Sediment Deposits and Trap Efficiencies of Irrigation Reservoirs

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ABSTRACT/The objectives of the paper are to apply the gross erosion and sediment delivery ratio method for estimating sediment deposits and to define their trap efficiencies. For twenty irrigation reservoirs which have sediment survey data, the gross erosion was estimated from the channel erosion as well as the soil losses by applying USLE. The gross erosion was reduced to the sediment yields by mutiplying the sediment delivery ratios. The results were multiplied by trap efficiencies after Brune method to estimate sediment deposits, which were compared to sediment surveyed data. The comparisons showed that some 20 percent discrepancies exist between the estimated and surveyed sediment deposits. And a trap efficiency relationship was derived from a regression method, which appeared better suited for irrigation reservoirs.

Introduction

Major concerns to sediment deposits at a reservoir include the reduction of the storage capacities (ASCE, 1975), which may endanger the reservoir functions to overcome droughts. A recent survey on the sediment deposits at irrigation reservoirs indicated that they are responsible for the reduction of reservoir capacities by an average of approximately 20 percent of the initial storage (Kim and Park, 1993a). The results are based on reservoir survey data available at Farm Land Improvement Associations (FLIA), and it could be much worse when small reservoirs were considered. In fact, hundreds of irrigation reservoirs often failed their functions under a moderate drought period because of the storage shortage, and that has wasted sizable revenues to develop supplemental water resources for rice irrigation (Kim and Park, 1993b).

Accurate estimates of sediment deposits are a prerequisite to the design of a reservoir or dam. They may be estimated from various methods, which include an empirical relationship for sediment deposits and a sediment yield and trap efficiency method. Sediment deposit relationships consider the

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factors affecting the surveyed data, such as climatic and hydrologic parameters, and watershed physiographic variables. Examples are those by Yoon (1981), Suh et al. (1988), and Kim and Park (1993a). A sediment yield and trap efficiency method is applied when incoming sediment yield is given, in which the trap efficiency is the ratio of the deposits to the incoming sediment.

Watershed sediment yields may be estimated from 1) discharge-sediment load relationships, 2) sediment yield empirical relationships, 3) gross erosion and sediment delivery ratio method, and 4) sediment yield models. Among those, the gross erosion (GE) method which has been widely practiced by US SCS (1971), has not been well applied to the Korean peninsula. The method has many merits, including one that it is not site specific like other empirical relationships. Not all gross erosion at a watershed contributes to incoming sediment yield at a reservoir, but some of it deposits along the water course. The ratio of sediment yield to GE is the sediment delivery ratio (SDR) (SCS, 1971). And the sediment yield is GE multiplied by SDR.

The trap efficiency, essential to estimate sediment deposits, has been assumed from the data or empirical relationships developed in other countries without proper justifications. The efficiency depends on numerous factors such as reservoir operational characteristics. Irrigation reservoirs for paddy rice have the operational characteristics significantly different from those for other uses, and thus, their trap efficiencies may be different. Therefore, it is important to document trap efficiencies for irrigation reservoirs.

This papar presents the applications of the GE-SDR method for estimating sediment yields, from which sediment deposits were computed and compared to the surveyed data from irrigation reservoirs, using a trap efficiency relationship in references. And a trap efficiency relationship was also to be derived, that can be applied for irrigation reservoirs.

Gross Erosion and Sediment Yields

Gross Erosion

Gross erosion from a watershed consists of soil losses from upland areas and sediment loads from channels.

$$GE = Au + Ec \tag{1}$$

where, GE = gross erosion (ton), Au = upland erosion, and Ec = channel erosion.

