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# Estimating the Suspended Sediment Load by Using the Historical Hydrometric Record from the Lanyang-Hsi Watershed

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## ABSTRACT

**The long-term (1950-94) hydrometric data archived by the Water Resources Bureau (WRB) at the gauge station near the Lanyang-Hsi river mouth were re-processed to derive the time-series of suspended sediment load. A bias-corrected rating-curve method was used to estimate the sediment load. The statistical analysis provides a criterion for the construction of adequate rating curves. In most cases, yearly data were used to establish the rating curves. Estimated results showed strong inter-annual variations of sediment loads, ranging from 0.05 to 37 Mt yr$^{-1}$, which differs from the narrow range (7.9-8.1 Mt yr$^{-1}$) of long-term averages reported in the Hydrological Yearbooks. Two peaks of sediment load (>15 Mt yr$^{-1}$) occurred in the years following two road construction events, indicating the exacerbation of erosion in the watershed induced by human activities. This study indicates that WRB's long-term average method smoothes out the temporal fluctuation and, therefore, misses important information borne in the data. Hence, we suggest that historical data can be reprocessed to estimate yearly sediment load, which may lead to a better understanding of the sediment yielding process and its response to human disturbances.**

**(Keywords: Lanyang-Hsi River, Sediment Load, Taiwan, Rating Curve)**

## 1. INTRODUCTION

Riverine sediment discharge and its associated material fluxes dominate the land to ocean fluxes; consequently, they constitute a major link in global biogeochemical cycles (Allan 1986; Walling 1989; Meybeck 1993; Meybeck 1999). Estimation of suspended-sediment flux thus has become a major goal of biogeochemical studies of land-ocean boundary zones (e.g., LOIS Community Research Programme; Wilkinson et al. 1997). In Taiwan, given growing concern about soil erosion, the establishment of long-term records of sediment load is needed for better

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water and soil conservation and watershed management.

Taiwan's sediment production per unit area (14400 t $km^{-2}$ $yr^{-1}$) is over two orders of magnitude greater than the world mean value (Milliman and Meade 1983; Milliman 1991; Milliman and Syvitski 1992). The number highlighted by international researchers was derived from sediment load data published in the Hydrological Yearbook by the Water Resources Bureau (WRB). It is widely accepted that energetic tectonic activities result in high physical denudation rates in Taiwan (Li 1976). However, the exceptionally high sediment yields in modern Taiwan are not just attributed to natural conditions, such as steep slope, small watershed area, torrential rains and earthquakes. Increasing anthropogenic perturbations may also exacerbate the erosion rate, as demonstrated in recent works based on records made during the last twenty years (Kao and Liu 1996).

A longer record of sediment loading is needed to better define the natural condition and the response of sediment yield to human disturbances. The historical hydrometric records of widespread WRB gauging stations in Taiwan might provide temporal and spatial records of sediment load, and offer revealing information about sediment yielding processes and their controlling factors. Unfortunately, the WRB only publishes long-term averages of sediment loads, which preclude the delineation of anthropogenic effects on sediment yield. In this paper, we reprocessed the WRB data for Lanyang-Hsi during the period of 1950-94 in order to see whether we could extract more revealing information from the historical data and ascertain the suitability of applying the rating-curve method to yearly data sets.

## 2. STUDY SITE

Lanyang-Hsi, originating at an altitude of 3535 m, has a total length of 70 km with a mean gradient of 1/21 (Fig. 1), and it drains a total catchment of 980 $km^2$. The gauge station providing the data used in this study represents a catchment basin of 820 $km^2$. Two small tributaries that join the main channel at the tidal inlet are not included in this study. There is no dam blocking the river. The basement rock is composed mainly of Tertiary argillite-slate and metasandstone (Ho 1975). The denudation rate is rather high in the same manner as other watersheds of Taiwan (Li 1976). Lanyang-Hsi experiences a mean annual precipitation of approximately 3000 mm and over 70 % of the precipitation turns into surface runoff. Generally speaking, the lithology and climate conditions are homogeneous in this small watershed. A branch of the Central Cross-Island Highway was constructed during 1957-60 (Fig.1) and a massive county road construction project took place during 1975-80 (Taiwan Provincial Archives 1985). These two construction efforts were the major anthropogenic disturbances in the watershed.

