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Sediment balance of the lowland tropical reservoir of Timah Tasoh, Perlis, Malaysia

Imbangan endapan di tanah pamah tropika empangan Timah Tasoh, Perlis, Malaysia

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Abstract
A study was carried of out to assess the sediment balance of a shallow Timah Tasoh Reservoir (Area: 191 km^2). Streamflow gauging and water sampling was carried out at three river inputs to the reservoir, and at the reservoir outlets. River water samplings were carried out every two weeks but frequent and intensive sampling during storm events. The land use in the catchment area ranging from urban area to agriculture, sugar cane, rubber, paddy, rural villages, small towns, quarrying and mining activities. Suspended sediment load data was used to derive the sediment balance. Jarum River (S1), Upper Pelarit River (S2) and Chuchuh River (S3) produced 10,032.3 t; 6,439.2 t; 1,061.4 t of sediment respectively while suspended sediment yield in S1, S2 and S3 were 155.8 $tkm^{-2}yr^{-1}$, 150.7 $tkm^{-2}yr^{-1}$, and 71.7 $tkm^{-2}yr^{-1}$ respectively. Storms play a major role in transporting sediment from the catchment areas. Almost 88.7% of the total suspended sediment yield is transported from S1, 56.7% from S2 and 80.1% from S3. The annual sediment output load at the reservoir outlet was 1 653.0 t. From the total of 17 532.9 t of suspended sediment input to the reservoir, 15 879.9 t was stored in the reservoir. The estimated trapping efficiency of the reservoir is 90.6%. Designing sediment control and management strategies as well as increasing storage elsewhere in the watershed will help reduce the efficiency of sediment delivery from the individual catchment to the river. Alternatively, reductions could also be achieved by reducing sediment output through the construction of wetlands and the use of buffer strips.

Keywords
sediment balance, sediment yield, lowland reservoir, tropical, Timah Tasoh

Abstrak
Satu kajian telah dilakukan pada tahun 2002 dengan tujuan untuk menilai imbangan endapan sebuah kawasan takungan yang cetek iaitu Empangan Timah Tasoh (berkeluasan: 191 km^2). Pencerapan luahan sungai dan sampel air telah dijalankan di tiga input sungai yang mengalir masuk ke empangan, dan juga di saluran keluar empangan. Pencerapan di lapangan dilakukan setiap dua minggu dan digabungkan dengan pencerapan intensif secara berkala semasa kejadian hujan ribut. Guna tanah di kawasan lembangan terdiri daripada kawasan perbandaran serta pertanian, iaitu penanaman tebu, getah, padi sawah, perkampungan, bandar kecil serta aktiviti

kuari dan perlombongan. Data beban endapan terampai telah digunakan untuk menghasilkan imbangan endapan di dalam kajian ini. Sungai Jarum (S1), Sungai Pelarit Hulu (S2) dan Sungai Chuchuh (S3) masing-masing telah mengeluarkan endapan sebanyak 10 032.3 t; 6 439.2 t; 1 061.4 t sementara hasilan endapan yang dihasilkan di S1, S2 dan S3 ialah 155.8 $tkm^{-2}yr^{-1}$, 150.7 $tkm^{-2}yr^{-1}$, dan 71.7 $tkm^{-2}yr^{-1}$. Hujan ribut telah memainkan peranan yang penting dalam mengangkut endapan dari kawasan lembangan iaitu kira-kira 88.7% yang telah disumbangkan kepada jumlah hasilan endapan di S1, 56.7% di S2 dan 80.1% di S3. Beban endapan tahunan di saluran keluar empangan ialah sebanyak 1 653.0 t. Daripada jumlah keseluruhan input endapan terampai sungai yang masuk ke dalam empangan, iaitu sebanyak 17 532.9, sejumlah 15 879.9 t telah disimpan di dalam empangan. Anggaran kecekapan perangkap oleh empangan ialah 90.6%. Rekabentuk kawalan sedimen dan strategi pengurusan serta meningkatkan penyimpanan di tempat lain di kawasan tadahan akan membantu mengurangkan kecekapan penyampaian sedimen dari tadahan individu ke sungai. Selain itu, pengurangan juga boleh dicapai dengan mengurangkan pemendapan sedimen melalui pembinaan wetland dan penggunaan jalur penampan.

Kata Kunci
imbangan endapan, hasilan endapan, empangan tanah pamah, tropika, Timah Tasoh

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Introduction

Human activities in catchment areas will ultimately affect the sediment sink in a lake or reservoirs at the receiving end of the catchment. Accelerated soil erosion in catchment areas are the result of many human activities such as logging, the introduction of rubber plantations, tin mining activities or deforestation associated with land conversion for agricultural, industrial or urbanization purposes (Douglas et al., 1992; Brooks et al., 1993; Baharuddin & Abdul Rahim, 1994; Ismail, 1997; Ziegler et al., 2000; Rahaman & Ismail, 2006) and could affect the sediment input into reservoirs. Besides disrupting the soil productivity in agricultural areas (Oyedele, 1996), soil erosion could also become an off-site effect in terms of siltation problems, disruption of water supply and the damaging the freshwater resources (Murtedza & Chuan, 1993). In recent years, much attention has been focused on the individual and cumulative effects of dams on rivers (Collier et al., 1996; Graf, 1999). The most significant impact of dams on the fluvial sediment system is in trapping sediment with both upstream and downstream consequences (Meade et al., 1990). This has been observed in the 20th century where reservoirs have proven to be a major sediment sink (Renwick et al., 2005). Further, it is estimated that more than 30% of the global sediment flux is trapped in reservoirs (Vorosmarty et al., 2003). Consequently, the global sediment flux from the rivers to the sea has decreased significantly (Milliman, 1997; Syvitski et al., 2005).