Upland erosion may be estimated from Equation (2).

$$Au = \sum(A_i \times As_i) \tag{2}$$

where, A = the area of a subarea (ha), As = annual averaged soil loss (ton/ha/yr), and subscript i = i-th subarea. The annual averaged soil loss may be estimated from the universal soil loss equation, USLE (Wischmeier and Smith, 1975).

$$As = 2.24 \times R\ K\ LS\ C\ P \qquad (3)$$

where, As=annual average soil losses (ton/ha/yr), R=rainfall erosivity factor, K=soil erodibility factor, LS=topographic factor, C=cropping management factor, and P=erosion control practice factor. LS may be expressed as

$$LS = \frac{(\lambda/22)^n \times (0.42 + 0.30s + 0.043s^2)}{6.574} \qquad (4)$$

where, λ=slope length (m), s=slope gradient (%), and n=exponent depending on slope gradient.

Channel erosion, Ec consists of the removal of soil and rock by a concentrated flow of water, such as gully erosion, streambank erosion, streambed degradation, flood-plain scour, and valley trenching. SCS provides with a nomograph for computing average annual channel erosion (SCS, 1971).

Sediment Delivery Ratio

Sediment yield from gross erosion is defined as

$$SY = SDR \times GE \qquad (5)$$

where, SY=sediment yield and SDR=sediment delivery ratio.

SDR varies with watershed physiographic and drainage variables, meteorologic events, and a land use and management (ASCE, 1975). Williams and Berndt (1972) found that SDR is related to main stream slope and drainage areas. However, SDR may be subject to a significant error when no field data are available. It is often defined from the field data at a basin the characteristics of which are similar to those of studied sites (SCS, 1971). Unfortunately, no field data were available, and the empirical relationship by Maner (1958), which was found to be applicable to Texas reservoirs by Williams and Berndt (1972), were applied in this study.

Sediment yield from Equation (5) is an annual averaged value, and is not necessarily for a particular year. The total sediment yield for a given period of T years is determined from Equation (6).

$$SYT = SY \times T \qquad (6)$$

where, SYT=total sediment yield (ton).

Trap Efficiency

Trap efficiency, TE depends on hydrologic and hydraulic features of the reservoir and the sediment characteristics. Brune (1948) proposed a trap efficiency relationship as related to the ratio of inflow to storage capacity from field surveyed data in the western United States. Churchill (1952) also suggested an empirical relationship similar to Brune (1948). Their applications may be limited to those lakes and reservoirs, the operational characteristics of which are similar to those used for the relationships.

Sediment deposit is defined as the sediment yield multiplied by TE.

$$SD = \frac{SYT \times TE}{100} \tag{7}$$

where, SD = sediment deposit (ton), TE = trap efficiency (%).

Sediment Density

Sediment deposit of Equation (7) is in a densimetric weight unit, while sediment survey data are in a volumetric unit. The conversions of sediment surveys to the sediment yield require the sediment density, which may be expressed as a function of the duration (Strand and Pemberton, 1982).

$$Sd = So + 0.4343\ Ks\left(\frac{T}{T-1}\log_e T - 1\right) \tag{8}$$

where, Sd = sediment density at T year, So = initial density, and Ks = constant.

Sediment Deposit Comparisons

Reservoir Descriptions

Twenty irrigation reservoirs were used in this study, which have recent reservoir survey data. They are located throughout the nation ; three in Kyungki ; two in Kangwon ; five in Chungcheong; four in Chunnam ; and six in Kyungsang (Figure 1). Table 1 lists the reservoirs, in which the watershed physiographic characteristics are tabulated. Topographic maps of 1 : 25,000 scale were used to define the watershed characteristics, which include the watershed areas, stream lengths, watershed perimeters, shape factors, and drainage densities. Land use data were also surveyed from topographic maps and adjusted using the land use statistics, Land uses were grouped to forestry, paddies, uplands, and others. Table 1 also shows rainfall erosivity factors and the averaged soil erodibility factors for each watershed.