## 3. DATA SETS

At Lanyang-Hsi watershed, the WRB data (1950-94) were recorded at the gauge station by the Lanyang Bridge (Fig. 1) located near the river mouth, yet without tidal influence. The publication of WRB Hydrological Yearbooks started in 1970. The records prior to 1970 were not published in the Hydrological Yearbooks, but kept in data files at the WRB archive. The

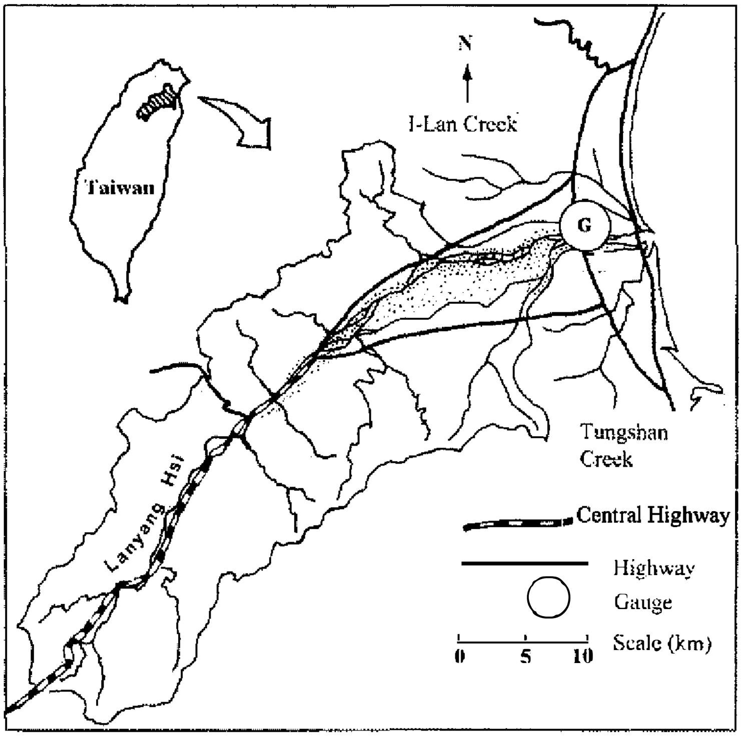


*Fig. 1.* Map of the Lanyang-Hsi watershed and the location of gauge station. The branch of the Central Cross Highway and major road is marked.

WRB hydrological data include two sets: (1) the discrete data of suspended sediment concentration ($C_s$ in ppm; about 30 samples per year) and concurrently recorded water discharge rate (Q in cms); and (2) continuous records of daily water discharge rate.

In the following we briefly introduce the protocols for WRB's data collection which were reported in detail by Lan (1974). The daily water discharge rate in the second data set was the mean value of hourly runoff, which was derived from continuous water level record by a conversion formula calibrated by direct measurements. Samples for measurement of total suspended matter concentration in the first data set were collected by using the standard type of depth-integrating suspended-sediment sampler (DH-48) recommended by the Federal Inter-agency Sedimentation Project of the USA (http://fisp.wes.army.mil/). The sampler is suitable for stream flow-rate up to 300 cms. The sampler can efficiently collect suspended-sediments at every water depth during the entire time of submergence.

For comparison, we also analyzed data of suspended sediment concentration collected at a site near the WRB Gauge station (Fig. 1) reported by Kao and Liu (1996). This set of data was collected about every five days from September 1993 to August 1994. During the invasion of typhoon Tim (9-11 July 1994), intensive sampling was conducted every 4-5 hours to analyze the short-term variations. Water samples were collected in mainstream with 2-L polyethylene bottles. A 4-kg lead block was attached to each bottle in order to submerge the sampler vertically. Water samples were filtered immediately after collection on pre-weighed polycarbonate membrane filters. The filters were dried in an oven at 60 °C for 24 hours before weighing.

## 4. ESTIMATION OF SEDIMENT LOADS

The estimation of annual sediment load of a river can be quite straightforward, if there exist continuous records of both the discharge rate and the sediment concentration, which give a continuous record of sediment loads that may be summed up to yield the annual load. However, in most cases, the continuous record of sediment concentration is not available, and indirect methods must be employed to make the estimation. There are two approaches: one is to multiply the annual runoff with the mean sediment concentration, and the other is to use the sediment rating-curve method (Fergurson 1987; Gordova and Gonzalez 1997). The former approach has been shown to produce serious errors, if the flow condition changes in a wide range and the sampling is not intensive. The other approach is thus the most widely used.

The rating curve, which depicts an empirical relationship between suspended-sediment load (L) and streamflow (Q) (e.g., Campbell and Bauder 1940; Crawford 1991). This relation is usually defined as a power function

$$L = kQ^b \tag{1}$$

where $Li = Qi \bullet [C_s]i$. Although the accuracy of this approach has been questioned (Walling 1977), the applicability appears to be adequate for many purposes (e.g., Colby 1955; Crawford 1991). This approach has been formulated in many different ways. It has been demonstrated that improvement of the regression formulation can significantly reduce the bias introduced in the calculation (Cohn et al. 1989; Cohn 1995).

