Estimation of Trap Efficiency and Life of Large Reservoirs by using Empirical Equations

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Abstract—This paper explores the rate of sedimentation and trap efficiency empirical methods which are important regarding the performance of reservoirs. There are various empirical relations that may be usedfordetermining trap efficiency of reservoirs. Among them, Brown (1943), Churchill (1948), Brune (1953), Dendy (1974), Gill(1979), USDA-SCS (1983) and Siyam (2000) relationshipshave been used for determination of trap efficiency of Tarbela & Mangla reservoirs. The results were compared with the observed trap efficiencies. Trap efficiency (TE) equations were also developed both for Tarbela & Mangla reservoirs along with a combine equation for both of the reservoirs. Performance of the developed equations was evaluated using reservoir data. Further, by using capacity / inflow (C/I) ratio, TE and density of sediments, useful life of Tarbela reservoirwas estimated as of 51 years (up to year 2065) and of Mangla reservoir as 154 years (up to year 2168).

Keywords—Trap Efficiency, Sediment, Empirical relations, Life of Reservoir.

I. INTRODUCTION

With the construction of a dam the velocity of incoming sediment reduces and the sedimentstart to settle down in the reservoir. The major factors which result in reservoir sedimentation are (a) capacity/inflow, (b) capacity/watershed area, (c) sedimentation index (S.I.) (period of retention/velocity). Based upon these factors, empirical relations have been developed by different researchers. Among the methods commonly used to estimate the trap efficiency of reservoir are Brune (1953) Method & Churchill (1948) Methods.Brown (1943) used capacity/watershed area (C/W), Churchill (1948) used sedimentation index, while Brune (1953) Dendy (1974), Gill (1979), USDA-SDC (1983) used capacity/inflow (C/I) and Siyam (2000) used inflow/capacity (I/C) ratio in estimation of Trap Efficiency of reservoirs.

II. STUDY OBJECTIVES

This study mainly focuses on investigation of sediment related parameters of Tarbela and Mangla reservoirs. Trap Efficiency is a very important parameter; it can be predicted using several empirical equations as stated earlier. This study has been conducted to determine the applicability of various existing empirical approaches for the estimation of trap efficiency of Tarbela and Mangla Reservoirs. The objective of this study is to investigate the best method which predicts the trap efficiency and to make comparison with actual trap efficiency computed by Hydrographic Surveys. The other objective of the study is to predict life of the reservoir from the best method which predicts trap efficiency closer to the actual trap efficiency. The other objective of this study is to develop equations for the trap efficiency of large reservoirs using the data of Mangla and Tarbela reservoirs.

III. DESCRIPTION OF STUDY AREA

Mangla and Tarbela reservoirs are located in the northern region of Pakistan near to capital city of Islamabad. The location of both of the dams may be seen in Fig. 1.

Mangla dam was completed in 1967 on the river Jhelum. The gross reservoir capacity at completion time was 7.26 Bm^3 (Billion cubic meter) and live storage of 6.59 Bm^3 which reduced to 5.67 Bm^3 and 4.50 Bm^3 in 2010receptively i.e. 21.92 %reduction in gross storage and 15.84% in live storage. Jhelum, Poonch and Kanshi rivers, contribute sediment to Mangla Reservoir.

For Mangla reservoir, Average Annual flow series from 1967 to 2010 is shown in Fig. 2. Average Annual Inflow of Mangla reservoir is 819 cumecs and maximum inflow came in years 1996. Computation of total sediment inflow to Mangla reservoir is calculated considering the sediment inflow of Jhelum, Poonch andKanshi River. Maximum sediment load came as 135.06 MST in year 2006 as represented in Fig. 4.

Tarbela dam was built on the river Indus and have catchment area of 169,600 km^2. It is an earth and rock fill dam which was completed in year 1974 to regulate the seasonal flows of the upper Indus both for irrigation and hydropower generation and receives average annual inflow of 2324 cumecs. The gross reservoir capacity at completion in 1974 was 14.34 Bm^3 (Billion cubic meter) and live storage of 11.94 Bm^3 which reduced to 9.54 Bm^3 and 8.17 Bm^3 in 2010receptively i.e. 33.5% reduction in gross storage and 31.5 % in live storage [i]. Location of Tarbela dam is shown in Fig. 1.

The annual inflow of Tarbela reservoir for 1974-2014 (40 years) is shown in Fig. 3. Average Annual inflow of Tarbela reservoir is 2324 cumecs and maximum inflow came in year 1994.Maximum sediment load came in year 2010.