Accelerated sedimentation rate in the reservoir can significantly reduce a reservoir's surface area, eliminating wetland area surrounding the reservoir and making the areas near the shore of the reservoir shallower. The sedimentation of reservoirs may have one of the most economically crippling effects in the near future because of large investments in dams for irrigations and hydroelectric power (Nagle et al., 1999). Worldwide, a rough estimate for the loss of water storage due to sedimentation was 0.5% to 1% annually (WCD, 2000), and the cost of replacing lost storage was estimated to be $130 billion (Mahmood, 1987). A study by Postel (1999) has shown that the Nizamsagar reservoir in Andhra Pradesh (India) lost more than 60% of its water storage capacity over only 40 years.

In response to this problem, much attention has been given in recent years to propose a number of programmes. These approaches have been implemented to control erosion and slow sedimentation as well as to gain a better understanding of erosion and sedimentation processes within a catchment area. An increasing dissatisfaction with the sediment yield approach to study and predict erosion within the catchment area has led to the increased utilization of so-called "sediment budgeting" concepts. This approach was stressed by Wolman (1977), when he stated that within the sediment field there needs to be a closer link between events of erosion from source areas, storage, and transport in channel systems.

Few reliable assessments of the magnitude of erosion and its impacts in the humid tropics have been attempted (Lal, 1993), and in the case of Malaysia, very few studies carried out focusing on the use of the sediment budget concept. The sediment budget is defined as the accounting of sources, sinks and redistribution pathways of sediments in a unit region over unit time (Slaymaker, 2003). Sediment budgets are most useful when they are constructed for a specific geomorphic system for which mass transfers in or out of the system is relatively small or well known (Colman & Foster, 1994). Although many works on sediment budget have been done elsewhere (e.g. Sutherland & Bryan, 1991; Rahaman, 2004 and Slaymaker, 2003) the studies by Balamurugan (1991), Ismail (2001) and Rahaman et al. (2003) constitute examples of applying the sediment budget concepts to study the impact of land uses on erosion and sediment yield in Malaysia.

This study was carried out from January 2002 to December 2002 with the aim to assess the impact of land uses on hydrology and suspended sediment of the Timah Tasoh Reservoir catchment using the sediment balance approach.

The study area

Timah Tasoh reservoir (6° 36'N and 100° 14'E) is located approximately 13 km north of Kangar town near the Thailand border (Figure 1). The reservoir has a mean surface area of 13.33 km^2 and a storage capacity of about 40 million m^3. The reservoir receives inputs from two main rivers, the Tasoh River and Pelarit River, which have a combined area of 191 km^2 and supply approximately 97 million m^3 of water into the reservoir annually. The Tasoh River consists of two inputs, the Jarum River (S1) and the Chuchuh River (S3). The area surrounding the reservoir and its upstream catchments includes mainly agriculture such as sugar, rubber, paddy and timber plantations, urban area such as Padang Besar town and quarry near Kaki Bukit (Table 1). The reservoir is shallow with the maximum depth of 10m and submergence aquatic plant can be seen along the shoreline and shallow area. At present, the main purpose of the reservoir is to supply water for domestic and industrial use as well as for irrigation and flood control.

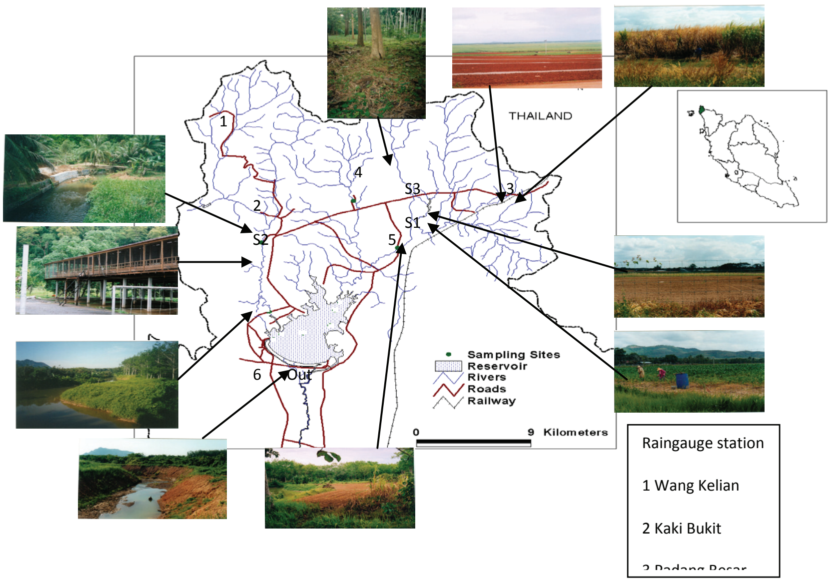

Figure 1 Study sites and land uses around the catchment areas

Table 1 Distribution of land use in the study catchments

Catchments	**Jarum River (S1)**		**Upper Pelarit (S2)**		**Chuchuh River (S3)**	
Land-use type	**Area (km^2)**	**%**	**Area (km^2)**	**%**	**Area (km^2)**	**%**
Sugarcane	11.58	18.0	–	–	–	–
Urban & settlement	0.74	1.1	0.35	0.8	0.19	1.3
Mixed crop	2.22	3.4	0.21	0.5	–	–
Scrub	2.79	4.3	0.33	0.8	–	–
Rubber	12.94	20.1	2.09	4.9	–	–
Paddy	5.23	8.1	0.4	0.9	–	–
Forest	28.90	44.9	38.72	90.6	14.61	98.7
Grass	–	–	0.13	0.3	–	–
Quarry	–	–	0.5	1.2	–	–
Total	64.40	100	42.72	100	14.80	100