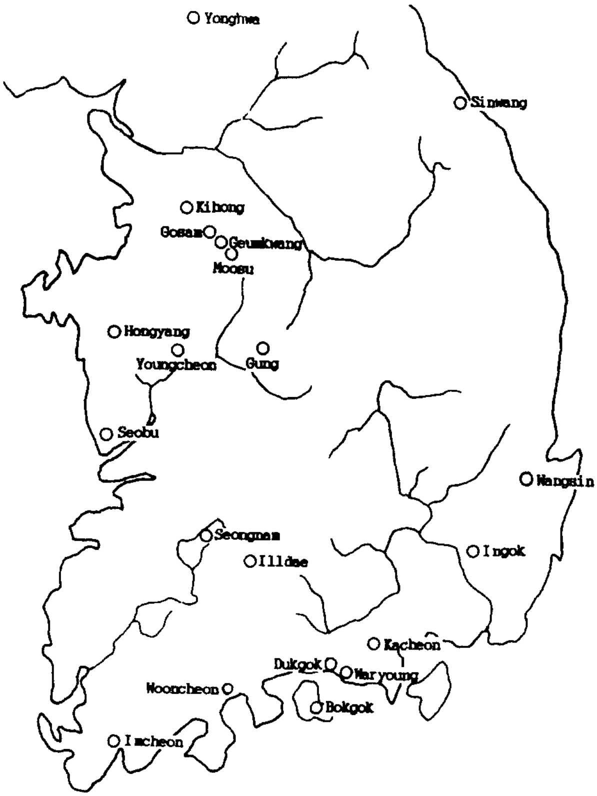

Fig 1. The location of the studied reservoirs

Sediment Yield Estimates

Annual average sediment yields for reservoir watersheds were estimated using Equation (3). The watersheds were divided into subareas whose topographic, soil, and landuse characteristics are relatively uniform. And USLE factors were estimated and averaged for each subarea. Examples of subarea divisions are as shown in Figure 2, where 116 subareas were used for the tested reservoir. The, number of subareas for tested reservoirs varied from 2 to 641, and the averaged size was 0.55 km^2 as described in Table 2.

The USLE factors for each subarea were defined as follows.

Rainfall Erosivity Factor R : R value of Equation (3) for each watershed was determined from a Thiessen method for rain gaging stations having the R factors by Jung et al. (1981). It varied from 280 to 640 depending on the locations as shown in Table 1.

Soil Erodibility Factor K : Soil groups for a subarea were defined from soil map of 1 : 50,000 scale. K factor for a soil group was defined from Wischmeier and Smith (1971) nomograph where it is related to percent sand, organic matter contents, soil structures, and permeability (Jung et al., 1976). For subareas having more than one soil groups, K factor for each was defined and the averaged values were used. The mean K factors were from 0.18 to 0.32 (Table 1).

Topographic Factor LS : The slope length and gradient for each subarea were defined from the averaged values. Typical slope lengths were less than 50 meters for forests, and were 30 to 60 meters for upland areas.

Cropping Management Factor C : The cropping management factor for each subarea was defined from the USLE manual (Wischmeier and Smith, 1976), based on the landuse characteristics. For crop lands, crop patterns and tillage practices were considered for annual averaged C values. And C factors for forestry were defined from the manual as undisturbed wood areas.

Erosion Control Practices P : P factors were determined from the USLE manual for crop lands. And unity was assumed for forest areas.

The annual averaged soil losses for each watershed are listed in Table 2. They vary from 790 to 19048 ton/km^2/yr. The values were relatively high for watersheds located upstream while small for the reservoirs located in lower areas. The mean soil losses were 4951 ton/km^2/yr.

Table 1 Watershed physiological characteristics for selected reservoirs.