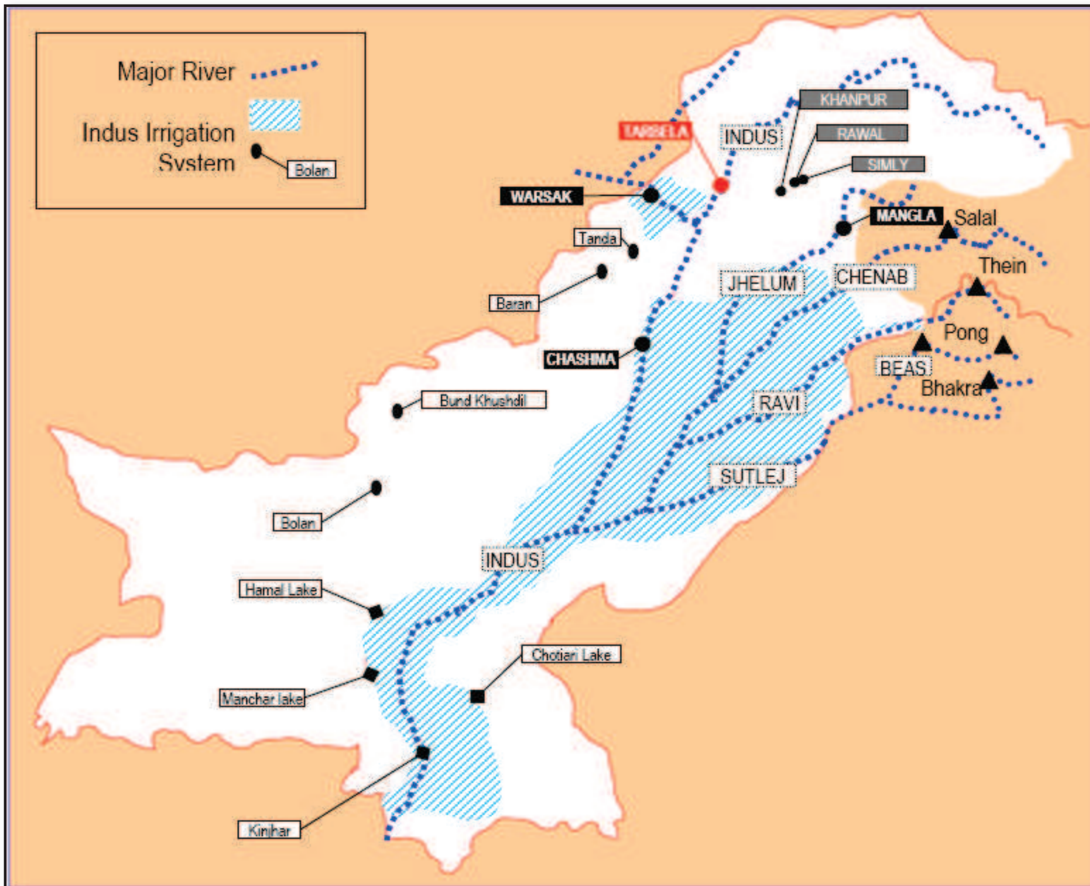

Fig. 1. Location of Tarbela and Mangla dams.

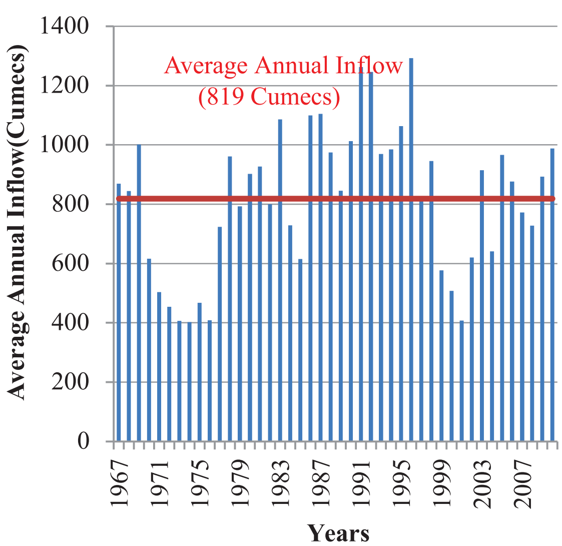

Fig. 2. Average annual inflows of Mangla reservoir.

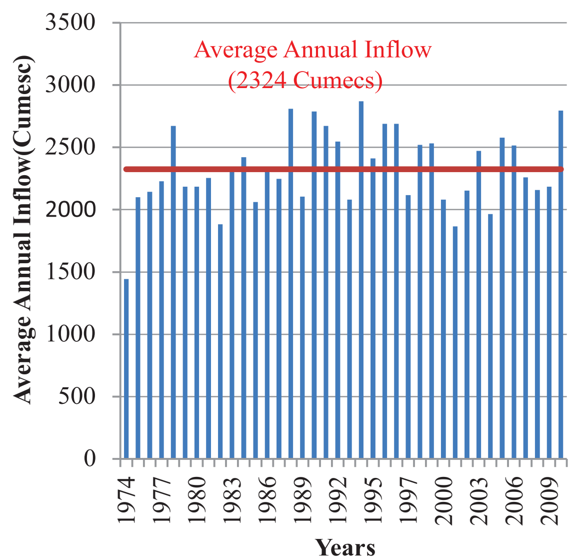

Fig. 3. Average annual inflows of Tarbelareservoir.

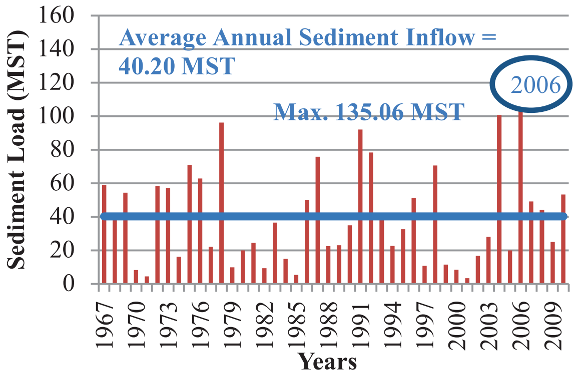

Fig. 4. Sediment load series of Mangla reservoir.

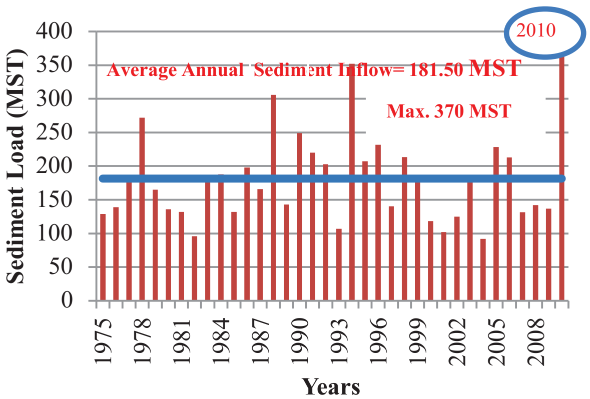

Fig. 5. Sediment load series of Tarbela reservoir.

Total sediment inflow to Mangla reservoir in year 2006 was 135.06 MST (Million Short Ton) as shown in Fig. 4, whereas, Total sediment inflow to Tarbela reservoir was estimated using the data from Besham Qila Gauging Station. Maximum sediment inflow in Year 2010 was 370 MST (Million Short Ton) as shown in Fig. 5.

IV. Sediment Trap Efficiency

Reservoir sediment trap efficiency is the ratio of the sediment deposited to the totalsediment inflowtoa reservoir.SedimentTrapEfficiencyiscalculatedbyequation (1):

$$E=\frac{[Y_s(in)-Y_s(out)]}{Y_s(in)} \quad (1)$$

where, E is the Trap efficiency, Y_s(in) is the sediment inflow in the reservoir and Y_s(out) is the sediment outflow from the reservoir.

Trap Efficiency decreases due to sedimentation. Knowledge of Trap Efficiency is needed to control the sediment accumulation and thereby the life of the reservoir, and to assure its proper operation.

There are various empirical methods for trap efficiency with some limitations. Overview of these empirical methods is discussed below.

V. Trap Efficiency Determination Methods

A. Capacity-Watershed Area Method

Brown (1943) developed a curve that shows relation of trap efficiency to capacity/watershed area, where capacity (C, in acre-ft.) and watershed area (W, in mi^2) [ii]. This curve is shown in Fig. 6 and its mathematical expression is given in equation (2):

$$E=100\ \left[1-\frac{1}{1+\frac{KC}{W}}\right] \quad (2)$$

K is the coefficient with value ranging from 0.046 to 1.0 having 0.1 value for median curve.