### 4.1 WRB's Estimator

The WRB selected one of the commonly used methods, the Flow-Duration Rating-Curve (FDRC) method, to estimate the mean suspended-sediment load. In this method, the average quantity of suspended sediment transport in a river over a given period of time is expressed as

$$Lm = \sum_{\min Q}^{\max Q} f(Q)p(Q) \tag{2}$$

where $Lm$ is the mean load and the sediment rating-curve is represented by a function of Q, $f(Q)$. Along with the probability density of Q, $p(Q)$, which is derived from the flow-duration data, one may obtain the mean sediment load.

For the past 25 years, the WRB has been reporting long-term average values of sediment load in Hydrologic Yearbooks, all within a narrow range (7.9-8.1 Mt $yr^{-1}$). The reported sediment load is composed of three parts: (1) the suspended load, which is derived from long-term flow-duration and all-data-pooled rating-curve method, as mentioned above; (2) an extra constant percentage (15%) for the bed load; (3) and an additional linear extrapolation to the full drainage area (980 $km^2$), which includes the 19% of area below the gauge station that is not accounted for in the previous two items.

For a highly responsive and frequently perturbed river system, the relationship between sediment load and discharge rate may change dramatically from year to year. It is conceivable that the long-term empirical rating curve averages out these changes and misses important information recorded in the valuable data set. In order to remedy such a deficiency, we used yearly data to construct rating curves and set up some criteria to ensure the applicability of our approach.

### 4.2 Method Adopted for this Study

Following the recommendation of Cohn (1995), we adopted a log-linear formulation of the rating curve with a bias correction term first introduced by Duan (1983). The logarithmic transformation yields a linear expression:

$$\text{LogL} = a + b\log Q + \varepsilon \tag{3}$$

where a and b are the intercept and slope of the rating curve, and $\varepsilon$ is the residual error (the amount by which the observed response differs from the predicted response). The least squares logarithmic regression procedure generally results in underestimation because of the bias given to the values below the fitted line by the regression (Farr and Clarke 1984). Duan (1983) proposed a non-parametric correction for the transformation bias

$$\beta = (1/n)\sum_{i=1}^{n} \exp(\varepsilon_i) \tag{4}$$

where $n$ is the number of observations in the sample data set. A relationship between L and Q can be obtained from an inverse transformation of Equation (3). An unbiased relationship between L and Q is then given by

$$L = \exp(a)Q^b \beta \tag{5}$$

where $\beta$ is the correction for transformation bias. The bias-corrected rating curve was then applied to transform daily water runoff to daily sediment load. The annual load was derived by summing up the estimated daily loads.

## 5. RESULTS AND DISCUSSION

### 5.1 Comparison of Parallel Data Sets

During the sampling period (1993-94) of Kao and Liu (1996), the river's discharge rate showed a wide range of variation (8 to 3350 cms, Fig. 2a). The river flow was characterized by high frequency fluctuation with the base flow at about 8 to 10 cms. The steady rise and fall of discharge rate in wet and dry seasons were absent. Instead, the discharge rate rose and fell rather rapidly during rainy months from October to December when northeast monsoon prevailed and during summer months with torrential rains associated with typhoon invasions. The three discharge peaks from July to late August 1994 marked the occurrences of Typhoons Tim, Doug and Fred with daily mean discharges of 1440, 652 and 448 cms, respectively.

From September 1993 to August 1994 Kao and Liu (1996) collected 77 samples, including those intensively sampled during invasion of Typhoon Tim. In the same period, the WRB data set showed 44 samples, including those collected during invasions of Typhoon Doug and

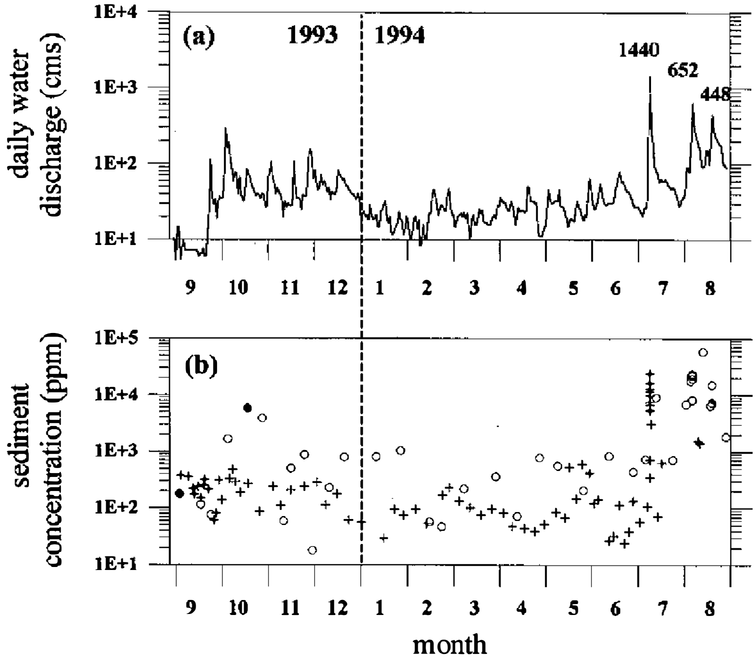


*Fig. 2.* The variations of (a) daily water discharge rate (cms) and (b) suspended sediment concentrations (ppm) of data sets for this study (+) and WRB (o) during the period of 1993-94. The numbers mark three peaks of daily water discharge rate.

Fred. Both data sets demonstrated that very high concentrations of total suspended matter (TSM) were associated with very high discharge rates during floodings (Fig. 2b). However, there are also apparent inconsistencies between the two data sets. The apparent inconsistencies may be partially attributable to the high variability of the TSM resulting from rapid change of flow conditions. Different sampling devices and schemes used in the two data sets may also contribute to the apparent inconsistencies. Therefore, it is necessary to determine what consequences the inconsistencies in TSM data may cause in the calculation of the sediment load.

The logQ (Q in cms) and logL (L in t $d^{-1}$) scatter plot (Fig. 3) for the WRB data and our data showed similar linear trends. Both data sets exhibit low scattering at high flow rate but high scattering at low flow rate. A more serious scattering of data distribution was reported for Oregon Coast Range streams, where suspended-sediment concentration varied over an order of magnitude at any given discharge due to land use (Beschta 1978). The regression functions for the data set of Kao and Liu (1996) and that of WRB are respectively:

$$\mathrm{LogL} = -0.64 + 2.17\,\mathrm{logQ} \qquad R2=0.89, \text{ and}$$
$$\mathrm{LogL} = -0.19 + 2.12\,\mathrm{logQ} \qquad R2=0.83\ .$$

The positive relationship corroborated the importance of runoff strength in affecting sediment transport. The two data sets show higher consistency in both the upper and lower ends of the discharge rate but rather large differences in the middle range, over which Kao and Liu (1996) collected relatively few samples. In fact, these two data sets with a total sampling number of 120 covering three major typhoon events appear to compliment each other. The combined data set undoubtedly is more representative than either set alone. The regression function for the combined set is:

$$\text{LogL} = -0.31 + 2.13 \log Q \qquad R2=0.85.$$

The bias-correction factors are calculated to be 1.24, 1.45 and 1.35, respectively, for the data sets of Kao and Liu (1996), WRB and the combined one. Using Equation (5), we calculated the daily sediment loads from the daily runoff data. The bias-corrected annual sediment loads calculated for the data set of Kao and Liu (1996), that of WRB and the combined one are 3.7, 6.2 and 5.0. Mt $yr^{-1}$, respectively. Undoubtedly, the estimate from the combined set is the most accurate. The estimates from the two subsets are all within ~25 % of the best estimate. In spite of the apparent inconsistencies between the data sets of Kao and Liu (1996) and WRB, a reasonable estimate of sediment load may be produced from either data set. The differences between the estimates indicate that errors associated with under-sampling and data scattering are at an acceptable level in our approach. This lends support to the use of yearly data sets from historical records to derive rating curves for the estimation of historical sediment loads.

### 5.2 Rating Curves Derived from Historical Data

Figure 4a plots all the data from the 45 years of WRB records. The log-linear regression

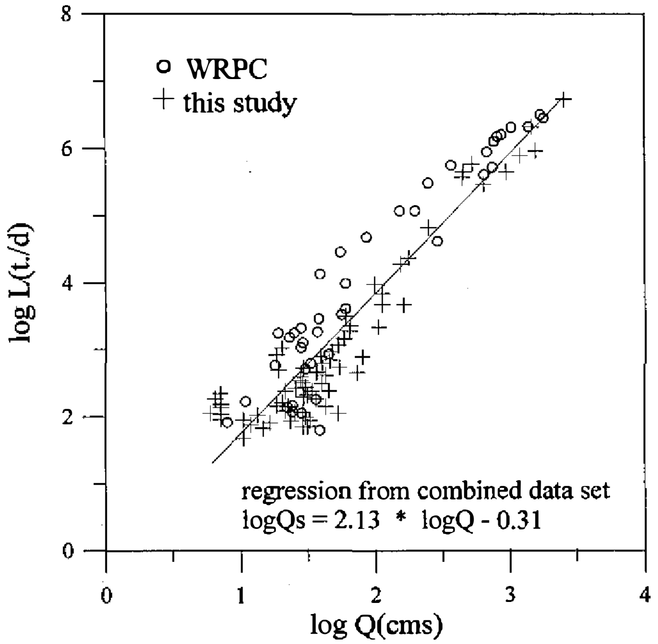


*Fig. 3.* The log-log scatter plot of sediment load (L) and water discharge rate (Q) for this study and WRB's data. The rating function for combined data sets is shown.

line has a coefficient of determination ($R^2$) of 0.68 (n=1244, p<0.01). The sediment load (L) varies in ranges up to 3 orders of magnitude for a given runoff value, so the residuals of the regression result can be very large. Such high variation of sediment load might be attributed to changes in conditions of watershed and channel system, which cause strong inter-annual variation and lead to quite distinct rating relationships (e.g., Fig. 4b). In general, 30 samples are needed to describe a rating relationship (Cohn et al. 1989). In the WRB data set, there are 30 samples or more in most years. Therefore, we chose one year to be the interval for regression analysis.

The results of yearly regression (Table 1) show that the regression slopes (0.92 to 2.77) and intercepts (-1.6 to 1.6) vary in wide ranges with most of the p values less than 0.01, except 1959 (p=0.27) and 1990 (p=0.05). Therefore, statistical analyses demonstrate that in most years regression results are significant. In other words, the strong variability in the yearly rating relationships shown in Table 1 is scientifically meaningful in most years.

It has been cautioned that the sediment sampling in high flow-rate is crucial in constructing a rating curve (Gordova and Gonzalez 1997). The lack of significant correlation in the data sets of 1959 and 1990 (as indicated by the rather large p values) is apparently attributed to the rather small range of flow conditions sampled. This is demonstrated in Fig. 5, which plots the flow rates on sediment sampling occasions in each year from 1950 to 1994. Because the limited sampling missed the peak flow rates in most years, it is necessary to make extrapolation in the calculation of daily sediment load from the discharge rate. In order to avoid excessive error resulting from extrapolation, researchers in this field employ a Q-range check (J. Syvitski, personal communication). The purpose is to ensure the yearly curve suitable for transforming entire range of stream-flow. We qualify a data set as adequate for rating curve construction, if its maximum Q of sediment sampling is greater than 15% of the peak daily Q in that year. (We

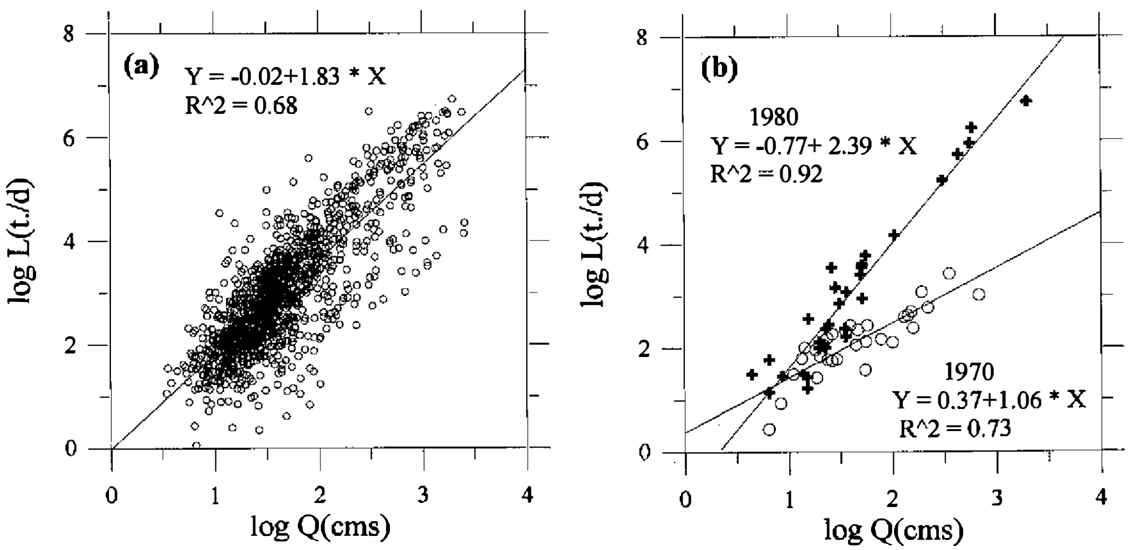


*Fig. 4.* The logQ-logL scatter plot for, (a) the pooled 45years data set, and (b) for the year of 1970 (o) and 1980(+).

Table 1. The parameters of regression analysis on yearly data set.

| Year | Intercept | Slope | $R^2$ | Sampling frequency | Modified intercept | Modified slope |
|---|---|---|---|---|---|---|
| 1950 | 1.59 | 0.92 | 0.71 | 18 | | |
| 1951 | 0.74 | 1.46 | 0.74 | 18 | | |
| 1952 | 1.37 | 1.29 | 0.99 | 5 | | |
| 1953 | 0.14 | 1.70 | 0.95 | 7 | | |
| 1954 | 0.31 | 1.73 | 0.97 | 7 | | |
| 1955 | 1.23 | 1.10 | 0.72 | 11 | | |
| 1956 | 0.57 | 1.47 | 0.88 | 16 | | |
| *1957* | 0.66 | 1.40 | *0.30* | 16 | | |
| ***1958*** | 0.36 | 1.68 | ***0.64*** | 12 | 0.32 | 1.63 |
| ***1959*** | 0.20 | 1.31 | ***0.11*** | 13 | −0.61 | 2.06 |
| 1960 | -1.33 | 2.66 | 0.86 | 20 | | |
| 1961 | -0.75 | 2.40 | 0.91 | 34 | | |
| 1962 | -0.18 | 2.09 | 0.85 | 25 | | |
| 1963 | -0.01 | 2.22 | 0.94 | 26 | | |
| 1964 | 0.10 | 1.95 | 0.84 | 29 | | |
| 1965 | -1.62 | 2.77 | 0.86 | 32 | | |
| 1966 | -0.78 | 2.14 | 0.87 | 32 | | |
| 1967 | -0.19 | 1.86 | 0.79 | 38 | | |
| 1968 | -0.00 | 1.74 | 0.77 | 35 | | |
| 1969 | 0.13 | 1.27 | 0.85 | 33 | | |
| 1970 | 0.37 | 1.06 | 0.73 | 31 | | |
| 1971 | -0.71 | 1.42 | 0.85 | 34 | | |
| *1972* | -0.45 | 1.62 | *0.52* | 32 | | |
| 1973 | -0.89 | 2.28 | 0.89 | 32 | | |
| 1974 | -0.80 | 2.07 | 0.89 | 31 | | |
| 1975 | -0.40 | 1.84 | 0.91 | 30 | | |
| 1976 | 0.29 | 1.30 | 0.69 | 33 | | |
| 1977 | -0.43 | 2.23 | 0.84 | 33 | | |
| 1978 | 0.07 | 2.00 | 0.89 | 32 | | |
| 1979 | -1.00 | 2.55 | 0.92 | 33 | | |
| 1980 | -0.77 | 2.39 | 0.92 | 31 | | |
| 1981 | -0.86 | 2.44 | 0.93 | 33 | | |
| 1982 | -1.01 | 2.52 | 0.89 | 30 | | |
| 1983 | -0.13 | 2.02 | 0.80 | 30 | | |
| 1984 | -0.86 | 2.32 | 0.77 | 30 | | |
| 1985 | 0.06 | 2.10 | 0.86 | 30 | | |
| 1986 | -1.02 | 2.39 | 0.82 | 32 | | |
| 1987 | 0.10 | 1.87 | 0.70 | 31 | | |
| 1988 | 0.34 | 1.75 | 0.86 | 30 | | |
| 1989 | 0.28 | 1.89 | 0.65 | 30 | | |
| ***1990*** | 1.51 | 1.37 | ***0.26*** | 30 | 0.97 | 1.59 |
| 1991 | 1.27 | 1.41 | 0.83 | 30 | | |
| ***1992*** | -0.55 | 2.38 | ***0.65*** | 30 | 0.36 | 1.82 |
| *1993* | 0.22 | 1.75 | *0.60* | 30 | | |
| 1994 | 0.10 | 2.02 | 0.87 | 52 | | |

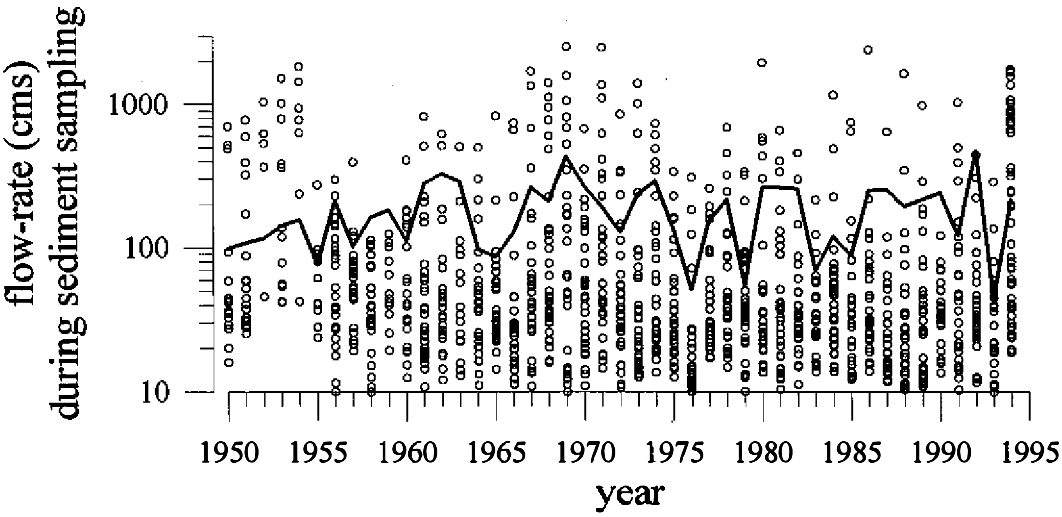


*Fig. 5.* The plots of corresponding water discharge rate during sediment sampling in each year of the WRB's data set. Solid line stands for the criterion defined by 15% of maximum daily water discharge (see text).

did not adopt the criterion of J. Syvitski that the sampled flow rates must exceed 10% of the long-term average of the peak flow-rate, because the peak flow-rate of Lanyang-Hsi changes drastically from year to year.) Figure 5 shows that the upper limit of flow rates during sampling exceeds 15% of the peak daily Q (shown by the solid line in Fig. 5) in the corresponding year for all years except 1958, 59, 90 and 92.

Subject to the p-value check and Q-range check, the data for the years of 1958, 1959, 1990 and 1992 are not qualified for constructing the yearly rating curve. To supplement the data deficiency for these 4 years, longer-term rating curves were created for them by including the data from the two adjacent years. The 3-year rating curves indeed have lower p-values and higher $R^2$. The modified rating parameters are shown in Table 1.

### 5.3 Inter-annual Variation of Sediment Load

Using the revised set of rating curves, we estimated annual sediment loads (Table 2), which fluctuate in a range of over 3 orders of magnitude. By comparison, the annual water runoff varies within a factor of 8 (0.54-4 $km^3$). The lowest sediment load (0.05 Mt $yr^{-1}$) occurred in 1976, which was a very dry year without typhoon visitation. The highest sediment load (37 Mt $yr^{-1}$) occurred in the year of 1992 with a Q value of historical maximum. Although, the sediment loading is dependent on the water discharge rate to a certain extent, the significant inter-annual variation of sediment load is not entirely determined by annual runoff.

Two peaks of high sediment load with values of 36.6 and 25.1 Mt $yr^{-1}$ (Table 2) were recorded right after two road construction events (Fig. 6). The sediment loading remained high for 3-4 years and then dropped abruptly back to the normal level. This road construction effect is similar to the previous report on two small watersheds in Oregon's Coast Range (Beschta

Table 2. The results of estimated suspended load.

| Year | Annual runoff (km3/y) | Annual total sediment load (Mt./y) | #Historic mean (This study) | *Historic mean (WRPC) |
|---|---|---|---|---|
| 1950 | 2.26 | 0.8 | | |
| 1951 | 2.47 | 2.5 | | |
| 1952 | 2.52 | 3.0 | | |
| 1953 | 4.00 | 3.2 | | |
| 1954 | 2.90 | 4.4 | | |
| 1955 | 1.74 | 0.6 | | |
| 1956 | 3.13 | 1.9 | | |
| 1957 | 2.09 | 1.3 | | |
| 1958 | 1.97 | 1.9 | | |
| 1959 | 1.88 | 9.7 | | |
| 1960 | 2.54 | 14.6 | | |
| 1961 | 1.94 | 26.7 | | |
| 1962 | 2.50 | 19.8 | | |
| 1963 | 1.43 | 36.6 | | |
| 1964 | 1.73 | 4.4 | | |
| 1965 | 1.46 | 3.9 | | |
| 1966 | 1.44 | 2.5 | | |
| 1967 | 2.21 | 4.9 | | |
| 1968 | 2.54 | 4.1 | | |
| 1969 | 2.67 | 0.3 | | |
| 1970 | 2.21 | 0.1 | 7.0 | 5.8 |
| 1971 | 2.95 | 0.1 | 6.7 | 5.8 |
| 1972 | 1.83 | 0.5 | 6.4 | 5.8 |
| 1973 | 1.82 | 11.4 | 6.6 | 5.8 |
| 1974 | 2.93 | 5.2 | 6.6 | 5.8 |
| 1975 | 1.51 | 0.6 | 6.3 | 5.8 |
| 1976 | 0.54 | 0.1 | 6.1 | 5.8 |
| 1977 | 1.34 | 12.8 | 6.3 | 5.8 |
| 1978 | 1.72 | 8.6 | 6.4 | 5.8 |
| 1979 | 1.34 | 2.9 | 6.3 | 5.8 |
| 1980 | 1.53 | 25.1 | 6.9 | 5.8 |
| 1981 | 1.85 | 23.8 | 7.4 | 5.8 |
| 1982 | 1.54 | 21.6 | 7.9 | 5.8 |
| 1983 | 1.45 | 1.7 | 7.7 | 5.8 |
| 1984 | 1.66 | 6.2 | 7.6 | 5.9 |
| 1985 | 1.22 | 6.4 | 7.6 | 5.9 |
| 1986 | 1.82 | 10.7 | 7.7 | 5.9 |
| 1987 | 1.38 | 5.6 | 7.6 | 5.9 |
| 1988 | 1.47 | 3.4 | 7.5 | 5.9 |
| 1989 | 1.49 | 34.9 | 8.2 | 5.8 |
| 1990 | 1.45 | 10.0 | 8.3 | 5.8 |
| 1991 | 1.86 | 4.4 | 8.2 | 5.8 |
| 1992 | 2.53 | 37.1 | 8.8 | 5.8 |
| 1993 | 0.90 | 0.8 | 8.7 | 5.8 |
| 1994 | 2.63 | 34.8 | 9.2 | 5.8 |