Reservoir	Watershed area (km^2)	Ages (year)	Main stream length (km)	Circumferential length (km)	Shape factor	Drainage density (m/km^2)	Reservoir storage/watershed area(C/A)	Land uses			USLE factors	
								Forest area (km^2)	Paddy area (km^2)	Upland area (km^2)	R	Ave. K
Gosam	71.0	31	15.8	41.5	0.28	1.01	21338	46.00	10.51	4.64	490	0.31
Geumkwang	48.3	34	1.0	31.6	0.99	1.01	21843	42.83	2.88	0.38	500	0.31
Kihong	53.0	30	13.6	34.4	0.29	1.19	20170	37.96	6.43	3.40	530	0.32
Yonghwa	14.0	26	8.2	25.1	0.31	2.34	14129	13.70	0.05	0.01	560	0.25
Sinwang	26.2	26	3.1	26.5	0.15	1.28	4022	21.24	0.42	0.07	280	0.27
Gung	11.4	43	4.3	12.2	0.62	1.39	12668	9.62	0.78	0.22	420	0.31
Moosu	8.6	28	4.8	13.0	0.37	1.66	15986	7.33	0.59	0.05	490	0.25
Youngcheon	7.0	26	4.3	12.5	0.38	2.40	18409	6.16	0.18	0.84	560	0.31
Seobu	30.7	61	4.9	22.6	0.59	1.01	26852	20.48	5.82	1.01	460	0.18
Hongyang	24.1	42	6.7	20.1	0.54	1.05	6913	12.21	3.27	2.10	540	0.32
Seongnam	10.2	20	5.4	15.0	0.35	1.96	7779	8.69	0.77	0.04	420	0.20
Ildae	6.3	38	3.5	10.1	0.52	2.14	126025	2.94	1.27	1.95	440	0.27
Wooncheon	6.9	15	3.2	10.6	0.68	1.16	12987	4.31	1.63	0.28	530	0.27
Imcheon	9.0	51	4.3	12.8	0.49	1.06	10233	4.68	2.93	1.09	480	0.25
Wangsin	22.0	10	8.6	21.2	0.30	1.28	7636	13.84	1.81	0.75	290	0.20
Ingok	7.0	7	3.9	13.0	0.28	1.95	23127	6.40	0.01	0.01	370	0.31
Kacheon	13.9	32	4.4	18.0	0.23	1.45	7869	6.87	1.83	0.48	440	0.32
Waryoung	7.3	28	3.5	10.0	0.59	2.27	15800	6.23	0.01	0.28	550	0.20
Dukgok	6.9	28	4.1	10.3	0.41	1.15	8496	6.49	0.01	0.01	540	0.32
Bokgok	5.6	3	4.0	11.4	0.35	1.19	27661	5.52	0.01	0.01	640	0.20

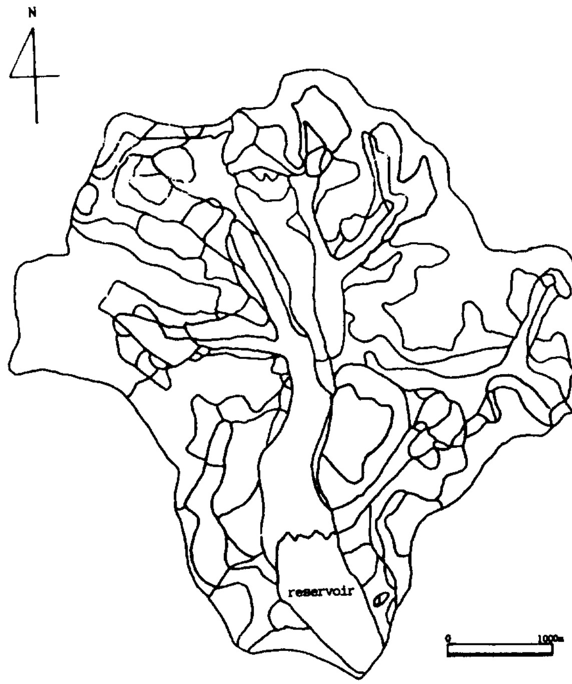

Fig 2. An example of subarea divisions for the tested reservoir

The channel erosion was estimated from field data using the SCS nomograph. The initial results were adjusted for physical features of main streams for the reservoirs. The annual values were from 118 to 2857 ton/km^2/yr with the mean value of 742 tons. The values were about 15 percent of the upland erosion.

