Sediment transport characteristic of the Ping River basin, Thailand

Butsawan Bidorn\textsuperscript{a,c,}\textsuperscript{*}, Stephen A. Kish\textsuperscript{a}, Joseph F. Donoghue\textsuperscript{b}, Komkrit Bidorn\textsuperscript{b}, Ruethaithip Mama\textsuperscript{d}

\textsuperscript{a}Florida State University, 909 Antarctic Way, Tallahassee, Florida, 32306, United States  
\textsuperscript{b}University of Central Florida, 4111 Libra Drive, Orlando, Florida, 32816, United States  
\textsuperscript{c}Chulalongkorn University, Phayathai Road, Pathumwan, Bangkok, 10330, Thailand  
\textsuperscript{d}Chungnam National University, 99 Daehak-ro (St), Yuseong-gu Daejeon, 305-764, South Korea

Abstract

This study examined the river sediment transport characteristics of the Ping River basin, which is one of the major river basins in Thailand. River surveys of the Ping River were carried out nine times between 2011 and 2013. Survey data included river cross sections, flow velocities, suspended sediment concentration, and bed load transport in the river. Analyzes of these data indicated that suspended transport rates in the Ping River during normal flow conditions in 2012-2013 ranged between 107 and 9,562 metric tons/day (mt/d), but increased to 35,300 mt/d during high flooding conditions (Thailand’s Great Flood of 2011). The rate of bed load transport was 1,401 mt/d during the Flood of 2011. However, the measured bed load in 2012-2013 varied between 0 and 482 mt/d. The bed-to-suspended load ratio in the Ping River fluctuated in the broad range of 0-2.0. Estimates of total sediment transport in the Ping River were made using some of the classic equations from the hydrologic literature. The results obtained from the different methods show that the Laursen-Copeland formula gives the best estimate of total sediment transport rate of the Ping River compared to other methods. Results from this study also reveal that the Bhumibol Dam, constructed in 1964, has had a significant effect on suspended sediment load reduction downstream of the dam.

Keywords: Suspended sediment load; bed load; total sediment load; sediment estimation; river basin

* Corresponding author. Tel.: +1-850-980-2104; fax: +1-850-980-2104.  
E-mail address: bb11x@my.fsu.edu
1. Introduction

Changes in the sediment loads of the world’s rivers are influenced by many factors, such as deforestation for agriculture, population pressure, water resources development, dam construction, and climate change. A more complete understanding of river response to human activities and climate change is necessary to better manage natural resources.

The Ping River basin (Fig. 1) is one of the major sub-catchments of the Chao Phraya basin, which is the largest river basin in Thailand [1]. In 1952, Thailand started to pursue a 25-year irrigation development program. The program began in 1953 with the Chao Phraya project, which was considered to be the largest irrigation project in Asia. The Bhumibol Dam (Fig. 1) was constructed on the Ping River (completed in 1964) as an additional component of the Chao Phraya Project for water supply, flood control, hydroelectric power generation, and river integrity. With a normal storage capacity of $9.7 \times 10^9 \text{ m}^3$, the Bhumibol Dam controls runoff from about 16 percent of the area of the entire Chao Phraya River basin. Later, other large dams, such as the Sirikit and Kiew Lom Dams, including barrages and numerous canal systems, have been constructed within the Chao Phraya River basin to increase the surface water storage and to deliver water to the lower Chao Phraya River basin irrigation systems. The changes in the hydrologic regime of the Ping River basin caused by the Bhumibol Dam’s water regulation may have changed the sediment balance in the basin [2].

The objectives of this study were to determine sediment transport characteristics of the Ping River, which is the major sediment source to the Chao Phraya River, and to study sediment functions for predicting total sediment loads of the Ping River. The Ping River’s sediment characteristics were studied based on river survey data during 2011-2013. The observed river flow and sediment data were used to evaluate the applicability of five classical sediment transport prediction methods for the Ping River. By comparing sediment data observed at two locations downstream from the Bhumibol Dam between 2011 and 2013, effects of the Bhumibol Dam on sediment characteristics of the Ping River can be assessed.