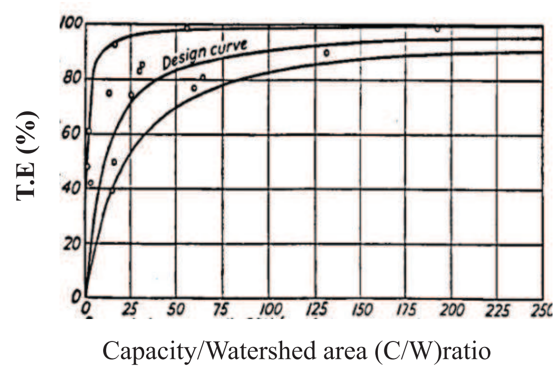

Fig. 6. Trap Efficiency curve by Brown (1943).

B. Capacity-Inflow Method (Brune Curve)

Brune (1953) used a capacity–annual inflow ratio (C/I) to predict Trap Efficiency. Brune's curves are not recommended for dry reservoirs. Trap Efficiency equation proposed by Brune is given in Equation (3):.

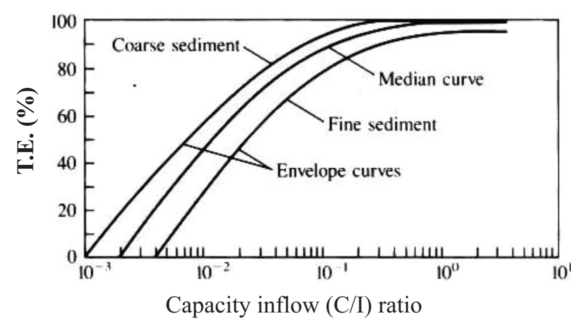

Fig. 7. Trap Efficiency curve by Brune (1953).

C. Sedimentation Index Method (Churchill's Curve)

Churchill (1948) proposed a relation between sedimentation index and percentage of silt passing through the reservoir.

The sedimentation index is defined as ratio of period of retention and mean velocity. This can be mathematically expressed as given in Equation (4):

$$S.I. = \frac{R}{V} \tag{4}$$

In this method percentage of silt passing through reservoir is obtained by subtracting Trap Efficiency from 100, which is on ordinate axis and sedimentation index is on X-axis as shown in Fig. 8. This method is used for small reservoirs [iv]. Trap Efficiency is calculated using the equation (5):

$$(1 - T.E.) = (800) \cdot (S.I.)^{0.2} - 12 \tag{5}$$

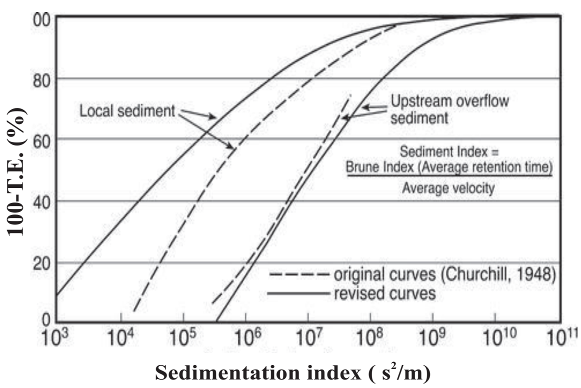

Fig. 8. Trap Efficiency curve by Churchill.

D. USDA-SCS Curves

USDA-SCS (1983) developed Trap Efficiency equations using Capacity / Inflow ratios for different textures. Trap efficiency be lowered for sandy and fine sediments [xxiv]. USDA-SCS curves are shown in Fig. 9 and Equations are shown in Table I.

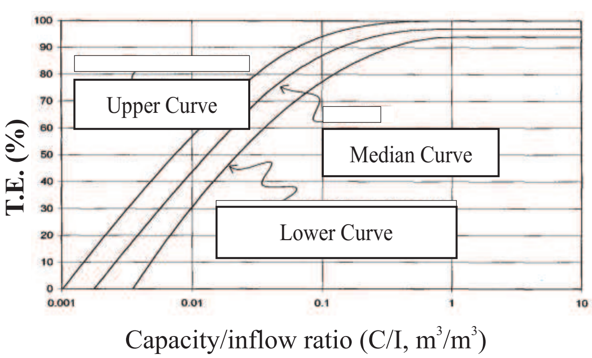

Fig. 9. Trap Efficiency curves by USDA-SCS.

TABLE I
USDA-SCS PREDICTION EQUATIONS

	C/I>1	1>C/I>0.02	C/I<0.02
Upper curve	100	$100 - (0.485)\lvert\ln(C/I)\rvert^{2.99}$	$124 - (6.59)\lvert\ln(C/I)\rvert^{1.52}$
Median curve	97	$97 - (1.275)\lvert\ln(C/I)\rvert^{2.47}$	$128 - (11.51)\lvert\ln(C/I)\rvert^{1.304}$
Lowerc urve	94	$94 - 3.38\lvert\ln(C/I)\rvert^{1.92}$	$94 - 3.38\lvert\ln(C/I)\rvert^{1.92}$

E. Dendy (1974) Method

Dendy (1974) developed a Trap Efficiency equation (6) for the median curve:

$$E = (100)(0.97)^{\left[0.19*LOG\left(\frac{C}{I}\right)\right]} \tag{6}$$

This equation was developed by Dendy by adding more data to Brune method [v].

F. Gill (1979) Method

Gill (1979) developed equations (Eqs.7-9) which provide close results to Brune's curves [viii].

Lower Curve:

$$T_e = \frac{\left(\frac{C}{I}\right)^2}{\left[0.994701\left(\frac{C}{I}\right)^2 + 0.006297\left(\frac{C}{I}\right) + 0.3 \cdot 10^{-5}\right]} \tag{7}$$

Median Curve:

$$T_e = \frac{\left(\frac{C}{I}\right)}{\left[0.012 + \left(\frac{1.02C}{I}\right)\right]} \tag{8}$$

Upper Curve:

$$T_e = \frac{\left(\frac{C}{I}\right)^3}{\left[1.02655\left(\frac{C}{I}\right)^3 + 0.02621\left(\frac{C}{I}\right)^2 - 0.133 \cdot 10^3 \cdot \left(\frac{C}{I}\right) + 0.1 \cdot 10^{-5}\right]} \tag{9}$$

where, T_e is trap efficiency of the reservoir in decimal, C is capacity of reservoir in volume units and I is mean annual inflow in volume units.

F. Siyam (2000) Method

Siyam (2000) developed a new relationship for the trap efficiency of reservoirs showing that Brune curves are a case of trap efficiency in exponential function as shown in Equation(10):

$$T.E.(\%) = 100[e]^{-\beta\left(\frac{I}{C}\right)} \tag{10}$$

where I/C is the ratio between average annual inflow (I) and reservoir capacity (C), β is a sedimentation parameter which have valuesequalto0.0055,0.0079and0.015for upper, lower and median curves respectively [xix].

VI. USEFUL LIFE ESTIMATION

Useful life of reservoir is defined as the period up to which reservoir can serve the defined purpose;while, economic life is defined as the period after which the cost of operating the reservoir exceeds the additional benefits expected from it; whereas, design life is generally the useful life; likewise; full life period is that when no capacity is available in the reservoir for useful purpose. In most of the developed countries full life is said to be arrived, when half of the total capacity of reservoir is depleted [vii].

In the present study, trap efficiency calculated using Dendy method, Brune Method, Gill Method, Churchill Method and Hydrographic survey methods have been adopted to estimate the life of Tarbela and Mangla reservoirs. Life of reservoirs is determined considering the sedimentation rate will remain constant and 80% of reservoir useful capacity will deplete.

VII . METHODOLOGY

To investigate sediment related parameters data mentioned below was assembled from Besham Qila stream gauging station for Tarbela reservoir and Mangla Cableway gauging station for Mangla reservoir. The data obtained was analyzed and Trap efficiencies were calculated using the Trap Efficiency equations considering the parameters of Capacity, Average Annual Inflow, Sedimentation Index, Watershed area. Suspended Sediment data was collected through Hydrographic surveys. Life of reservoirs was calculated considering the sedimentation rate and predicting trend equations, considering useful life of reservoir as 80%.

A. Data Collection for Mangla reservoir and Trap Efficiency Estimation

Suspended sediment inflow data was assembled for Jhelum River at Kohala, Poonch River at Kotli and Kanshi River near Palote for years (1967-2010) from SWHP (Surface Water Hydrology Project), WAPDA.

Average daily inflow data from Mangla cableway gauging station was collected, which is upstream of Mangla reservoir, for years (1967-2010) from SWHP (Surface Water Hydrology Project), WAPDA.Bed load was calculated using the Modified Einstein Method, according to which 10 to 20 % of suspended sediment load is considered as bed load.

Actual Trap Efficiency of Tarbela reservoir was calculated as ratio of Suspended Sediment inflow to Total Sediment inflow

After analyzing data, Trap Efficiency of Mangla reservoir was estimated using the equations of Brown (1943), Churchill (1948), Brune (1953), Dendy (1974), Gill (1979), USDA-SDC (1983) and Siyam (2000).

B. Data Collection for Tarbela reservoir and Trap Efficiency Estimation

Suspended sediment inflow data from Besham Qila [which is upstream of Tarbela reservoir] stream gauging station were assembled, for years (1974-2010) from SWHP (Surface Water Hydrology Project), WAPDA,along with sediment data, mean daily inflow data were also assembled for this site.

Bed load was calculated using the Modified Einstein Method, according to which 10 to 20 % of suspended sediment load is considered as bed load. Actual Trap Efficiency of Tarbela reservoir was calculated as ratio of Suspended Sediment inflow to Total Sediment inflow.

After analyzing data, Trap efficiency of Tarbela was estimated using the equations of Brown (1943), Churchill (1948), Brune (1953), Dendy (1974), Gill (1979), USDA-SDC (1983) and Siyam (2000).

C. Comparison of Trap Efficiencies

After trap efficiency calculation by empirical methods for both reservoirs, a comparison of computed trap efficiencies was made with the trap efficiencies calculated using Hydrographic Survey data to analyze which method gives close fit value to the observed trap efficiency, so that a method for future use may be proposed.

D. Development of Equations for Trap Efficiency

To develop correlation for trap efficiency, factors of capacity/inflow (C/I), capacity/watershed (C/W) and sedimentation index (S.I.) were analyzed for both reservoirs, which predicted that C/I has more influence on trap efficiency. Hence 3 equations between C/I and T.E. were developed, one using the data of Mangla reservoir, one using the data of Tarbela reservoir, one combined equation using the data of Tarbela & Mangla reservoirs. Performance of these equations was evaluated using the data of Simly reservoir.

VIII. RESULTS & DISCUSSIONS

A. Tarbela Reservoir Trap Efficiency Results

Comparison of trap efficiency using Hydrographic Survey data and estimated trap efficiencies by different empirical methods of Tarbela reservoir is shown in Table II and Fig. 10.

Trap Efficiency curve calculated through Hydrographic Survey shows that data is so scattered. Comparison of Tarbela reservoir trap efficiency calculated by different methods shows that new developed curve has close relation with the Hydrographic Survey curve as shown in Fig. 10.