SDR was estimated from Manner equation as shown in Table 2. The ratios ranged from 0.15 to 0. 24, with the mean value of 0.20. This implies that only 20 percent of the gross erosion reached to the reservoirs as incoming sediment yields. And sediment yields were determined by multiplying SDR and GE. And the specific sediment yields were defined from the sediment yields divided by the watershed areas, and listed in Table 2. The specific sediment yields ranged from 395 to 3737 ton/km^2/yr, with the mean of 1117. They varied with watershed sizes.

Sediment Deposits

The sediment densities estimated from Equation (8) averaged 1.30 as listed in Table 2. The variations of sediment densities were small, implying that the sediment size distributions did not cause much effects on the densities. The densimetric sediment deposits were then computed from the surveyed data multiplied by the sediment density as shown in Table 2.

Sediment Yield Comparisons

Sediment deposits may be converted to the incoming sediment yields by considering the trap efficiencies. The efficiencies from Brune method were estimated as shown in Table 2. They ranged from 30 to 91 percent depending on the storage capacity and inflow rates. Inflow rates were estimated by rainfall data considering runoff ratios for river basins, which were 47 to 53 percent. Dividing the densimetric sediment deposits by trap efficiencies, we obtained the sediment yields. The sediment yields were from 169 to 4258 ton/km^2/yr, with the mean of 961 ton/km^2/yr (Table 2).

Figure 3 shows a mass curve between the estimated sediment yields from GE-SDR method and the surveyed ones. The two values were in a fair correlationship with the correlation coefficient of 0. 79. The average of the estimated sediment yields was approximately 15 percent greater than the surveyed. The results may be considered to be a relatively acceptable degree of accuracy considering many uncertainties in parameter estimations and conversion factors. This suggests that the GE-SDR method may be applied for estimating sediment deposits at irrigation reservoirs. However, attention should be given to adequately estimate USLE parameters and delivery ratios, and trap efficiencies in a practical application, since many of them are subject to personal judgement and experiences.

Table 2 Sediment yields and trap efficiencies of selected reservoirs

Reservoir	Reservoir Survey Data					Annual average sediment yields, (ton/km^2/yr)			Sediment delivery ratio	Specific sediment yields	Estimated trap efficiencies
	Volumetric deposits (m^3/km^2/yr) (1)	Specific weight (ton/m^3) (2)	Densimetric deposits (ton/km^2/yr) (3)=(1)×(2)	Trap efficiency (%) (4)	Specific sediment yields (ton/km^2/yr) (5)=(3)/(4)	Upland	Channel	Total (6)	(7)	(ton/km^2/yr) (8)=(6)×(7)	(%) (3)/(8)
Gosam	87.7	1.31	114.9	68.0	169.0	2293	344	2637	0.15	395.6	29.0
Geumkwang	146.1	1.31	191.6	66.0	290.4	2157	323	2480	0.17	421.7	45.4
Kihong	138.4	1.31	181.3	65.0	279.0	2284	342	2627	0.16	420.3	43.1
Yonghwa	318.7	1.30	416.8	55.0	757.9	3456	518	3974	0.20	794.9	52.4
Sinwang	77.9	1.30	101.8	30.0	339.6	2810	421	3232	0.19	614.1	16.5
Gung	883.8	1.31	1163.0	58.0	2004.8	19048	2857	21906	0.16	3505.0	33.1
Moosu	791.8	1.30	1036.4	80.0	1295.6	4283	642	4926	0.18	886.7	116.8
Youngcheon	1274.7	1.30	1667.3	66.0	2526.1	10929	1639	12568	0.24	3016.5	55.2
Seobu	128.4	1.32	169.6	75.0	226.2	1917	287	2204	0.17	374.8	45.2
Hongyang	256.9	1.31	337.8	47.5	711.4	3804	570	4374	0.18	787.4	42.9
Seongnam	198.3	1.30	258.5	47.5	544.4	3611	541	4153	0.22	913.7	28.3
Ildae	2880.6	1.31	3785.1	91.0	4258.6	14128	2119	16247	0.23	3737.0	101.2
Wooncheon	432.9	1.30	562.8	60.0	937.7	4032	602	4634	0.24	1112.3	50.6
Imcheon	420.1	1.32	553.8	60.0	923.0	10268	1534	118002	0.17	2006.5	27.6
Wangsin	150.0	1.29	194.1	51.0	380.6	858	128	986	0.18	177.6	109.3
Ingok	796.0	1.29	1026.2	72.5	1415.4	1965	294	2259	0.24	542.1	189.3
Kacheon	232.1	1.31	304.3	41.0	742.2	3837	573	4410	0.20	882.0	34.5
Waryoung	1230.0	1.31	1610.1	55.0	2927.5	10423	1557	11980	0.24	2875.2	56.0
Dukgok	1699.3	1.31	2224.4	42.0	5296.3	34312	5127	39439	0.24	9465.5	23.5
Bokgok	1309.5	1.28	1674.6	69.0	2426.9	22500	3362	25862	0.25	6465.6	25.9