2. Study area

The Ping River basin is located in the northern Thailand between latitudes 15° 45’ N to 19° 45’ N and longitudes 98° 06’ E to 100° 12’ E (Fig. 1) with a catchment area of 34,453 km² [3]. The river basin is mainly characterized by terraced mountains and valleys with elevations ranging from 330 to 2000 m above MSL [4]. The length of the Ping River is approximately 740 km [2] with the river gradient varying from 1:1,600 to 1:2,300 [5]. The channel is 150- to 350-wide with river depths of 5 to 15 m [5]. The average annual discharge of the Ping River is 62 m³/s [4], which contributes about 24 percent of the total average annual river flow of the Chao Phraya River [6].

The climate of the basin is dominated by the southwest monsoon (mid-May through September wet season) and the northeast monsoon (November to mid-March dry season). Annual rainfall averages about 1,097 mm, and 90 percent of rainfall occurs during the wet season [6,7]. The Bhumibol Dam, which is the largest dam in the Chao Phraya system, was completed on the Ping River in 1964 for water storage, hydroelectric power generation, flood mitigation, fisheries and saltwater intrusion control [8]. The dam has a maximum storage capacity of about 13.4 billion m³, compared to mean annual inflow of 5.7 billion m³ from the catchment area of about 26,400 km² [9].

In 1960, subtropical forest covered about 70 percent of highland areas in the northern part of Thailand, and more than 27 percent of forest areas had been converted to agricultural areas by 1998 [4].

3. Methods

Historical data on river discharge and sediment load observed at the gauging Station P.2A (Fig. 1) operated by Royal Irrigation Department (RID) were collected for studying average river flow conditions and sediment characteristics of the Ping River. Unfortunately, the sediment data are insufficient for systematic sediment study, especially bed load analysis. Because sediment transport processes are complex, site-specific, field observation data are necessary for evaluating the sediment characteristics of the Ping River. Hydrologic surveys were conducted on nine occasions between 2011 and 2013 at Stations SP-01 and SP-02, which are located downstream 70 and 230 km...
from the Bhumibol Dam, respectively (Fig.1), to investigate sediment transport characteristics in the Ping River basin. Survey data included river cross-sections, flow velocities, suspended sediment, and bedload sample concentrations.

The flow velocities were measured using an AEM1-D in-situ portable single-axis current meter. The measurement range of the current meter was between 0.01 m/s and 5 m/s. The flow velocities were averaged from six separate measurements at various depths for estimating the mean velocity of each river flow condition. River depth was gauged along the traverse distance to provide a cross-sectional profile of the river. Suspended sediment was collected using an inverted and corked cylindrical bottle at the proportional depths of 0.2, 0.4, 0.6, and 0.8 between the river bed and water surface. Suspended sediment was filtered from the samples using GIF filter paper, which retained particles larger than 0.45 μm. The filters were dried and weighed, and the suspended sediment concentration was calculated by weight difference.

Bedload sediment was collected using a Helley-Smith sampler, which is a medium-weight sampler containing a polyester sampling bag. The sampler operation is limited to flow velocity less than 2.5 m/s, and the sample bag allowed the collection of gravel and sand with a diameter greater than 0.25 mm. Each bedload sample was taken over 30 to 60 seconds. The bedload samples were sieved using a standard test method of particle-size analysis of soil (ASTM D422).

Total sediment transport in rivers and streams is often separated into bed load (transported near or along the bed by rolling, bounding and sliding) and suspended load (carried in suspension through the water column). The total sediment transport processes in any one river system varies across river catchments, depending on the interaction among sediment size, discharge energy, channel bed conditions, and channel obstructions [8]. There are several equations, which have been developed for estimating sediment transport in an alluvial channel. However, because sediment transport process are sensitive to a number of variables representing the strength of the flow, the fluid, and the sediments, the sediment transport potential can vary by an order of magnitude depending on the similarity of material and hydraulic parameters between the river of interest and developed functions. In this study, some of the principal classic equations proposed by Acker and White [10], Engelund Hansen (1967) [11], Laursen-Copeland [12], Toffaletti [13], and Yang [14] have been tested to evaluate the sediment predictive applicability of each model for the Ping River.
4. Results and discussion