Three rivers flowing into the reservoir have been selected as the study area, namely the Jarum River (S1), Upper Pelarit River (S2) and the Chuchuh River (S3). The location of each study catchment is illustrated in Figure 1. The catchment area of S1 is 64.4 km^2, S2 is 42.7 km^2 and S3 is 14.8 km^2 respectively. The table also illustrates the land use of each of the study catchments. The catchments can be categorised into three based on the percentage of forest cover. S3 is nearly 99% covered with forest with minimum anthropogenic disturbance. S2 is categorised as partially disturbed, with almost 91% forest cover. However, quarrying activity in this catchment will likely influence the production of suspended sediment. The third catchment, S1 is considered disturbed with anthropogenic activities on 55.1% of the land area. The disturbances are in the form of agriculture activities such as sugar plantation, rubber and paddy.

Methodology

Stream flow gauging and water samples were collected every two weeks but with frequent and intensive sampling were made during storm events. The river water samplings were carried out pre-selected locations of three river inputs to the reservoir (S1, S2, and S3) and at the reservoir outlets (OUT) (Figure 1). Hourly water level records for S1 and S2 were obtained from the Malaysian Department of Drainage and Irrigation which were continuously transmitted telemetrically. The sediment outflow was measured at the outlet of the reservoir. Parameters for water discharge such as channel cross section, velocity and depth were measured. Water velocity was measured using the SEBA current meter and by using the Velocity Area Method (Gordon et al., 1992) the river discharge were estimated. For sediment in water samples, three replicates were taken for further analysis in the laboratory. The samples were then filtered using Whatman GFC 47 mm filter paper, oven dried for 24 hours and weighted to obtain sediment concentrations. The suspended sediment concentrations was

Table 2 Suspended sediment rating curve equation used to compute the suspended sediment concentration for each study catchment

Type	Regression equation	R^2	n	Significance Level
S1				
All Data	$y = 0.063x^{0.494}$	0.67	110	0.01
Baseflow	$y = 0.061x^{0.562}$	0.34	22	0.01
Highflow	$y = 0.03x^{0.079}$	0.12	32	0.01
Rising Limb	$y = 1.352x^{-0.554}$	0.27	23	0.01
Falling Limb	$y = 0.057x^{0.293}$	0.34	27	0.01
S2				
All Data	$y = 0.032x^{0.777}$	0.66	183	0.01
Baseflow	$y = 0.017x^{0.516}$	0.44	49	0.01
Highflow	$y = 0.024x^{1.815}$	0.63	54	0.01
Rising Limb	$y = 0.081x^{0.508}$	0.38	43	0.01
Falling Limb	$y = 0.034x^{0.55}$	0.38	36	0.01
S3				
All Data	$y = 0.125x^{0.4023}$	0.41	195	0.01
Baseflow	$y = 0.049x^{0.2863}$	0.36	97	0.01
Highflow	$y = 0245x^{0.2518}$	0.35	46	0.01
Rising Limb	$y = 0.438x^{1.567}$	0.63	17	0.01
Falling Limb	$y = 0.095x^{1.3553}$	0.72	35	0.01

estimated by applying suspended sediment concentration rating curve equation and are summarized in Table 2. The suspended sediment load for each station was determined by multiplying water discharge and sediment concentrations. The suspended sediment output was measured at the outlet of the reservoir to obtain the total suspended load transported out of the reservoir.

Suspended sediment load data was used to derive the sediment balance in this study. The approached used to the sediment balance, modified from Colman and Foster (1994) is a source and sink model. Briefly, a sink model is essentially a box model in which each major source or sink of sediment is contained within the box. The advantage of this method is that we can assess the relative importance of different erosional and depositional environments, without having an understanding of the actual physics of the processes involved (Colman & Foster, 1994).

Rainfall

The mean annual rainfall for Chuping (24 years of record – the nearest rainfall gauging station with long-term record) was 1754.8 mm, with a minimum and maximum value of 1349.8 mm to 2196.3 mm respectively. The highest annual rainfall recorded was in 1988, while the lowest rainfall recorded was in 1992 (Figure 2). The highest monthly rainfall recorded was in October 1998 (412.5 mm). The month of October has recorded the highest long-term average of monthly rainfall, while January was the lowest at 23.0 mm. The annual rainfall recorded during the study period was below the annual long-term record, except for Lubok Sireh (1889 mm) and Wang Kelian (1899.5 mm). Although Guar Jentik recorded the highest annual rainfall during the study period, it was not considered because of its location downstream of the reservoir and will not affect the runoff generation at upstream catchments.