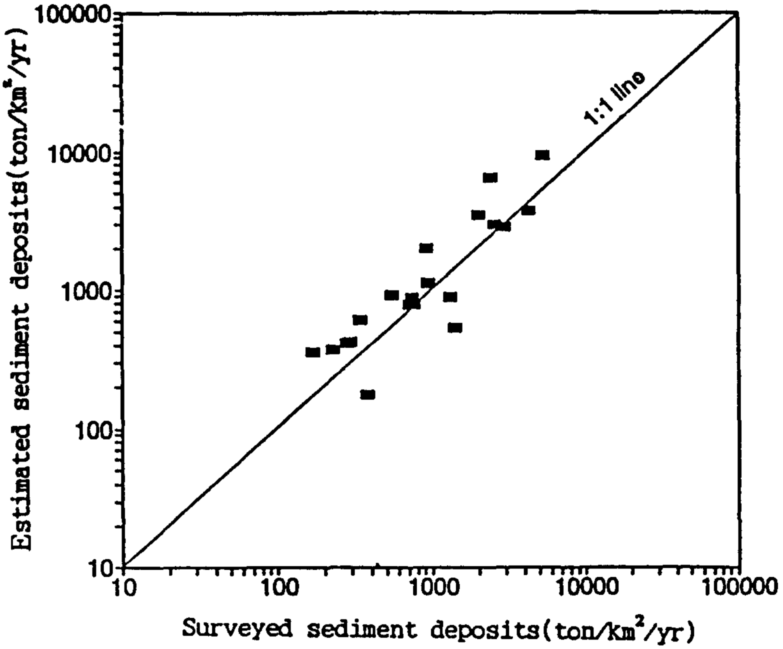

Fig 3. Comparisons between the estimated sediment deposits and the surveyed results

Trap Efficiency of Irrigation Reservoirs

Estimated Trap Efficiency

Trap efficiencies may be estimated from the surveyed deposit data and the estimated sediment yields. The surveyed sediment deposits were divided by the sediment yields from the GE-SDR method. The results were listed in Table 2, which varied from 17 to 189 percent. The efficiencies for the Gung, Ildae, Wangsin, Ingok reservoirs exceeded 100 percent, which are theoretically not justifiable. This result appeared that the estimated gross erosion rates and sediment delivery ratios were too small or similar errors. Williams et al. (1972) also presented trap efficiency data exceeding 100 percent. This may imply that such errors could be inheritant in this procedure.

Estimated trap efficiencies were plotted as related to the ratios of reservoir capacity to inflow as shown in Figure 4. In Figure 4, trap efficiencies exceeding 100 percent were plotted as 100. Figure 4 also compares the estimated efficiencies with the Brune and Churchill curves. They were close to the lower curve by Brune, but smaller than those by Churchill. Figure 4 may indicate that either of the two empirical relationships by Brune and Chuchill is not adequate for estimating trap efficiency for irrigation reservoirs for paddy rice, whose operational characteristics are different from those used for their relationships.

