Analysis of suspended sediments and flow under sub-tropical environment of Taiwan

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Abstract: - The total amount of suspended load carried by a stream during a year is usually transported during one or more extreme events related to high river flows and intense rainfall, leading to high suspended sediment concentrations (SSC). Therefore, the purpose of the study is to build a model to estimate sediment discharge based on observed flow and SSC from torrential rain events. Price meter and depth-integrating suspended-sediment sampler, model DH-59, are used to measure flow velocity and SSC, respectively during six events in Shi-wen River, southern Taiwan. These data were collected every two hours in the period, July 2011 to August 2012. The results evidenced that sampling high flows is sufficient to generate SRC’s with higher confidence ($R^2 = 0.87$) in estimating sediment load as it underestimated sediment load from Typhoon Nanmadol by 18% compared to 73% from the 10-day interval SRC ($R^2 = 0.26$) developed using data collected January, 2011 to August, 2012.

Key-Words: - suspended sediment, sediment discharge, flow, torrential rain, Shi-wen River, sub-tropical

1 Introduction

Being located in a sub-tropic area, Taiwan faces serious attacks from torrential rains accompanied with typhoons during a summer-autumn season (June to August), and has a mean precipitation of 2500 mm/year and reaches 3000-5000 mm/year in the mountainous regions. The frequency of typhoon with torrential rainfall happened one time for every two years before year of 2000, once a year after 2000 and three to four times since 2008 [1]. These typhoons induce severe hazards in the form of flooding [2,3]. By comparing the rivers around the world, the ones in Taiwan have the steepest slopes, largest discharge per unit drainage area and the shortest time of concentration [4]. The watersheds are formed by fragile sandstone, and downstream reaches of rivers have heavy deposits from the poor geologic upstream catchments by these extreme events. Consequently, sediment concentrations are large, as evidenced by the fact that 7 of the 10 global rivers with the highest sediment yields are Taiwanese [5]. These high sediment concentrations worsen the severity of these disasters as illustrated by [6] and [2]. In addition, damage caused by typhoon Morakot in 2009 was mostly due to sediment related disasters [1].

In the wake of such events, the ability to accurately quantify sediment loads in rivers is essential. However, measuring and estimating suspended sediments concentrations (SSC) in rivers have long been subject to confusion and uncertainty. Many methods have been developed for collecting data and estimating sediment discharge in rivers, which suggests complexity in river studies. According to [7], river study is necessary for reliable forecasting, but it is a difficult task due to the complexity and inherent non-linearity of its hydrological system. Regardless of the complexity, correct estimation of SSC is becoming more and more essential in engineering design, planning, maintenance, and operation of water resources [8]. In addition, suspended sediment has been identified by [9] as a leading direct cause of river impairments. For example, high concentration of suspended sediment can increase cost of water treatment; damage pumps and turbines; fill reservoirs; impede navigation and increase frequency and severity of floods by reducing channel capacities. The sediments in a river are usually caused by erosion on upstream section, washing of soil within catchment area or because of man interfering with riverbed.

There are two common approaches for estimating suspended load; first one being the interpolation procedure [10]. This requires regular sediment sampling over a relatively long period.
The load is estimated as a product of mean sediment concentration and water discharge over some time such as 1 hr, 1 day, or 1 month. The second approach is the regression analysis (Walling and Webb 1981), the most popular of which is the sediment-rating curve (SRC) [11, 12]. A sediment-rating curve is an empirical relationship between suspended sediment concentration, \( C \) (mg/L) and the associated discharge \( Q \) (m\(^3\)/s), and since SSC and sediment discharge often vary over several orders of magnitude the rating curve is expressed in a form of a power function:

\[
C = aQ^b
\]  

(1)

Where \( C \) is the suspended sediment concentration; \( Q \) is water discharge; and \( a, b \) are coefficients. The coefficients \( a \) and \( b \) are dependent on each river and are determined by mechanism of transport. The rating curve is assumed to represent a continuous relationship over the entire range of water discharge. Thus one can apply a full range of \( Q \) records to interpolate (sometimes extrapolate) suspended loads over a given time period. Using the established SRC and the available continuous discharge data, sediment load for a given period maybe calculated by summing daily loads or by the magnitude frequency method [13]. The main advantage of the rating curve method is that long-term historical data can be stratified and more than one rating curve for specific time intervals can be constructed [14].