4.1. Historical river flows and sediment characteristics

Daily river flow during the period 1952-2012 and daily suspended-sediment discharge from 1989 to 2001 at Station P.2A located at Ban Tha Kae, Tak (Fig. 1) were obtained from the RID. Based on statistic analysis of historical runoff and suspended sediment data, an average runoff in the Ping River at station P.2A during the period 1952-2012 is approximately 240 m$^3$/s with the maximum river discharge of 4,760 m$^3$/s in 1959. The variation in daily river flow is depicted in Fig. 2. It reveals that the Bhumibol Dam has completely controlled and changed the river flow regime of the Ping River downstream from the dam. Between 1989 and 2001, suspend sediment discharge at Station P.2A ranged between 0.04 to 35,300 mt/d, with an average suspended sediment load of about 2,270 mt/d. Fig. 3 illustrates time series of suspended sediment discharge during the past two decades. A significant reduction of suspended load occurred beginning in 1991 after the Lower Mae Ping Dam, the additional component of the reversible hydropower plant system, was constructed 5 km downstream of the Bhumibol Dam.

![Graph showing daily river discharge at different stations](image1)

![Graph showing time-series for sediment load](image2)

4.2. River flow and sediment characteristics during the period 2011-2013

A summary of field observation data during the period 2011-2013 is listed in Table 1, and Fig. 4 illustrates the observed sediment discharge (suspended load and bed load) at Stations SP-01 and SP-02. Based on river surveys at Station SP-01 (Fig.1) on the Ping River, the observation data covered the Thailand’s Great Flood of 2011, which was
one of the most severe floods in the Thailand’s history. The flood caused significantly high river discharge at SP-01 of 1,412 m$^3$/s with a flow velocity of 2.08 m/s. The flood also yielded the suspended and bedload sediment transports of 35,300 and 1,400 mt/d, respectively. Based on the bed load samples, the Ping River bed material was very coarse sand with a median diameter ($d_{50}$) of 1.13 mm. After the 2011 Flood, the river discharge at Station SP-01 during the wet season varied between 100 and 550 m$^3$/s with an average flow rate of about 470 m$^3$/s. Suspended loads also dropped to 330-3,200 mt/d, whereas, bed load could be detected only when the flow velocity was greater than 0.9 m/s. The bed load varied from 0.0 to 0.47 of suspended sediment loads.

During the dry season, observed river discharge at Station SP-01 varied between 195 and 250 m/s, which was higher than the minimum flow rate observed during the wet season, but suspended loads were significantly lower than suspended loads associated with low flows in the wet season. The obvious difference in suspended sediment concentration between the wet and dry seasons at Station SP-01 may be related to water regulation by the Bhumibol Dam. The bed load was measured once during the dry period, when the flow velocity was about 0.8 m/s. The bed load was twice as much as suspended sediment load because the water released from the Bhumibol Dam during dry period contained much less suspended materials compared to the wet season. During 2011-2013, the total sediment transport of the Ping River at Station SP-01 varied between 300 and 36,720 mt/d.

Table 1. Summary of field observation data.

| Date          | Water depth (m) | Flow velocity (m/s) | Flow area (m$^2$) | Discharge, $Q_w$ (m$^3$/s) | Suspended load, $Q_s$ (mt/d) | Bed load, $Q_b$ (mt/d) | $Q_b/Q_s$ |
|---------------|-----------------|---------------------|-------------------|----------------------------|---------------------------|----------------------|-----------|
| SP-01 (wet season) : |                 |                     |                   |                            |                           |                      |           |
| 20-Oct-11     | 4.9             | 2.08                | 680               | 1,412                      | 35,299                    | 1,401                | 0.04      |
| 4-Jun-12      | 2.2             | 0.84                | 636               | 538                        | 3,253                     | 0                    | 0.00      |
| 4-Aug-12      | 0.9             | 1.09                | 330               | 358                        | 1,026                     | 482                  | 0.47      |
| 19-Oct-12     | 0.8             | 0.90                | 249               | 224                        | 1,024                     | 265                  | 0.26      |
| 10-May-13     | 1.6             | 1.00                | 543               | 541                        | 746                       | 0                    | 0.00      |
| 19-Jul-13     | 0.8             | 0.64                | 202               | 130                        | 329                       | 0                    | 0.00      |
| 22-Sep-13     | 0.9             | 0.45                | 228               | 103                        | 689                       | 0                    | 0.00      |
| SP-01 (dry season) : |                 |                     |                   |                            |                           |                      |           |
| 28-Jan-13     | 1.0             | 0.78                | 322               | 251                        | 136                       | 275                  | 2.02      |
| 10-Mar-13     | 0.9             | 0.68                | 287               | 196                        | 107                       | 0                    | 0.00      |
| SP-02 (wet season) : |                 |                     |                   |                            |                           |                      |           |
| 2-Jun-12      | 2.8             | 0.51                | 581               | 296                        | 2,344                     | 1,377                | 0.59      |
| 2-Aug-12      | 2.7             | 0.34                | 621               | 210                        | 721                       | 0                    | 0.00      |
| 16-Oct-12     | 2.6             | 0.17                | 556               | 94                         | 176                       | 0                    | 0.00      |
| 9-May-13      | 1.3             | 0.67                | 242               | 161                        | 762                       | 0                    | 0.00      |
| 23-Jul-13     | 1.7             | 0.29                | 330               | 97                         | 1,782                     | 0                    | 0.00      |
| 21-Sep-13     | 5.2             | 0.61                | 1,089             | 665                        | 9,562                     | 295                  | 0.03      |
| SP-02 (dry season) : |                 |                     |                   |                            |                           |                      |           |
| 26-Jan-13     | 1.8             | 0.93                | 363               | 336                        | 1,024                     | 253                  | 0.16      |
| 8-Mar-13      | 2.0             | 0.29                | 257               | 74                         | 112                       | 0                    | 0.00      |

For Station SP-02, located about 140 km downstream of Station SP-01, the observation data show that the Ping River discharge during the wet season at Station SP-2 ranged between 176 and 2,344 m$^3$/s. This was typically less than values at Station SP-01 during the same period, except in September 2013. Flow velocities were also relatively low (0.17-0.67 m/s) compared to Station SP-01. Observed suspended loads fluctuated between 176 and 9,600 mt/d during the wet season. Meanwhile, bed loads were occasionally observed when flow velocities were greater than 0.5 m/s. For the dry season, the highest observed river discharge of 1,600 m$^3$/s occurred in the middle of the dry period, and the lowest observed river flow (74 m$^3$/s) took place at the end of the season. Suspended loads at Station SP-02 were relatively high compared to those at Station SP-01. Bedload transport was also observed once (at the same sampling period as for Station SP-01) when the flow velocity was more than 0.9 m/s. The ratio of bed-to suspended loads at Station SP-02 varied within wide range of 0.0 to 0.60 for the wet season and of 0.0 to 0.15 for the dry season. At Station SP-02, total sediment transport during the period 2012-2013 varied from 186 to 10,300 mt/d.
4.3. Predicted total sediment loads at the Ping River

In this study, observation data from river surveys were used to evaluate the applicability of the five classic sediment transport functions developed for estimating sand-size bed transport. Table 2 shows total sediment transport rates computed from each function, and the comparison between measured total sediment transport rate and predicted sediment transport rates from sediment functions is illustrated in Fig. 5. It appears that almost all these functions tend to over-estimate total sediment loads of the Ping River. The Acker and White (1973), England Hansen (1967) and Yang (1984) functions over-estimate total sediment loads for most flow conditions at both stations, especially Station SP-01, with the root mean square error (RMSE) ranging between 12,094 and 37,401 mt/d (Table 2). The Toffaletti (1968) and Laursen-Copeland (1989) functions give either over- or under-prediction of total sediment loads. Both functions tend to over-estimate total sediment transport at Station SP-01. Meanwhile, the predicted sediment loads at Station SP-2 using these functions are mainly lower than observed data, especially during low flow conditions. However, in comparison among five methods, the Laursen-Copeland (1989) function gives the best prediction of total sediment loads for Stations SP-01 and SP-02 with a RMSE of 9,946 and 3,691 mt/d, respectively.