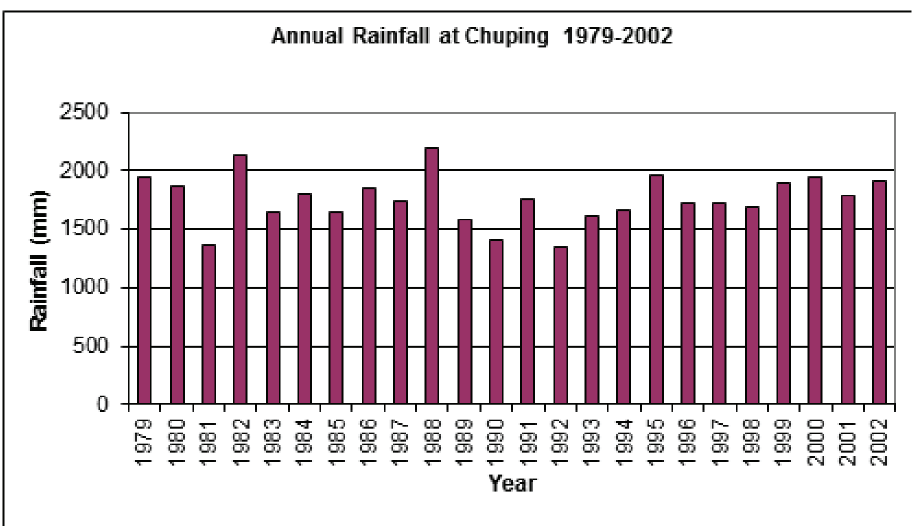

Figure 2 Long term annual rainfall record at Chuping station from 1979-2002

The pattern of monthly rainfall depth displayed a similar behavior to that of annual pattern. The highest monthly rainfall during the study period was recorded at Wang Kelian in September (377 mm) but was below the highest long-term rainfall recorded in October 1998 at 412.5 mm (Table 3). The same month also recorded the highest monthly rainfall at Padang Besar (356.5 mm), while at Lubok Sireh and Tasoh, the highest monthly rainfall was 338.0 mm recorded in November, and 291 mm recorded in October, respectively. There's a period of drought from January to February at Kaki Bukit and Wang Kelian and based on the long-term rainfall record, rainfall was recorded twice during these periods during January 1980 and February 1986. This implies that Wang Kelian and Kaki Bukit exhibit a long period of drought during the period of this study.

Table 3 Monthly rainfall distribution of all rain gauge station during the study period

Station Month	Pdg Besar (mm)	Tasoh (mm)	Lubok Sireh (mm)	Kaki Bukit (mm)	Wang Kelian (mm)	Guar Jentik (mm)
Jan-02	18.0	13.5	7.0	0.0	0.0	5.5
Feb-02	0.0	0.0	0.0	0.0	0.0	0.0
Mar-02	52.0	51.0	39.0	42.0	86.5	34.8
Apr-02	270.5	212.5	267.0	157.0	313.5	207.7
May-02	106.0	46.0	127.0	87.0	160.5	74.5
Jun-02	28.5	63.0	32.0	54.0	41.0	218.5
Jul-02	110.0	177.5	123.0	108.5	28.5	224.0
Aug-02	193.5	149.5	227.0	134.0	298.0	212.2
Sep-02	356.5	240.5	242.0	237.5	377.0	317.6
Oct-02	187.5	291.0	251.0	216.0	198.5	271.0
Nov-02	236.5	246.0	338.0	211.0	143.0	212.0
Dec-02	154	177.5	236	185.5	253	200
Total	1713.0	1668.0	1889.0	1432.5	1899.5	1977.8
Average	142.8	139.0	157.4	119.4	158.3	164.8
Min	0.0	0.0	0.0	0.0	0.0	0.0
Max	356.5	291.0	338.0	237.5	377.0	317.6

Results

Rainfall Frequency

Daily rainfall frequency was estimated for this study to analyse rainfall distribution at the six rain gauge stations (Figure 3).The storms exceeded 10 mm to 25 mm account for a rainfall frequency of 35.6% at Tasoh, 31.1% at Kaki Bukit, 27.3% at Wang Kelian, 23.5% at Padang Besar, 21.2% at Guar Jentik, and 20.6% at Lubok Sireh. Tasoh rain gauge station also recorded the highest rainfall frequency of a magnitude greater than 25 mm (21.8%), followed by Guar Jentik (21.2%), Lubok Sireh (20.6%), Wang Kelian (17.5%), Padang Besar (17.4%) and Kaki Bukit accounted 8.2% only. Although the amount of rainy days at Guar Jentik was high compared to the other stations, it will not affect the hydrological behaviour of the catchment areas because of its location downstream of the reservoir. Due to their location, the Wang Kelian rain gauge station will have a greater impact on the streamflow of the Pelarit catchment, while rain gauge stations at Padang Besar and Lubok Sireh strongly influence the streamflow at Tasoh catchment. This also implies that if rainfall alone is the most dominant governing factor of a catchment hydrology, we would expect areas affected by Lubok Sireh and Wang Kelian to be more conducive to storm flow occurrence compared to areas under Padang Besar and Kaki Bukit. Similarly, if rainfall alone is the dominant governing factor, the erosion rate would be higher in areas affected by Lubok Sireh and Wang Kelian because of higher proportion of the rain exceeding 25 mm. Hudson (1965) has shown that erosion is mostly caused by rain falling at intensities greater than 25 mm h^{-1}.