Most suspended sediments move during infrequent high flows that collectively account for only a small portion of the measurement period [15]. According to [16], one variability in the sediment transport that should be considered is the season of the year and the relative magnitude of the precipitation. [11] earlier report this when they demonstrated a decrease of the coefficient of determination (\( R^2 \)) from 0.85 in summer to 0.39 in winter. The associated high transport rates and variances dictates that most data be collected during high flows as suggested by [17] in his study on concentration and transport in Slovene rivers. However, the infrequency and brevity of the high flow periods combined with measurement and access cause acute problems in collecting data. Nonetheless, data collected during high flows are still essential to the development of good rating curves. Hence, the purpose of the paper is to estimate sediment discharge through rating curves developed from data collected during torrential rainfall events.

### 2 MATERIALS AND METHODS

#### 2.1 Study Area

Our study area was in Shiwen River, located (21°34 48 North latitude and 120°47 56 East longitude) in the southern part of Taiwan (Fig.1). The length of the main stream is about 22.3 km and the basin covers 89.61 km\(^2\). The average slope is about 0.03 with a design flood at 1300 m\(^3\)/s.

![Fig.1 Shi-wen river basin](image)

#### 2.2 Monitoring suspended sediment concentration

The Taiwan Water Resources Agency (WRA) manually measures discharge and corresponding concentrations of suspended sediment three times a month (10 days interval) at Shiwen River as part of river management. Based on these measurements, rating curves of flow discharge and sediment discharge were obtained. For the same station, we collected the same data during six torrential rainfall events for estimating sediment discharge through establishment of a sediment-rating curve. These events included four typhoons, namely, Nanmadol (28 August to 31 August 2011), Talim (20 June to 21 June 2011), Saola (2 August to 3 August 2012) and Tembin (24-25 August and 28 August 2012). During these events, samples were collected every two hours using DH-59 and price meter for SSC and flow velocity respectively. [18] give the operation and descriptions of this equipment. The mid-section method of measurement as shown by Fig.2 was employed. This method of measurement assumes that the velocity samplesat each depth samplingpoint \( D_i \), represents the mean velocity in apar ticular rectangular cross sectional area. The total depth of that particular vertical determined the measurement depths of velocity. If depth was less than 75 cm, measurements were carried at 0.6 depth of vertical.
If depths were more than 75 cm, measurements were done at 0.2 and 0.8 depths of verticals. The partial area extends laterally from half the distance from the preceding meter location to half the distance to the next, and vertically from the water surface to the measured depth and the computations are done using equation 2 to equation 4 based on Fig.2.

\[
A = (W_i \times D_i) \ldots + (W_n \times D_n) \quad (2)
\]

\[
V = 0.68 \times N + 0.005 \quad (3)
\]

\[
Q = (V_1 \times A_1) + \cdots + (V_n \times A_n) \quad (4)
\]

Where A is area (m\(^2\)), W is width of each segment (m), D is depth (m), V is velocity (m\(^2\)/s), and N (rev/s) Q is discharge (m\(^3\)/s).

The collected samples were subsequently taken to the Hydraulic laboratory at National Pingtung University of Science and Technology (NPUST) and their sediment concentrations were measured using the evaporation method. Units of measurement of sediment concentration are reported in the USGS field methods measurement of fluvial sediment [18] as follows: Milligrams of sediment per litre of water. However, as a matter of convenience, we determined it in the laboratory in parts per million (ppm), which is the dry weight of suspended material per million equal weights of water-sediment mixture, or milligrams (mg) per kilogram (kg). It is found by the formulae: parts per million = (weight of sediment * 1000000) / (weight of water-sediment mixture).

