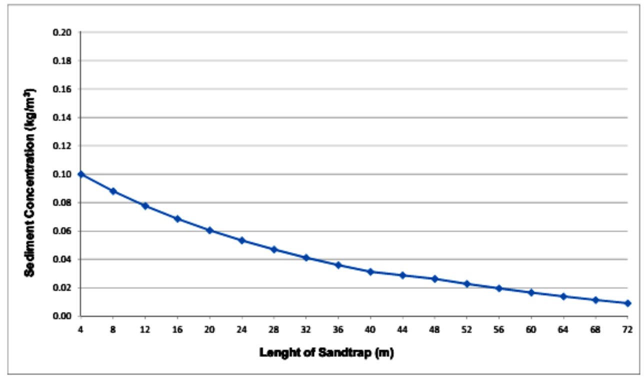


Figure-13: Sediment Concentration

Then computations for sedimentation thickness (m) performed shows that sedimentation thickness of the deposited sediment in the chamber was initially 2.9060 m at the inlet and reduced to 0.5570 m at the outlet as shown in following figure:

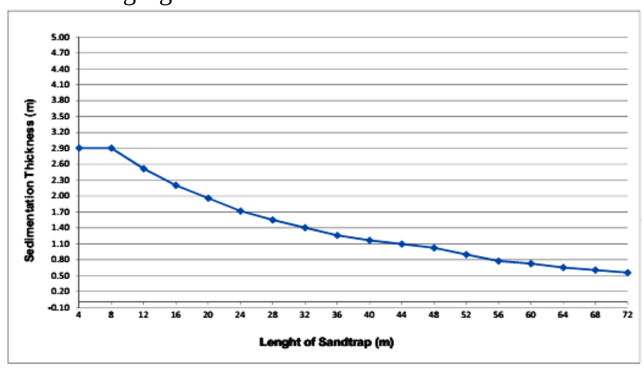


Figure-14: Sediment thickness

After that, accumulative sedimentation rate determined that comes out to be 91.00 % at the outlet as shown is following figure:

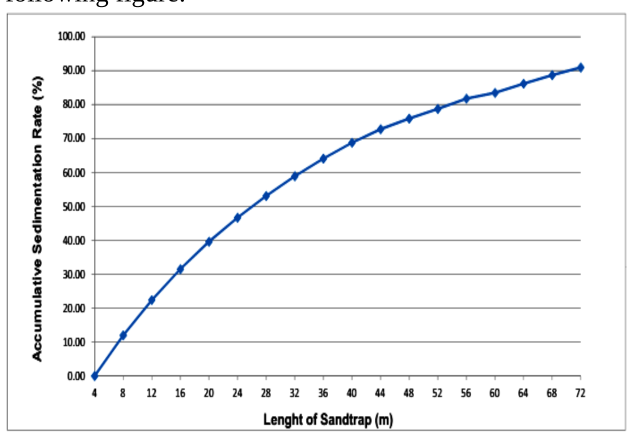


Figure-15: Accumulative Sedimentation Percentage

Finally, a comparison between initial and final bed elevation after sedimentation in the sand trap chamber is made as shown in the following figure:

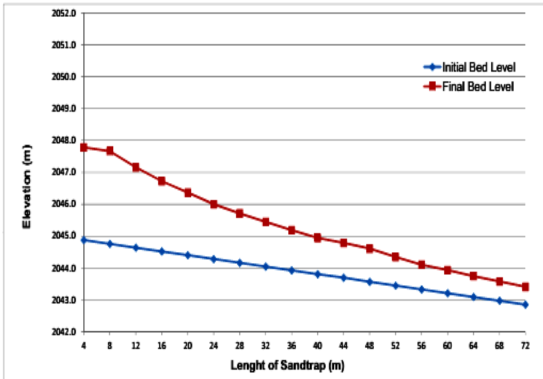


Figure-16: Initial and final bed elevations

Resulted cross-section was then drawn on AutoCad Software as shown in the following figure in order to compute area of sedimentation, so that threshold value of sedimentation can be calculated for the formulation of operational mode of operation:

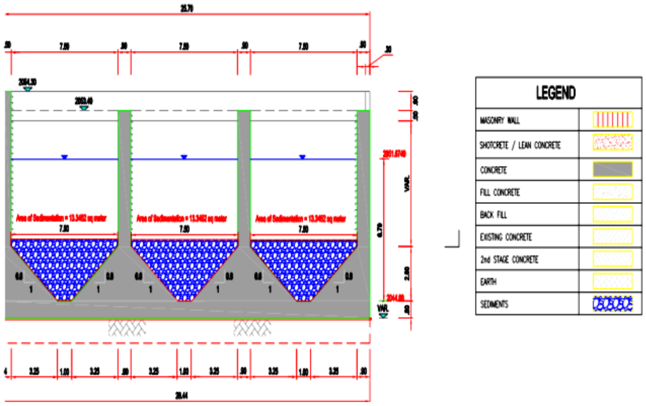


Figure-17: Sedimented cross-section

Hence, it is concluded that during 24 hours operation, 125.93 Tons of suspended sediment load was entered in the chamber and the accumulative sedimentation amount of 114.59 Tons was deposited in the single chamber contributing to an accumulative sedimentation rate of 91.00 % and it would take one and half day for inlet thickness in order to attain the threshold value (when half the chamber is filled up with sediment) when the sediment concentration at inlet is 0.1 kg/m^3.

3.2.2. Diversion flow with sediment concentration 0.2 kg/m^3, 0.3 kg/m^3, 0.4 kg/m^3, 0.5 kg/m^3, 0.75 kg/m^3 and 1.0 kg/m^3 for Scenario-1

Similar computations were then performed for other sediment concentrations and results so obtained are shown in the following tabular form:

Table-3: Results for Scenario-2

Sr. No.	Sediment Concentration at Inlet (kg/m^3)	Sediment Concentration at Outlet (kg/m^3)	Maximum Sedimenttaion Thickness (m)	Acumulative Sedimenttaion Volume (tons)	Accumulative Sedimentation Rate (%)	Threshold Value = [$A_{t/2}$] x $A_{s/day}$ (days)
1	0.10	0.0090	2.9060	114.59450	91.00	1.59
2	0.20	0.0945	3.07555	117.6700	52.75	1.45
3	0.30	0.1833	3.24507	146.9580	38.90	1.34
4	0.40	0.2718	3.3904	161.4397	32.05	1.25
5	0.50	0.3602	3.55989	176.0473	27.96	1.16
6	0.75	0.5818	3.99579	211.81090	22.43	0.99
7	1.00	0.8033	4.40748	247.70038	19.6700	0.86

4. CONCLUSIONS AND RECOMMENDATIONS

Research used two different Scenario cases. Scenario-1 is that in which all three chambers in running state with a maximum discharge of 29.15 m^3/s and discharge passing through single chamber was 9.72 m^3/s and Scenario-2 considered operation of only two chambers having maximum discharge of 29.15 m^3/s and discharge passing through single chamber was 14.57 m^3/s with varying sediment concentrations of 0.1 kg/m^3, 0.2 kg/m^3, 0.3 kg/m^3, 0.4 kg/m^3, 0.5 kg/m^3 and 0.75 kg/m^3 and 1 kg/m^3 for 24 hours operation of the sand trap chamber.

Results of Scenario-1 indicates that power units can safely operate for 21 days without any stoppage to flush sedimentation in the sand trap when the diversion flow carries sediment concentration of 0.1 kg/m^3, but the power units is recommended to shutdown in order to flush out the sedimentation from the sand trap chamber after just 3 days in case when the diversion flow carries sediment concentration of 1.0 kg/m^3.

Results of Scenario-2 depicts that power units can safely operate for one and a half day without any stoppage to flush sedimentation in the sand trap when the diversion flow carries sediment concentration of 0.1 kg/m^3, but the power units is recommended to shutdown in order to flush out the sedimentation from the sand trap chamber in less than a day, when the diversion flow carries sediment concentration of 1.0 kg/m^3.

5. ACKNOWLEDGEMENT

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APPENDIX – NOTATION

Following symbols used in this paper:

A	= cross-sectional area (m^2)
t,x	= temporal & spatial coordinates
Q	= volumetric flow discharge (m^3/s)
q_x	= lateral in/outflow, in(+)out(-) (m^2/s)
H	= water level (m)
g	= gravity acceleration (m/s^2)
n	= Manning's coefficient
R	= hydraulic radius (m)
S	= sediment concentration (kg/m^3)
s_x	= lateral inflow concentration (kg/m^3)
S_*	= sediment-carrying capacity (kg/m^3)
ω	= settling velocity (m/s)
B	= cross-sectional width (m)
P_j	= particle size percentage (%)
Δx	= cross-sectional length
α	= sediment coefficient