TABLE II
TRAP EFFICIENCY OF TARBELA RESERVOIR (1974-2010) USING EMPIRICAL METHODS

Year	**Brown**	**Brune**	**Churchill**	**Gill**	**Dendy**	**USDA SCS**	**Siyam**	**New Developed Equation**	**Hydrographic Survey**
1974	94.88	90.07	92.48	90.78	90.60	95.93	96.05	92.34	94
1975	94.84	90.02	92.44	87.25	90.54	95.94	96.38	89.05	94
1976	94.79	89.98	92.39	86.96	90.48	95.95	96.27	89.05	94
1977	94.74	89.94	92.34	86.47	90.42	95.96	96.09	89.05	94
1978	94.70	89.90	92.29	84.44	90.36	95.98	95.28	89.05	94
1979	94.60	89.81	92.18	86.39	90.23	96.00	96.06	89.05	94
1980	94.60	89.81	92.18	86.38	90.23	96.00	96.05	89.05	92
1981	94.48	89.70	92.05	85.80	90.07	96.03	95.83	85.58	97
1982	94.44	89.67	92.01	87.55	90.02	96.04	96.48	85.58	84
1983	94.40	89.63	91.96	85.24	89.97	96.05	95.61	85.58	73
1984	94.32	89.56	91.88	84.72	89.86	96.07	95.40	85.58	86
1985	94.27	89.53	91.83	86.34	89.81	96.08	96.04	81.90	99
1986	94.23	89.49	91.78	85.04	89.75	96.09	95.53	81.90	72
1987	94.19	89.46	91.74	85.27	89.70	96.10	95.62	81.90	58
1988	94.13	89.41	91.68	82.66	89.63	96.11	94.51	81.90	54
1989	94.09	89.37	91.64	85.77	89.57	96.12	95.82	81.90	84
1990	94.02	89.31	91.55	82.51	89.48	96.14	94.43	81.90	84
1991	93.95	89.26	91.49	82.87	89.40	96.15	94.60	78.01	72
1992	93.91	89.23	91.44	83.33	89.34	96.16	94.81	78.01	59
1993	93.87	89.20	91.40	85.49	89.29	96.17	95.71	78.01	91
1994	93.75	89.10	91.26	81.58	89.14	96.20	94.00	78.01	90
1995	93.69	89.05	91.20	83.52	89.06	96.21	94.89	78.01	72
1996	93.62	89.00	91.13	82.12	88.98	96.23	94.26	78.01	87
1997	93.55	88.95	91.06	84.72	88.89	96.24	95.40	73.87	87
1998	93.50	88.91	90.99	82.64	88.82	96.25	94.50	73.87	87
1999	93.40	88.84	90.89	82.40	88.70	96.27	94.39	73.87	87
2000	93.40	88.83	90.89	84.64	88.70	96.27	95.36	73.87	86
2001	93.26	88.74	90.74	85.58	88.53	96.30	95.74	73.87	86
2002	93.19	88.69	90.67	83.89	88.45	96.32	95.05	69.44	87
2003	93.13	88.64	90.60	82.17	88.36	96.33	94.28	69.44	67
2004	93.07	88.59	90.53	84.68	88.29	96.34	95.38	69.44	61
2005	93.01	88.55	90.47	81.44	88.22	96.35	93.94	69.44	48
2006	92.89	88.47	90.34	81.52	88.07	96.38	93.97	69.44	84
2007	92.79	88.40	90.23	82.62	87.95	96.39	94.49	69.44	80
2008	92.72	88.36	90.16	83.04	87.87	96.41	94.68	64.68	70
2009	92.69	88.33	90.12	82.84	87.82	96.41	94.59	64.68	64
2010	92.50	88.21	89.92	79.46	87.60	96.45	92.94	64.68	85
	93.83	89.19	91.35	84.33	89.25	96.17	95.15	78.61	81

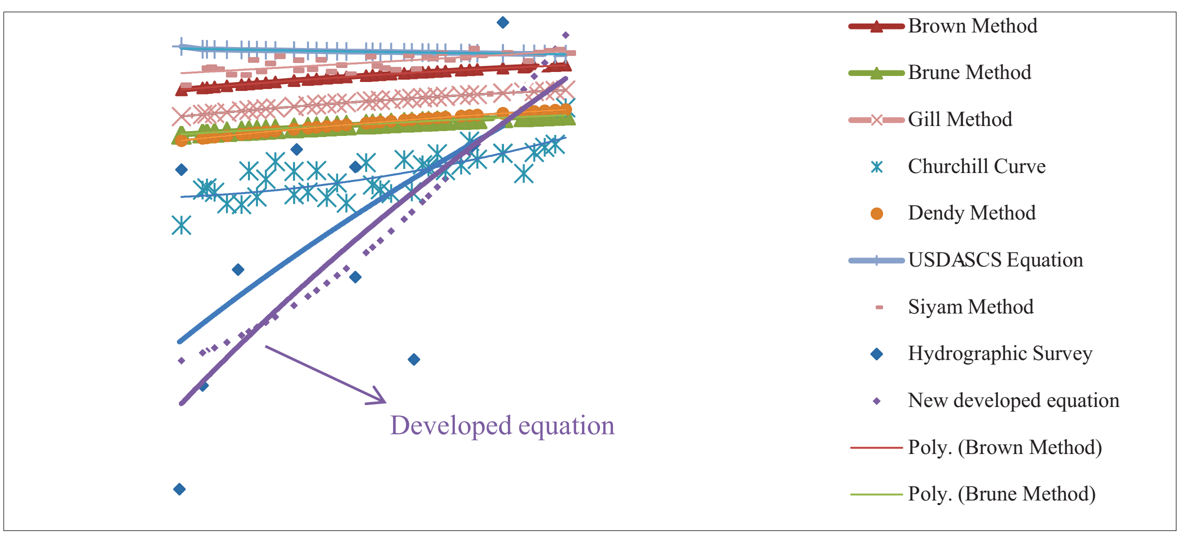

Fig. 10: Comparison of Trap Efficiencies of Tarbela reservoir using empirical methods.

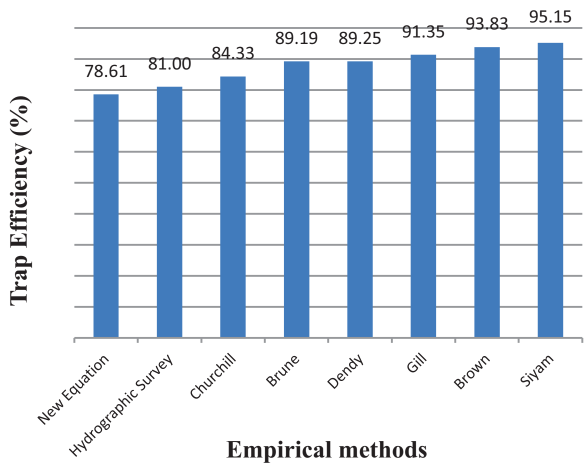

Fig. 11. Comparison of trapefficiencies of Tarbela reservoir.

Whereas, trap efficiency computed by Empirical methods in comparison with observed one is given in the following chronological order:

i. New Equation, 2.9% less than observed T.E.
ii. Churchill Method, 2.9% more than observed T.E.
iii. Brune Method, 10.11% more than observed T.E.
iv. Dendy Method, 10.19% more than observed T.E.

A. Life of Tarbela Reservoir Results

Comparison of life of Tarbela reservoir by different empirical methods is shown in Fig. 12. According to Hydrographic Survey Life of Tarbela reservoir is up to year 2064 and as per New developed equation Life of Tarbela reservoir is up to year 2065 as shown in Fig.12.

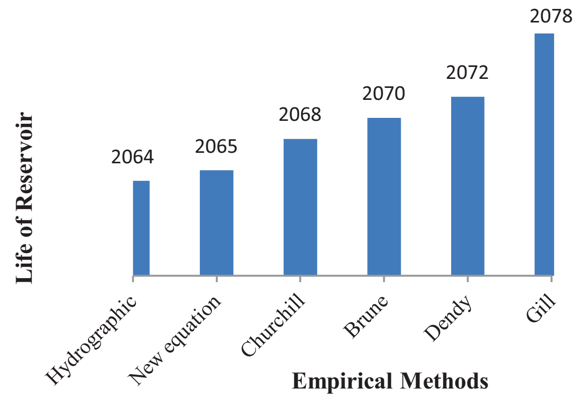

Fig. 12. Comparison of Life of Tarbela reservoir

B. Mangla Reservoir Trap Efficiency Results

Comparison of trap efficiency using Hydrographic Survey data and estimated trap efficiencies by different empirical methods of Mangla reservoir is shown in Table III and Fig. 13.

Comparison of Mangla reservoir Trap Efficiency calculated by different methods shows that new developed curve has close relation with the Trap Efficiency calculated through Hydrographic survey as shown in Fig. 13.

TABLE III
TRAP EFFICIENCY OF MANGLA RESERVOIR USING EMPIRICAL METHODS

Years	Brown	Brune	Churchill	Gill	Dendy	USDA-SCS	Siyam	New Developed Equation	Hydrographic Survey
1967	97.85	91.41	88.63	93.85	92.33	95.55	97.04	90.00	90.91
1968	97.85	91.41	88.89	93.85	92.33	95.55	97.04	90.00	90.91
1969	97.85	91.41	87.26	93.85	92.33	95.55	97.04	90.00	90.91
1970	97.81	91.32	91.46	93.76	92.22	95.58	96.98	90.00	90.91
1971	97.81	91.32	93.06	93.76	92.22	95.58	96.98	90.00	90.09
1972	97.81	91.32	93.83	93.76	92.22	95.58	96.98	90.00	90.09
1973	97.77	91.23	94.47	93.68	92.12	95.60	96.93	89.43	90.09
1974	97.77	91.23	94.54	93.68	92.12	95.60	96.93	89.43	89.29
1975	97.77	91.23	93.46	93.68	92.12	95.60	96.93	89.43	89.29
1976	97.77	91.23	94.43	93.68	92.12	95.60	96.93	89.43	89.29
1977	97.77	91.23	89.93	93.68	92.12	95.60	96.93	89.43	89.29
1978	97.67	91.03	86.83	93.50	91.88	95.66	96.79	88.84	89.29
1979	97.67	91.03	88.70	93.50	91.88	95.66	96.79	88.84	88.34
1980	97.67	91.03	87.47	93.50	91.88	95.66	96.79	88.84	88.34
1981	97.67	91.03	87.20	93.50	91.88	95.66	96.79	88.84	88.34
1982	97.67	91.03	88.62	93.50	91.88	95.66	96.79	88.84	88.34
1983	97.62	90.94	85.36	93.41	91.76	95.68	96.73	88.84	88.34
1984	97.62	90.94	89.29	93.41	91.76	95.68	96.73	88.84	88.89
1985	97.62	90.94	90.78	93.41	91.76	95.68	96.73	88.84	88.89
1986	97.62	90.94	85.23	93.41	91.76	95.68	96.73	88.84	88.89
1987	97.62	90.94	85.18	93.41	91.76	95.68	96.73	88.84	88.89
1988	97.57	90.83	86.24	93.30	91.62	95.72	96.65	88.22	88.89

1989	97.57	90.83	87.66	93.30	91.62	95.72	96.65	88.22	87.72
1990	97.57	90.83	85.84	93.30	91.62	95.72	96.65	88.22	87.72
1991	97.57	90.83	83.43	93.30	91.62	95.72	96.65	88.22	87.72
1992	97.57	90.83	83.57	93.30	91.62	95.72	96.65	88.22	87.72
1993	97.46	90.63	85.84	93.10	91.37	95.77	96.50	87.57	87.72
1994	97.46	90.63	85.68	93.10	91.37	95.77	96.50	87.57	87.57
1995	97.46	90.63	84.86	93.10	91.37	95.77	96.50	87.57	87.57
1996	97.46	90.63	82.65	93.10	91.37	95.77	96.50	87.57	87.57
1997	97.39	90.51	87.36	92.97	91.21	95.81	96.41	87.57	87.57
1998	97.39	90.51	85.82	92.97	91.21	95.81	96.41	87.57	87.64
1999	97.39	90.51	90.51	92.97	91.21	95.81	96.41	87.57	87.64
2000	97.36	90.44	91.47	92.90	91.12	95.82	96.35	86.89	87.64
2001	97.36	90.44	93.19	92.90	91.12	95.82	96.35	86.89	87.34
2002	97.34	90.42	89.72	92.88	91.09	95.83	96.34	86.89	87.34
2003	97.34	90.42	85.96	92.88	91.09	95.83	96.34	86.89	87.18
2004	97.34	90.42	89.42	92.88	91.09	95.83	96.34	86.89	87.18
2005	97.31	90.37	85.26	92.82	91.02	95.85	96.29	86.89	87.18
2006	97.31	90.37	86.28	92.82	91.02	95.85	96.29	86.89	86.88
2007	97.31	90.37	87.56	92.82	91.02	95.85	96.29	86.89	86.88
2008	97.31	90.37	88.12	92.82	91.02	95.85	96.29	86.89	86.88
2009	97.31	90.37	86.10	92.82	91.02	95.85	96.29	86.89	86.88
2010	97.27	90.29	84.83	92.73	90.91	95.87	96.23	86.89	86.88
Average	97.56	90.83	93.29	88.23	91.62	95.71	96.64	88.31	88.38

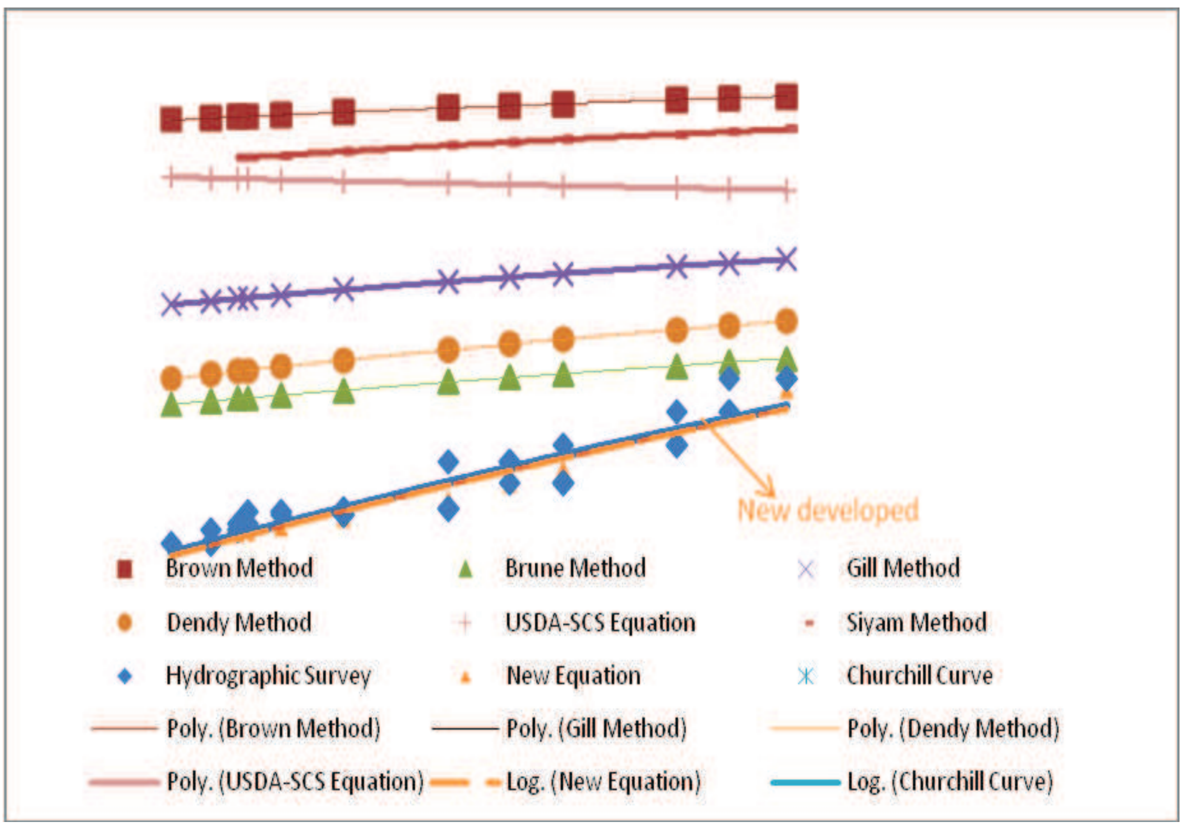

Fig. 13. Comparison of Trap Efficiencies of Mangla reservoir using empirical methods.

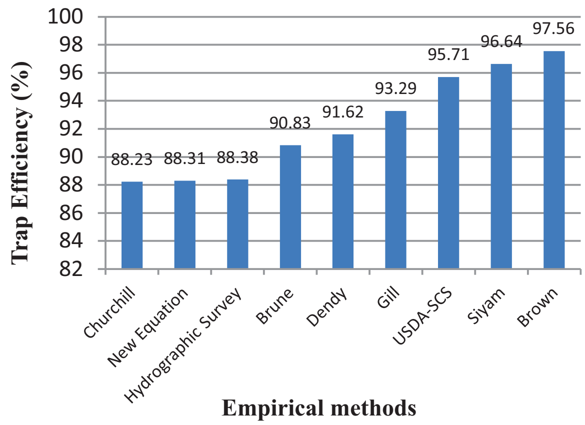

Fig. 14. Comparison of trap efficiencies of Mangla reservoir.

Figure 14 depicts such a comparison of trap efficiencies by different empirical methods for average value of all years. Comparison of Trap Efficiencies of Mangla reservoir for 1967-2010 by different empirical methods is represented in Table III.

Whereas, trap efficiency computed by Empirical methods in comparison with observed one is given in the following chronological order:

i. New developed equation, 0.08% less than observed T.E.
ii. Churchill Method, 0.17% less than observed T.E.
iii. Brune Method, 2.7% more than observed T.E.
iv. Dendy Method, 3.6% more than observed T.E.
v. Gill Method, 5.5% more than observed T.E.

C. Life of Mangla Reservoir Results

According to Bruneand Hydrographic Survey Method life of Mangla reservoir is up to year 2140 and as per new developed equation life of reservoir is up to year 2168 (154 years) as shown in Fig. 15.

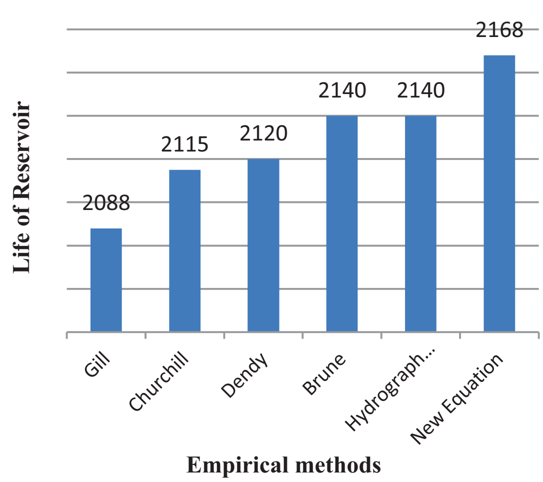

Fig. 15. Comparison of Life of Mangla reservoir.

D. Development of Equations for Trap Efficiency

In present study, considering C/I and S.I. factors, Trap efficiency equations have been developed. A comparison of influence of C/I and S.I. on trap efficiency for both Mangla and Tarbela reservoir is shown in Fig. 16 & 17 respectively, whereas, combined for both reservoirs is shown in Fig. 18.

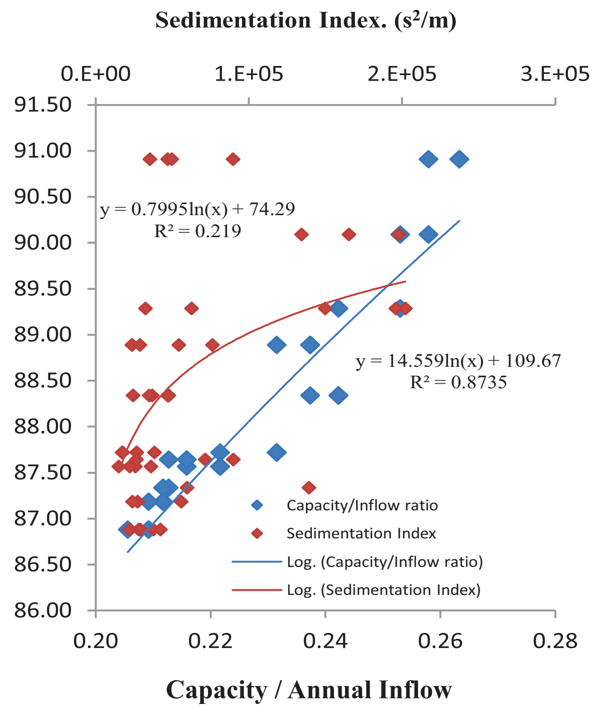

Fig. 16. Comparison of influence of C/I and S.I. on Trap Efficiency for Mangla reservoir.