#Historic mean is the average for the cumulative period before the given year.

* WRB historic mean is only in consideration of the part of suspended load (see text)

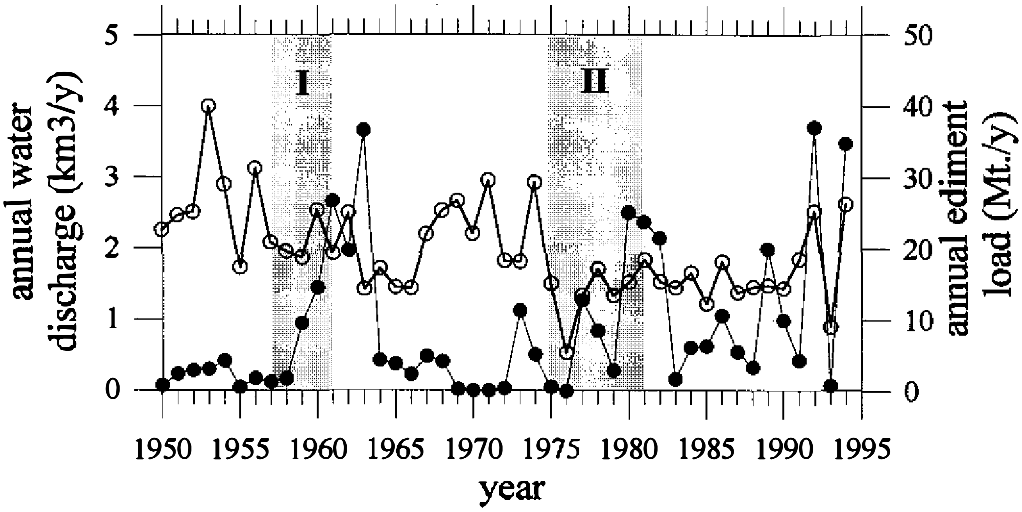


*Fig. 6.* The variation of annual water discharge rate (∘) and annual sediment load (•). Shaded areas, marked by I and II, represent the massive road construction periods of Central Cross Highway (I) and county roads (II).

1978). The close timing between two peaks of sediment loading and road construction events indicated anthropogenic impacts on soil erosion.

Table 2 compares the WRB's estimates of long-term averages of annual sediment load with those calculated from our yearly estimates over the same periods. In the Annual Hydrological Yearbooks, the mean sediment loads for Lanyang-Hsi range 7.9-8.1 Mt yr$^{-1}$. If we only consider the suspended load portion, the numbers will be 5.8-5.9 Mt yr$^{-1}$, which are slightly lower than our values ranging from 6.1 Mt. to 9.2 Mt yr$^{-1}$ (Table 2). If we neglect bias-correction in Equation (4), our multi-year means in the range of 4.1 Mt. to 7.4 Mt yr$^{-1}$ will brackets the estimates of WRB, suggesting the WRCP's estimates are subject to notable bias caused by log-linearization (Cohn 1995).

## 6. CONCLUSIONS

After re-analyzing the WRB data from 1950 to 1994, we found two cycles of "disturbance and recovery", which provide valuable information about how the watershed responded to human perturbation. Only from the yearly sediment loads, we are able to detect and differentiate the sediment yield under natural or human disturbed conditions. The above information could be very useful for watershed management and for model prediction. Thus, we suggest that in Taiwan where watersheds have great sediment load variability, historical data should be processed on yearly basis instead of a long-term basis in order to reveal valuable short-term variability of sediment loads, if the available data cover an adequate range of flow rates, with the maximum reaching 15% of the peak daily flow in that year. For those years without adequate coverage, data from the two adjacent years may be pooled together for the construction of the rating curve.

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