4.4. Effect of large dam construction on sediment loads in the Ping River system

Based on river flow and sediment data observed at Station SP-01 and SP-02 during the period 2011-2013, the data indicate that the Bhumibol Dam has affected sediment transport process of the Ping River in several ways as follows:

During Thailand’s Great Flood of 2011, all river inflow to the Bhumibol reservoir was diverted downstream after mid-October 2011 because the Bhumibol Dam reached its maximum capacity. At that time, the river flow in the Ping River can be considered as unregulated but also in a flood condition [3]. Fig. 4 shows the significant decrease in suspended sediment loads at Station SP-01 (70 km downstream of the Bhumibol Dam) after 2011 due to the Bhumibol Dam regulation. The reduction of suspended load downstream from the dam consequently caused the increase of bed-to suspended sediment ratio at Station SP-01 from 0.03 (unregulated flow condition) up to 0.47 (regulated flow condition) during the wet season. The effect of the Bhumibol Dam regulation on suspended sediment concentration is also noticeable during the dry season; the bedload transport was twice as high relative to suspended loads as a result of clear water released from the Bhumibol Dam.

However, the dam seems to have had less of an effect on suspended sediment in the river at increased distance downstream from the dam. Observation data at Station SP-02 (230 km downstream the dam) show that suspended loads measured at Station SP-02 were normally higher than suspended loads at the Station SP-01. Because the dam typically traps sediment behind it and may have limited sediment supplied to the basin outlet, the reservoir normally released water containing little sediment. However, the downstream flow may have eroded the downstream channel to equilibrate with the new upstream gradient, resulting in an increase of suspended loads downstream (SP-02).
Moreover, the downstream river may receive additional sediment from downstream basins. Sediment data measured in September 2013 (Fig. 4) illustrates that suspended load at Station SP-02 was higher than the suspended load at Station SP-01. The significantly high rate of suspended loads may be affected by high-intensity rainfall over the basin below the Bhumibol Dam due to a tropical storm passed the areas below the Bhumibol Dam during September 19-21, 2013.

Table 2. Observed and estimated sediment transport at Stations SP-01 and SP-02 on the Ping River.

| Station | Date     | River flow (m³/s) | Total sediment transport rate (mt/d) |
|---------|----------|-------------------|--------------------------------------|
|         |          | measured          | Ackers                               |
|         |          |                   | Engelund                              |
|         |          |                   | Laursen                              |
|         |          |                   | Toffaleti                            |
|         |          |                   | Yang                                 |
| SP01    | 20-Oct-11| 1,412             | 36,700                               |
|         |          |                   | 58,158                               |
|         |          |                   | 140,371                              |
|         |          |                   | 46,903                               |
|         |          |                   | 33,227                               |
|         |          |                   | 128,526                              |
| SP01    | 4-Jun-12 | 538               | 3,253                                |
|         |          |                   | 14,723                               |
|         |          |                   | 28,995                               |
|         |          |                   | 5,767                                |
|         |          |                   | 8,192                                |
|         |          |                   | 20,899                               |
| SP01    | 4-Aug-12 | 358               | 1,508                                |
|         |          |                   | 30,147                               |
|         |          |                   | 15,991                               |
|         |          |                   | 23,732                               |
|         |          |                   | 23,473                               |
|         |          |                   | 17,934                               |
| SP01    | 19-Oct-12| 224               | 1,289                                |
|         |          |                   | 13,261                               |
|         |          |                   | 7,891                                |
|         |          |                   | 9,241                                |
|         |          |                   | 10,559                               |
|         |          |                   | 9,288                                |
| SP01    | 28-Jan-13| 251               | 411                                  |
|         |          |                   | 9,708                                |
|         |          |                   | 8,419                                |
|         |          |                   | 5,718                                |
|         |          |                   | 7,315                                |
|         |          |                   | 8,852                                |
| SP01    | 10-Mar-13| 196               | 107                                  |
|         |          |                   | 5,884                                |
|         |          |                   | 5,308                                |
|         |          |                   | 3,626                                |
|         |          |                   | 4,602                                |
|         |          |                   | 6,452                                |
| SP01    | 10-May-13| 541               | 746                                  |
|         |          |                   | 25,993                               |
|         |          |                   | 29,482                               |
|         |          |                   | 14,085                               |
|         |          |                   | 16,456                               |
|         |          |                   | 24,912                               |
| SP01    | 19-Jul-13| 130               | 329                                  |
|         |          |                   | 3,653                                |
|         |          |                   | 3,086                                |
|         |          |                   | 2,380                                |
|         |          |                   | 2,965                                |
|         |          |                   | 3,826                                |
| SP01    | 22-Sep-13| 103               | 689                                  |
|         |          |                   | 1,083                                |
|         |          |                   | 1,861                                |
|         |          |                   | 609                                  |
|         |          |                   | 230                                  |
|         |          |                   | 2,096                                |
| SP02    | 2-Jun-12 | 296               | 3,721                                |
|         |          |                   | 2,201                                |
|         |          |                   | 10,964                               |
|         |          |                   | 627                                  |
|         |          |                   | 456                                  |
|         |          |                   | 6,641                                |
| SP02    | 2-Aug-12 | 210               | 721                                  |
|         |          |                   | 583                                  |
|         |          |                   | 5,105                                |
|         |          |                   | 139                                  |
|         |          |                   | 25                                  |
|         |          |                   | 3,028                                |
| SP02    | 16-Oct-12| 94                | 176                                  |
|         |          |                   | 33                                   |
|         |          |                   | 1,100                                |
|         |          |                   | 5                                   |
|         |          |                   | 0                                   |
|         |          |                   | 472                                  |
| SP02    | 26-Jan-13| 336               | 1,854                                |
|         |          |                   | 13,150                               |
|         |          |                   | 18,111                               |
|         |          |                   | 6,222                                |
|         |          |                   | 7,748                                |
|         |          |                   | 13,376                               |
| SP02    | 8-Mar-13 | 74                | 112                                  |
|         |          |                   | 153                                  |
|         |          |                   | 1,295                                |
|         |          |                   | 42                                   |
|         |          |                   | 5                                   |
|         |          |                   | 818                                  |
| SP02    | 9-May-13 | 161               | 762                                  |
|         |          |                   | 3,639                                |
|         |          |                   | 5,305                                |
|         |          |                   | 1,776                                |
|         |          |                   | 2,459                                |
|         |          |                   | 4,744                                |
| SP02    | 23-Jul-13| 97                | 1,782                                |
|         |          |                   | 237                                  |
|         |          |                   | 1,617                                |
|         |          |                   | 72                                   |
|         |          |                   | 8                                   |
|         |          |                   | 1,158                                |
| SP02    | 21-Sep-13| 665               | 9,857                                |
|         |          |                   | 5,161                                |
|         |          |                   | 39,554                               |
|         |          |                   | 1,137                                |
|         |          |                   | 1,799                                |
|         |          |                   | 18,089                               |