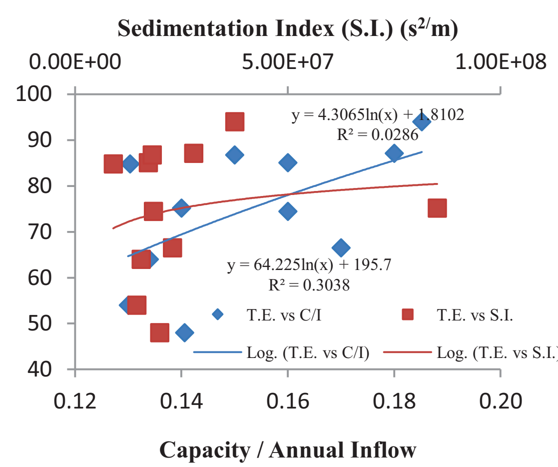

Fig. 17. Comparison of influence of C/I and S.I. on Trap Efficiency for Tarbela reservoir.

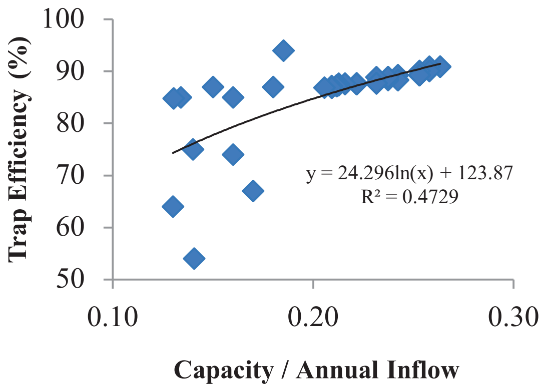

Fig. 18. Development of one combined equation for Tarbela and Mangla reservoir.

The developed correlations in this regard between C/I and T.E. given in Equations (11-13) respectively:

Mangla reservoir trap efficiency equation:

$$\text{T.E.} = 14.5 \ln\left(\frac{C}{I}\right) + 110 \quad (11)$$

Tarbela reservoir trap efficiency equation:

$$\text{T.E.} = 64.2 \ln\left(\frac{C}{I}\right) + 196 \quad (12)$$

Generalized trap efficiency equation:

$$\text{T.E.} = 24.3 \ln\left(\frac{C}{I}\right) + 124 \quad (13)$$

IX. Check the Performance of Newly Developed Equations

To check the performance of newly developed equations, these equations were used on Simly reservoir, which is located near Rawalpindi (330 43' 8" N and 730 20' 25"E) on Soan River. It was constructed in 1982; its storage capacity was 28.370 Mm3when developed, which was increased up to 40.70 Mm3 in 2005. Its watershed size is 153.5 km2. The elevation of Simly catchmentranges from 643-2274 meter. The comparison of performance of newly developed Trap Efficiency equations is shown in Table-IV and Fig.19.

Equation 12 gives higher results of Trap Efficiencies, so it is not recommended; moreover these equations are recommended for large reservoirs.

TABLE IV
TRAP EFFICIENCY OF SIMLY RESERVOIR USING NEWLY DEVELOPED EQUATIONS

Capacity (C), (Acre-feet)	Average Annual Inflow(I), (Acre-feet)	Capacity/Avg. Annual Inflow (C/I)	Equation-11 T.E.=14.5ln(C/I) +110	Equation-12 T.E.=64.2ln(C/I) +196	Equation-13 T.E.=24.3ln(C/I)+ 124
22919	77706	0.295	92.30	117.61	94.33
22838	77706	0.294	92.24	117.39	94.24
22757	77706	0.293	92.19	117.16	94.16
22676	77706	0.292	92.14	116.93	94.07
22595	77706	0.291	92.09	116.70	93.98
22514	77706	0.290	92.04	116.47	93.90
22351	77706	0.288	91.93	116.00	93.72
22189	77706	0.286	91.83	115.54	93.54
22027	77706	0.283	91.72	115.07	93.37
21865	77706	0.281	91.61	114.59	93.19
21703	77706	0.279	91.51	114.11	93.01
21541	77706	0.277	91.40	113.63	92.82
21338	77706	0.275	91.26	113.03	92.59
21135	77706	0.272	91.12	112.41	92.36
20933	77706	0.269	90.98	111.79	92.13
20730	77706	0.267	90.84	111.17	91.89
20487	77706	0.264	90.67	110.41	91.60
20244	77706	0.261	90.50	109.64	91.31
20000	77706	0.257	90.32	108.87	91.02
19757	77706	0.254	90.14	108.08	90.72
19514	77706	0.251	89.96	107.29	90.42
19271	77706	0.248	89.78	106.48	90.12

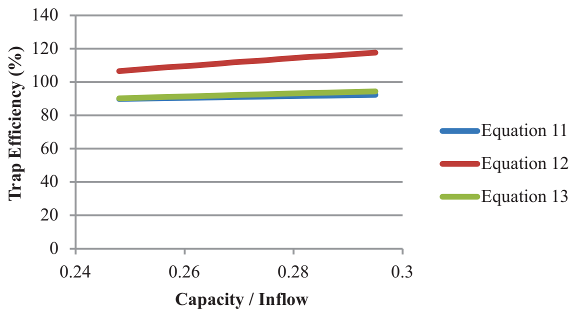

Fig. 19. Trap Efficiency of Simly reservoir using New developed equations.

X. CONCLUSIONS

In this study Trap Efficiency (T.E.) and useful life of Tarbela and Mangla reservoirs were investigated along with development and test of empirical equations. Firstly, the T.E. was estimated using Brown (1943), Churchill (1948), Brune (1953), Dendy (1974), Gill(1979), USDA-SDC (1983) and Siyam (2000) Methods and results were compared with the Trap Efficiency calculated through Hydrographic surveys. This comparison showed that Brune, Churchill, Gill and Dendy methods gave closer values to the Trap Efficiencies based on observed data. Secondly, the life of Tarbela and Mangla reservoirs was determined using the Brune, Gill, Dendy and Hydrographic survey methods and found to be 51 years (i.e. up to 2065) and 154 years (i.e. up to year 2168) respectively.

Finally, three empirical equations were developed between capacity/inflow and trap efficiency for Tarbela, Mangla reservoir along with a combine equation. During the tests of equations, it was found that empirical equationsgave fairly reasonable results when tested with Simly reservoir data.

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