The observed sediment discharge is obtained by multiplying the corresponding water discharge by SSC. Water discharge (Q) at the sampling cross section was measured using the velocity area method and computed by equation 4. We compared the sediment-rating curve from the 10 days interval and that from the torrential rainfall events. Regression analysis is employed for the analysis of sediment discharge and flow.

### 3 Results and discussion

#### 3.1 Behaviour of suspended sediment during the torrential events

In this study, suspended sediment samples were collected every two hours during torrential events. The sediment discharge was estimated accordingly. The important hydraulic characteristics of the six torrential events are given in Table 1. Among the six events, event 3 (Typhoon Nanmadol) had the highest duration (64 hours). Thus, observed concentration of suspended sediments were extremely high, with maximum observed value at 50014 ppm. The least SSC was observed in event 5 (Typhoon Saola), having 6920 ppm in a duration of 24 hours. Event 1, which was not a typhoon, resulted to a peak discharge (Q) of 72 cubic metre per second (cms) and maximum SSC of 16547 ppm. Table 1 shows that maximum Q does not always coincide with maximum Q\(_s\). For example, maximum Q for event 1 was 72 cms, but maximum Q\(_s\) occurred when Q was 70 cms. The same happened for event 2. Similarly, discharge does not always coincide with SSC. The maximum values of SSC preceded those of discharge for events 1, 2 and 3 (Fig.4). It was concluded that some soil sediments accumulated in the watershed during the dry season or some were deposited on the riverbed during the fall of river discharge from previous floods. Hence, the first events even though they had less peak discharge compared to other events, they resulted to increased values of SSC and Q\(_s\) due to readily available sediments. In addition, it is noted in Fig.4 that SSC decreased more rapidly than river discharge. Possible reasons behind this phenomenon are that some soil particles settled due to the drop in velocity during the falling stages of each event, or when the discharge started to decline, due to lack of sediment supply, the SSC decline abruptly. [9] when estimating reservoir sedimentation from three typhoons made similar observations.

#### 3.2 Discharge and suspended sediment discharge during the torrential events

The relationship between flow and sediment discharge for all events is shown in Fig.5. Event 2 had the lowest coefficient of determination (0.61) and event 6 (Typhoon Tembin) had the highest R\(^2\) (0.97). This is attributed to the different ranges of flow. Event 1 had range between about 30 cms to about 72 cms while event 6 covered a wide range of flow (about 130 cms to about 412 cms).
In addition, event 6 had the highest discharge (412 cms) among all the events observed (Table 1). The second highest $R^2$ is obtained from event 3 (Typhoon Saola) (0.93). The characteristics of this event are almost identical to event 6, having the second largest Q of 411 cms and more data sets collected as suggested by the highest rainfall duration (64 hours). [19] got positive correlation ($R^2$) of 0.95, 0.87 and 0.12 for typhoon Remason, Nakeli and Sinlaku respectively in the study of relationship between discharge and suspended sediment concentration. The SRC’s developed from each event differs, so is the estimated discharge. The hydrological factors, such as, differences in dry weather periods, land surface and river catchment after each rainfall event seem to affect the SSC and $Q_s$ on the next rainfall event.

### Table 1

<table>
<thead>
<tr>
<th>Item</th>
<th>Event 1</th>
<th>Event 2</th>
<th>Event 3</th>
<th>Event 4</th>
<th>Event 5</th>
<th>Event 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration (h)</td>
<td>36</td>
<td>36</td>
<td>64</td>
<td>36</td>
<td>34</td>
<td>26</td>
</tr>
<tr>
<td>Peak Q (cms)</td>
<td>72</td>
<td>51</td>
<td>411</td>
<td>307</td>
<td>45</td>
<td>412</td>
</tr>
<tr>
<td>Max SSC (ppm)</td>
<td>1161</td>
<td>481</td>
<td>8542</td>
<td>8484</td>
<td>312</td>
<td>8508</td>
</tr>
<tr>
<td>Max $Q_s$ (kg/s)</td>
<td>16547</td>
<td>12044</td>
<td>50014</td>
<td>27675</td>
<td>6920</td>
<td>20652</td>
</tr>
<tr>
<td>$Q$ at Max Q (cms)</td>
<td>70</td>
<td>50</td>
<td>411</td>
<td>307</td>
<td>45</td>
<td>412</td>
</tr>
</tbody>
</table>