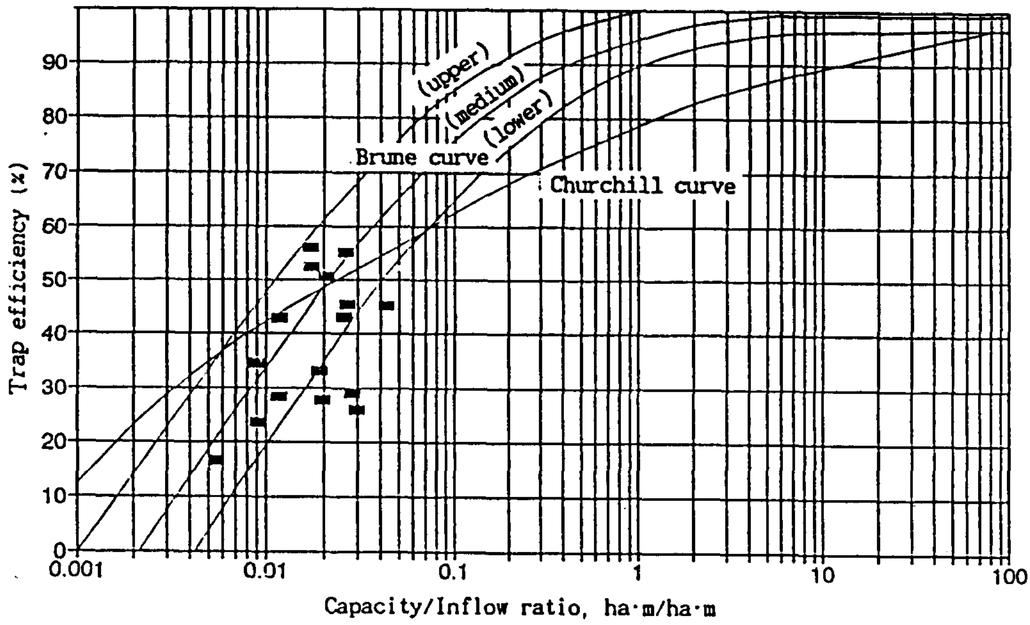

Fig 4. Comparisons between the estimated and Brune trap efficiencies

Empirical Trap Efficiency Relationship

Correlation coefficients between the estimated trap efficiencies for irrigation reservoirs and Brune relationships were 0.59 for the medium curve and 0.60 for the lower curve. The coefficient was 0.56 between the estimated and Chuchill values. However, Brown empirical relationship resulted in the efficiencies from 0.98 to unity, implying that the method is not applicable for irrigation reservoirs.

Since the trap efficiencies were not in good agreement with either of Brune or Churchill, attempts were made to identify factors affecting them. Regression analyses were to identify variables explaining the variations of trap efficiencies. Watershed characteristic variables listed in Table 1 and Brune and Churchill efficiencies were correlated with them. Table 3 summarizes the probable regression models, which include empirical relationships as a function of 1) the values from the Brune curve, 2) the Churchill curve, 3) capacity-inflow ratios, and 4) capacity-inflow ratios and watershed parameters. The results indicate that the coefficient of determination was higher with a power function of Brune curve than with their normal or semi-logarithmic values.

The regression model for the trap efficiency was poor with the coefficient of determination of 0.27 when only capacity-inflow ratio was used. However, a multiple regression model with the ratio and watershed area was significantly improved in explaining the variations of trap efficiencies with the coefficient of determination of 0.63. Therefore, it is suggested that empirical relationship for the trap efficiency of an irrigation reservoir is as follows.

$$T_e = 61.77\left(\frac{C}{I}\right)^{-0.15} A^{-0.41} \tag{9}$$

where, C= reservoir storage capacity (ha·m), I=annual inflow (ha·m), A=watershed area (㎢).