Root Mean Square Error 12,094 28,523  7,667 7,835  24,276

Fig. 5. Comparison of total sediment transport rate between observation and results from five sediment transport functions.

5. Conclusion

This study has demonstrated the characteristics of river flow and sediment transport rate of the Ping River. River surveys were carried out for data collection along river cross-sections, including flow velocities, and suspended and bed sediment loads over the period 2011-2013. The observed river flow and sediment data were used to test the applicability of five sediment transport functions for predicting sediment transport rates in a sand bed river. The characteristics of sediment transport of the Ping River at 70 km and 230 km downstream the Bhumibol Dam, which
is one of the largest dams in Thailand, were investigated and were used to study the effect of the dam on sediment processes of the Ping River. By comparing the flow and the sediment characteristics during the wet and dry season from 2011 to 2013, the effects of the Bhumibol Dam on sediment discharge in the Ping River can be assessed. The results of this study indicate that no strong correlation between sediment characteristics at Station SP-01 and SP-02 can be observed. The ratio between bed load and suspended load at Station SP-01 and SP-02 ranged between 0.0 to 2.0 and 0 to 0.6, respectively. Based on sediment prediction functions, it appears that the function proposed by Acker and White (1973), England Hansen (1967) and Yang (1984) over-estimate total sediment loads for most flow conditions at both stations, especially Station SP-01. The Toffaletti (1968) and Laursen-Copeland (1989) functions tend to mostly over-estimate total sediment loads at Station SP-01 but under-estimate total sediment loads at Station SP-02. Laursen-Copeland (1989) gives the best prediction of total sediment loads for Stations SP-01 and SP-02 compared to other functions.

The comparison of sediment characteristics between Stations SP-01 and SP-02 reveals that the Bhumibol Dam has had a significant effect on sediment characteristics of the Ping River by decreasing suspended sediment loads downstream of the dam. However, the effect decreases with distance downstream from, as a result of river gradient adjustment and input of additional sediment from the basin downstream the dam.

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