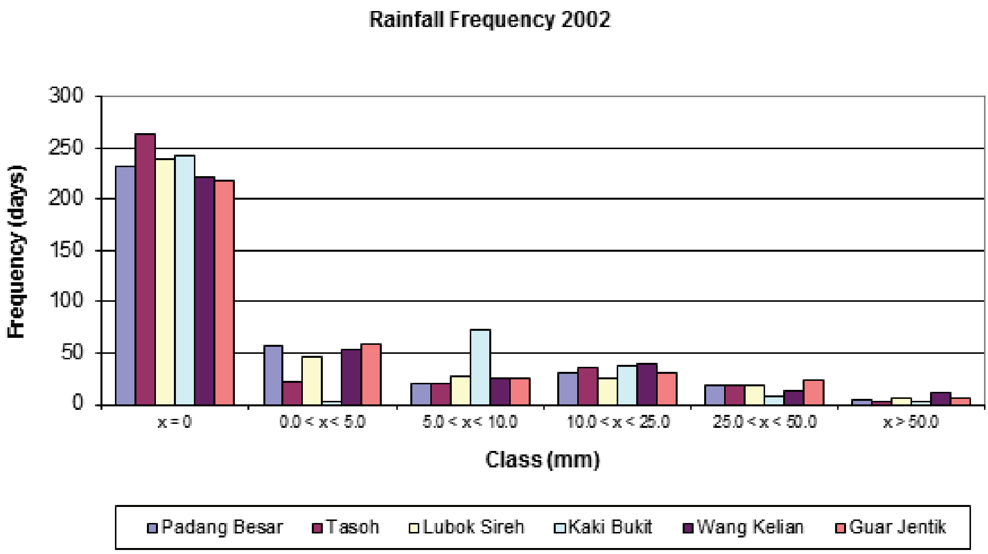

Figure 3 Daily rainfall frequency of all raingauge station during the study period

Annual Runoff

The Upper Pelarit River (S2) had the highest water yield during the study period at 1029.43 mm, while Chuchuh River (S3) and Jarum River (S1) recorded 611.61 mm and 585.69 mm respectively. The same trend existed when the rainfall runoff coefficients are compared. Coefficient of total runoff of S2 was 61.66%, while runoff in S3 was only 33.82% of the annual rainfall. For S1, the runoff coefficient was 32.9% of its total rainfall, which is comparable to that of S3.

Monthly Runoff

The mean monthly rainfall runoff coefficients of each catchment were 48.81 mm, 85.79 mm and 50.97 mm for S1, S2 and S3 respectively (Figure 4). There are several trends which can be generalized from the monthly variation of the rainfall runoff coefficients obtained. The wet months (September and October) show the highest monthly runoff total for the S2, catchment, while the dry months recorded a low monthly runoff total. But, for S1 and S3, the highest monthly rainfall runoff total was recorded in January, which can be considered a relatively dry month. This could be due to the runoff delay from the previous month (December 2001), which recorded a high rainfall during that period. The total monthly runoff yield during the wet months from S2 was 450.7 mm, followed by S3 (263.08 mm) and S1 (254.73 mm). The total contribution of runoff from all gauging stations in the wet months was approximately 43% of total annual runoff. During the dry months (February and March), S2 yielded a runoff of 12.96 mm, followed by S1 (16.73 mm) and S3 (17.96 mm).

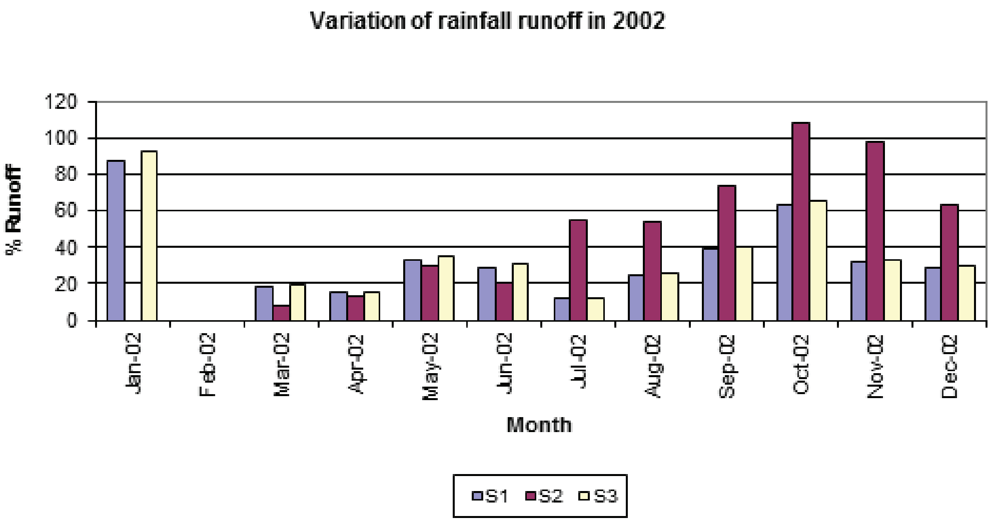

Figure 4 Variation of rainfall runoff during the study period for all gauging stations

Sediment Budget Component

The Inputs

The suspended sediment loads and sediment yields for S1, S2 and S3 catchments are given in Table 4. The annual sediment load from the S1 catchment was 10,032.33 t. The period ranging from September to December recorded the highest sediment load during the study period (74.8% of the total load). The annual sediment load for the S2 catchment was 6,439.19 t. This is further shown schematically in Figure 5, the highest amount of sediment load were from September to December (87.2% of the total load). Similarly, the annual sediment load from the S3 catchment was 1,061.38 t and the September–December contribution was 76.3% of the total load. During the whole study period, the S1 catchment contributed the highest percentage of sediment inflow to the reservoir (57.22%), followed by S2 (36.73%) and 6.05% for the S3 catchment.

Table 4 Monthly suspended sediment load of the study areas

Month	S1				S2				S3			
	Load (t)	Yield (t/km^2)	Storm Load (t)	Storm Yield (t/km^2)	Load (t)	Yield (t/km^2)	Storm Load (t)	Storm Yield (t/km^2)	Load (t)	Yield (t/km^2)	Storm Load (t)	Storm Yield (t/km^2)
Jan-02	19.01	0.3	0	0	9.33	0.22	0	0	5.47	0.37	0	0
Feb-02	15.07	0.23	0	0	2.01	0.05	0	0	4.41	0.3	0	0
Mar-02	28.34	0.44	15.84	0.25	1.39	0.03	0	0	3.88	0.26	0.1	0.01
Apr-02	697.43	10.83	630.83	9.8	87.98	2.06	72.95	1.71	59.48	4.02	44.71	3.02
May-02	616.93	9.58	467.19	7.25	103.57	2.42	87.46	2.05	58.32	3.94	39.33	2.66
Jun-02	15.57	0.24	0	0	3.13	0.07	0	0	4.53	0.31	0	0
Jul-02	176.44	2.74	162.17	2.52	27.42	0.64	0	0	18.04	1.22	13.89	0.94
Aug-02	960.16	14.91	905.73	14.06	591.85	13.85	397.42	9.3	97.52	6.59	72.7	4.91
Sep-02	2009.89	31.21	1857.17	28.84	1950.76	45.66	0	0	244.57	16.53	212.2	14.34
Oct-02	2732.63	42.43	2615.05	40.61	1724.59	40.37	1461.88	34.22	277.83	18.77	234.78	15.86
Nov-02	1638.22	25.44	1519.64	23.6	1218.21	28.52	1034.54	24.22	175.81	11.88	144.08	9.73
Dec-02	1122.65	17.43	724.5	11.25	718.95	16.83	599.67	14.04	111.52	7.53	88.29	5.97
Total	10032.3	155.78	8898.12	138.18	6439.19	150.72	3653.92	85.54	1061.38	71.72	850.08	57.44
Average	836.03	12.98	741.51	11.52	536.60	12.56	304.49	7.13	88.45	5.98	70.84	4.79
Max	2732.63	42.43	2615.05	40.61	1950.76	45.66	1461.88	34.22	277.83	18.77	234.78	15.86
Min	15.07	0.23	0	0	1.39	0.03	0.00	0.00	3.88	0.26	0	0

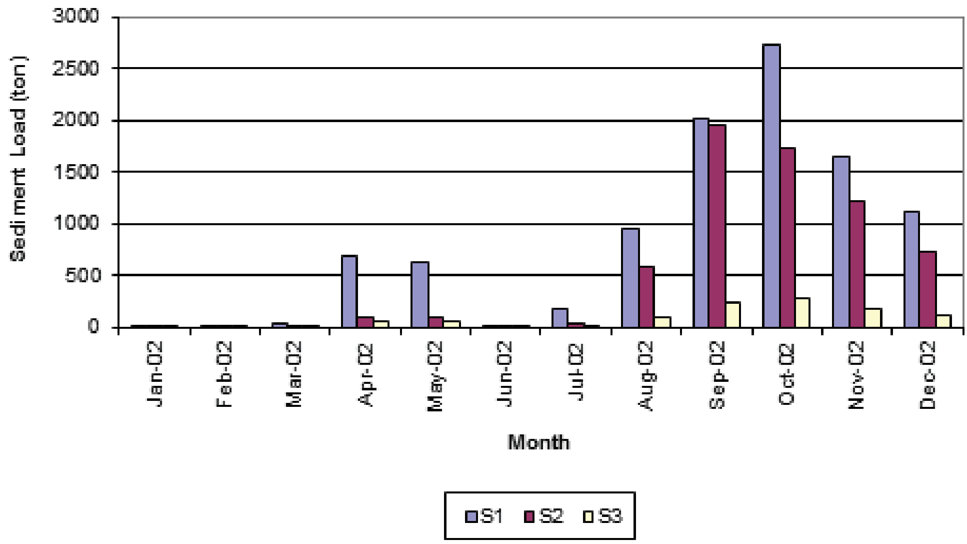

Figure 5 Suspended sediment load of the study area

Storm events play an important role in transporting the suspended sediment load in the catchments area. A total of 8 898.12 t or 88.7% of suspended sediment has been transported during the storm events in S1, 3 653.92 t or 56.7% in S2, and 850.08 t or 80.1% in S3. The results clearly indicated that the wet months (September to November) produced the highest amount of suspended sediment load in the catchments area. The suspended sediment yield is used to estimate the catchment erosion rates. An erosion rate was estimated for all three catchments using the sediment apparent specific weight as 1.60 t m^{-3}. The estimated erosion rate was approximately 0.1 mm yr^{-1} for S1, and 0.09 mm yr^{-1} and 0.04 mm yr^{-1} for S2 and S3 respectively.

Storage and Output

The total contribution of suspended sediment from S1, S2 and S3 that reached the reservoir is 17,532.9 t. From that amount, 15,879.9 t or 90.6% was deposited into the reservoir. This estimation was derived by subtracting the total amount of sediment input from the catchment area with the total amount of sediment load at the outlet of the reservoir, as given in Table 5. The period of January to February and June showed a negative storage during which the amount of sediment leaving the reservoir is higher than the input to the catchment areas. During this period, the amount of sediment entering the reservoir was low, due to decreased rainfall corresponding to this time period. Excluding this period, the sediment balance shows a high percentage of accumulation in the reservoir and frequently was recorded at more than 90% of sediment storage.

Table 5 Monthly sediment balance of the study area

Month	Input (t)	Output (t)	Storage (t)	% Storage
Jan-02	33.81	70.54	-36.73	
Feb-02	21.49	29.04	-7.55	
Mar-02	33.61	21.53	12.08	35.9
Apr-02	844.89	10.33	834.56	98.8
May-02	778.82	28.07	750.75	96.4
Jun-02	23.23	23.87	-0.64	
Jul-02	221.9	7.86	214.04	96.5
Aug-02	1649.53	10.48	1639.05	99.4
Sep-02	4205.22	182.66	4022.56	95.7
Oct-02	4735.05	331.28	4403.77	93.0
Nov-02	3032.24	369.32	2662.92	87.8
Dec-02	1953.12	568.03	1385.09	70.9
Total	17532.91	1653.01	15879.9	90.6

Discussion

It is well known that clearance of natural vegetation to provide land for cultivation and settlement will commonly cause increased rates of soil erosion (Douglas, 1996). Order of magnitude increases in rates of soil loss and sediment yield have been widely reported (Morgan, 1986; Douglas, 1996) and these must clearly result in increased sediment loads in rivers, whose catchments have been widely affected by such changes. Furthermore, the effect of land use changes and the effects of human activities on hydrology and sediment transport are well documented by several researchers (Nelson & Booth, 2002; Ismail & Rahaman, 1994; Baharuddin, 1998). Under natural conditions, a forest delays runoff and encourages infiltration (Bruijnzeel, 1990), but human activity such as urbanizations and settlements, constructions, and agriculture among many others, will greatly reduce infiltration thus increasing total runoff and peak flows. The results show that S2 has the highest rainfall runoff coefficient compared to the other catchments in this study. The higher total water yield and rainfall runoff coefficient caused by the high amount of rainfall from the hilly and steep gradient in the catchment area was comparable to that of the other two catchments.

The effect of human activities in the catchment areas contributed to significantly high amounts of suspended sediment transported from the catchments area. Human disturbance such as quarrying activity will clear the forest cover exposing weathered rocks at depths of several tens of meters and eventually exposing impermeable bare rock. Land clearing for agriculture and urban areas will also affect runoff and sediment production in the catchment areas. Morgan (1986), for example, compares soil erosion rates under natural vegetation with those on cultivated land in several areas of the world and shows that the latter may be up to several orders of magnitude greater. The intensification of land use, with associated expansion of tillage, use of heavy machinery, and increased stocking densities, can also be expected to cause increased rates of soil loss. Abernethy (1990) presents sediment yield data from several small reservoir catchments in Southeast Asia that had experienced substantial land clearance and land use intensification during the period of record, which indicate that sediment yields increased by up to an order of magnitude. In this study, the sediment yield for S1, S2 and S3 are 155.78 t km^2 yr^{-1}, 150.72 t km^2 yr^{-1} and 71.72 t km^2 yr^{-1} respectively. However, the sediment yield from these study areas is still low compared to other areas in Malaysia (Table 6).

The results also indicate that a high amount of sediment was produced in S1, which was likely influenced by urban areas of Padang Besar. Nelson and Booth (2002) found

Table 6 Estimates of sediment yields of small forested and disturbed catchments in Malaysia (modified from Ismail and Rahaman, 1994)

Catchment name	Catchment area (km^2)	Sediment yield (t/km^2/yr)	Source
A. Forested catchments			Shallow (1956)
Sg. Telom, Cameron highlands	77	53	
Sg. Mupor, Johor	21.8	41	Leigh & Low (1973)
Ulu Segama, Sabah	1.1	312	Douglas, et al. (1992)
B. Secondary forest catchments			
Sg. Tekam, Pahang	0.47	35	DID (1986)
Sipitang, Sabah	0.15	60	Malmer (1990)
C. Cleared or logged catchments			
Sg. Tekam, Pahang	0.47	660	DID (1986)
Bukit Berembun, Negeri Sembilan	0.13	189	Baharuddin (1988)
Sipitang, Sabah	0.15	300	Malmer (1990)
Ulu Segama, Sabah	0.56	1600	Douglas et al. (1992)
D. Catchment affected by urbanization			
Sg. Jinjang, Selangor	10.3	1056	Balamurugan (1991)
Sg. Kelang at Zoo Negara	14.2	1480	Balamurugan (1991)
E. Construction site and quarry			
Sg. Relau, Penang	8.9	2701	Ismail & Rahaman (1994)
Sg. Sering, Selangor	6.6	12125	Mykura (1989)
F. Mixed landuse (present study)			
Sg. Jarum (S1) (urban and agriculture)	64.4	155.8	Present study
Upper Pelarit (S2) (quarry and forest)	42.7	150.7	Present study
Sg. Chuchuh (S3) (forest)	14.8	71.7	Present study

that the sediment production increase almost doubled from the time before to the time after development of urban areas. Agriculture also has an effect on runoff and sediment production (Steegen et al. 2000; Nelson & Booth 2002). Steegen et al. (2000) also show that most cultivated fields contribute to both runoff and high sediment production. This provides strong evidence to explain the high amount of sediment produced from the S1 catchment area.

The quarry activities in the S2 catchment area has also contributed to the high sediment yield. Although the catchment area is dominantly covered with forest (91%), the sediment yield was significantly high due to the quarrying. Studies by Ismail and Rahaman (1994) and Mykura (1989) have also shown that quarry activities will significantly increase the amount of sediment transported in the catchment especially during the raining season.

Storm events play important roles in determining the amount of sediment being transported out of a catchment especially in the tropics (Ismail, 2000). In the Peninsular Malaysia, rainfall is characterized by high intensities and short duration with about 125 mm h^{-1} in a 30 minutes storms (occurring approximately once in five years) and 100 mm h^{-1} occurring once in two years (Dale, 1959, 1960; Lockwood, 1967; Leigh & Low 1973; Douglas, 1984). Such storms would definitely create a higher erosion rate and produce a high amount of suspended sediment transported by rivers. As such, the sediment balance shows that high amounts of suspended sediment produced in the catchment area during the wet months of September to November (Figure 6), this coincides with high amount of rainfall during this period and thus reflecting the seasonal rainfall variation of the catchment.

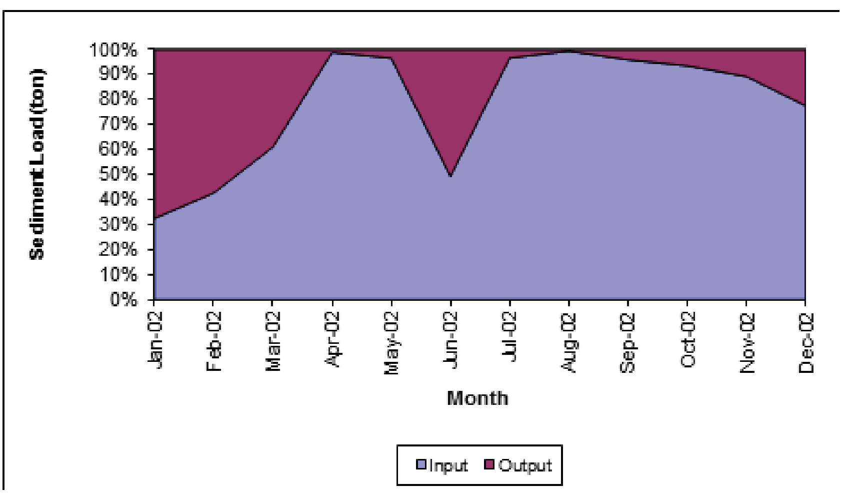

Figure 6 Sediment balance (total input – output) of the study area

The high rate of suspended sediment produced and transported from the catchment areas resulted in the high rates of sediment sink (trap) in the Timah Tasoh reservoir, with an annual rate of 90.6%. This is relatively high when compared to other sediment sink rate in other reservoirs such as Shih-Men, Cheng-Wen and Teh-Chi in Taiwan, with the rate of 71%, 25% and 33% respectively (Su-Chin Chen & Yi-Cheng Lai 2005). Substantial siltation in Taiwanese reservoirs generally results from natural collapse (e.g. landslides) and anthropogenic activities (e.g. urbanization). In addition, steep terrain and torrential rains (typhoons, storms) leading to intense transient flows, Taiwan is also experiencing severe sediment problems. Comparatively, in the United States, approximately 30-40% of sediment is deposited in reservoirs (Stallard 1998) and a study by Rausch and Schreiber (1981) shows that the Callahan Reservoir in central Missouri trapped an average of 85% of the incoming sediment. Dendy (1974) has shown that the trapping efficiency at 17 reservoirs around United States has a trapping efficiency of 82-98.5%. Study in the Three Gorges Dam shows approximately 73-87% of theoretical trapping efficiency, with Baihetan Reservoir having the highest theoretical trapping efficiency of 87% (Bangqi Hu et al., 2009).

Around the world, the construction of reservoirs for water supply, irrigation and flood control represent a key element of water resource exploitation in many areas of the world and sedimentation behind such dams must result in a substantial decrease in the downstream sediment flux (Walling & Fang, 2003). The most extreme example of the impact of reservoir construction on the sediment load of a river is the closure of the Aswan Dam on the River Nile, which reduced the annual suspended sediment load of that river from approximately 100×10^6 t $year^{-1}$ to almost zero. A similar impact has been reported by Meade and Parker (1985) for the Colorado River in the Southwest USA. The Colorado now discharges about 100 000 t of sediment to the Gulf of California each year, whereas before about 1930, the load was more than three orders of magnitude greater and averaged $125–150 \times 10^6$ t $year^{-1}$. Reservoir constructions represent the primary cause of the reduction of sediment transported downstream by trapping the sediment behind the dam.

Conclusion

The suspended sediment balance for the Timah Tasoh reservoir catchment shows that human activities in catchments area as well as the rainfall events that set up wetting conditions are favourable to erosion and mass movement, which provide sediment sources in the catchments area. From the total of 17,532.9 t sediment transported into the reservoir, 57.2% was contributed from the S1 catchment. The higher loading of suspended sediment by the S1 catchment was likely due to human activities around the catchment. By subtracting the sediment input and output, 90.6% of the suspended sediment load was deposited in the reservoir. The results of this study show a high amount of sediment being transported and deposited into the reservoir. This study will provide an insight into the problem of siltation in the reservoir and will give good information for a better management of the reservoir. The sediment balance presented in this study also could afford a basis for designing sediment control and management strategies for reducing the efficiency of sediment delivery from the individual areas to the river, and increasing storage elsewhere in the watershed. Additional reductions also could be achieved by reducing sediment output through the construction of wetlands and the use of buffer strips.

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