Figure 5 compares the surveyed TEs in Table 3 and the estimates by Equation (9). The estimated TEs are fairly correlated with the surveyed as evidenced that the values were close to the mass curve between the two. The standard error between the surveyed and estimated was 17 percent, and the average of the surveyed was 37.3 percent as compared to 38.1 percent by Equation (9). The estimated relative error was within 2 percent.

Table 3 Results of regression analysis

Cases	Regression equatons	R^2
Brune value vs. Te	$Te = 0.916\, Br^{0.913}$	0.353
Churchill value vs. Te	$Te = 0.065\, Ch^{1.584}$	0.317
C/I value vs. Te	$Te = 143.75\, (C/I)^{0.343}$	0.271
C/I, A value vs. Te	$Te = 61.77\, (C/I)^{-0.145} A^{-0.409}$	0.625

Te=estimated trap efficiency(%), Br=Brune trap efficiency(%), Ch=Churchill trap efficiency(%), C/I=reservoir capacity per inflow rate, A=watershed area(㎢)

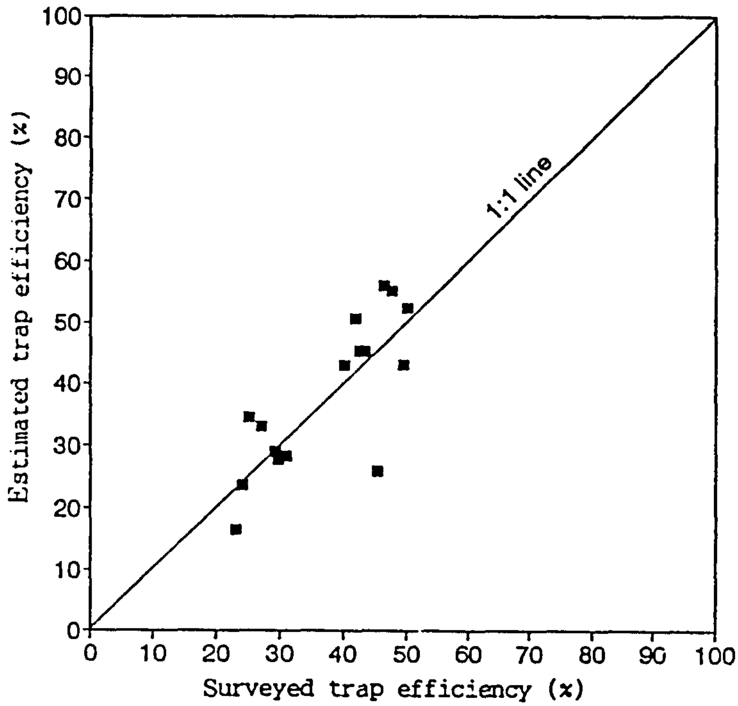

Fig 5. Comparisons between the estimated and surveyed trap efficiencies

Summary and Conclusions

The objectives of the study were to apply the gross erosion and sediment delivery ratio method for estimating watershed sediment yields, and to derive empirical relationship for trap efficiencies of irrigation reservoirs for paddy rice. Twenty reservoirs were selected that have reservoir survey data, and the physiographic and hydrologic data for their watersheds were investigated. For each watershed, subareas were identified, which consist of relatively uniform topographic, soil, and landuse characteristics, and the soil losses were estimated using the USLE. Gross erosion was defined from the summation of soil losses and channel erosion, and the result was multiplied by the sediment delivery ratio to estimate sediment yields. The sediment yield estimates were compared to the yields from sediment surveys, considering the trap efficiency from the Brune curve.

The resulting sediment yields were within 15 percent difference as compared to the observed. Among the trap efficiency relationships, the lower curve of Brune was found to be better correlated to the estimated than Churchill curve. An empirical relationship was proposed for the trap efficiency of irrigation reservoirs, which shows better correlation with the observed data than Brown, Brune, and Churchill relationships. The estimated errors would be within 17 percent for estimating the trap efficiencies. When good field estimates for USLE factors are ensured, the proposed methods may be applicable for estimating sediment deposits for irrigation reservoirs.

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