3.3 Comparison of 10-day interval and torrential rainfall events SRC

Data collected by the Taiwan Water Resources Agency (WRA), which included suspended sediment concentration and discharge was used to establish a rating curve for the period January 2011 to October 2012. The SRC developed is shown in Fig.6 In addition, all the data from the torrential rainfall events were used to develop a SRC to be compared with the SRC from the 10-day interval. The $R^2$ from the torrential events was higher (0.87) compared with 0.26 from the 10-day interval. This reveals the benefits of frequent sampling at high flows in rating curve construction. The 10-day interval does not develop good rating curves within a short period, for example, the approximately two years as it is in our study. This is because the 10-day interval reporting will capture only a few high flow events, which are essential in establishing good SRC’s. To develop a good rating curve the 10-day interval, data for at least 10 years must be collected [20]. This should cover most variability in the stream regime and climatic conditions. For example, [21] used data from 1950 to 2008 to assess sediments in the Yellow river and obtained $R^2$ of 0.84.

![Fig.5 Flow and sediment discharge relationship during the torrential events](image)

### 3.4 Application of the developed models

From the regression analysis (Fig.5 and 6), different models are developed for estimating sediment discharge ($Q_s$).
To evaluate their applicability, we applied $Q$ from all the events to each of the developed models and results are shown in Fig.7. Models from events 1 and 5 show over estimation of $Q_i$ mainly because the flow data used to develop these models is small and is comprised of low flows (30 to 80 cms) as seen in Fig.5. The 10-days interval shows underestimation of $Q_i$ since when there is no typhoon or torrential event, very limited sediments will be washed to river bodies. Further, to evaluate applicability, we selected models from low discharge (Event 1, having 30 to 80 cms), high discharge (Event 6, having 200 to 412 cms), 10 days interval and all torrential events to compare with the observed sediment load for Typhoon Nanmadol (Table 2). From the table, we can observe as already illustrated by Fig.7 that Event 1 overestimates (224%) and the model from the 10 days interval underestimates suspended load by 73%. The model from all the torrential events shows better estimation when compared to all events though it underestimated suspended load by 17%. In addition, the results further reveal that to develop a good relationship between $Q$ and $Q_i$, we need more data to capture most variation, one storm event and of low variation are insufficient as illustrated by event 1 and 6. These further justify the use of rating curves developed from combined torrential events such as Typhoons.

Table 2 Observed and estimates of suspended load for Typhoon Nanmadol.

<table>
<thead>
<tr>
<th>Item</th>
<th>Sediment load (MT)</th>
<th>Difference from observed (MT)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>0.94</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Event 1</td>
<td>3.04</td>
<td>2.10</td>
<td>224</td>
</tr>
<tr>
<td>Event 6</td>
<td>0.07</td>
<td>0.86</td>
<td>-92</td>
</tr>
<tr>
<td>10-days interval</td>
<td>0.25</td>
<td>0.69</td>
<td>-73</td>
</tr>
<tr>
<td>All torrential events</td>
<td>0.77</td>
<td>0.17</td>
<td>-18</td>
</tr>
</tbody>
</table>

4 Conclusions

Developing a reliable and consistent method of computing suspended sediment discharge within a river is one of the most important practical objectives of river studies. From the above analysis and discussions, we can conclude that a suspended sediment concentration is highly correlated to flow. When the flow is high, chances of transporting huge sediments are large. Estimating sediment discharge from rating curves established from 10-day interval yields lower correlation ($R^2 = 0.26$) compared to rating curve from the combined torrential rainfall events ($R^2 = 0.87$). In addition, the 10-day interval SRC underestimated observed sediment load for Typhoon Nanmadol by 73% while the torrential event SRC underestimated by 18%. We conclude that sediment discharge should be estimated from high rainfall events, because high accuracy can be attained within a few high rainfall events, unlike the 10 day-intervals, which may require long-term data to attain high accuracy.

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References:


