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ESTIMATION OF SEDIMENT YIELD IN A SMALL URBAN UNGAUGED WATERSHED BASED ON THE SCHAFFERNAK APPROACH AT SUGUTAMU WATERSHED, CILIWUNG, WEST JAVA

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ABSTRACT

The sediment yield is defined as the amount of sediment discharged by an area for a given period of time. Schaffernak proposed to estimate sediment yield in a watershed based on a sediment duration curve. The research objective is to test the applicability of a modified Schaffernak approach in estimating annual sediment yield in Sugutamu, a small urban watershed subsystem of the Ciliwung River where hardly any necessary data is available. The discharge-duration curve is developed based on daily runoff simulation using a hydrological model WinTR-55, while the sediment rating curve is derived based on field surveys and is developed only for a total suspended solid. The results of field surveys conducted in January 2015 were used for calibrating the physiographical parameters of the watershed as input data for WinTR-55, and the simulation was for the year 2014. Both calibration and simulation processes utilized the rainfall data from a nearby automatic rainfall recorder. The quantification of sediment yield resulted in 108.5 tons/km^2/year, which is acceptable when compared to the results of similar studies. The results showed that sediment yield from ungauged watershed are possible to be quantified using modified Schaffernak approach in combination withWinTR-55 application. Further study is needed in order to validate the applicability of the approach in similar conditions.

Keywords: Modified Schaffernak Approach; Sediment duration curve; Sediment yield; Small urban ungauged watershed; WinTR-55 Hydrological Model

1. INTRODUCTION

The sediment yield is defined as the amount of sediment passing a point of interest in a watershed for a given period of time (Lin et al., 2002; Heng & Suetsugi, 2013). Basically, there are three approaches that have been utilized for quantifying the sediment yield, namely qualitative methods, physically-based deterministic methods, and statistical methods. Those methods have unique advantages when employed in different conditions and also suffer from their own drawbacks (Ono et al., 2011).

Schaffernak proposed to estimate sediment yield in a watershed based on a sediment duration curve, which can be classified as a statistical method. The original approach of Schaffernak in deriving the sediment duration curve is as a combination of the stage duration curve and the sediment rating curve, where both of them are derived from direct measurements (Schaffernak, 1950). A previous study by Marsudiantoro et al. (1998) using the same approach in Cengkareng

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Drain System (395 km^2), West–Jakarta resulted in sediment yield of 767,376 tons/year, or, around 1,943 tons/km^2/year which is quite reasonable since the watershed was still dominated by rice-fields, farms and plantations at that time. Recent works by Rosen and Xu (2014) using a similar approach is a sediment availability assessment for the Mississippi River using stage hydrograph, while Ndomba (2013) used the Pacific Southwest Inter-Agency Committee (PSIAC) model for sediment yields estimation in ungauged catchments in Tanzania, and Curran-Cournane et al. (2013) used sampled storm events and the sediment yield events in Auckland.

The research objective is to test the applicability of modified Schaffernak approach in estimating annual sediment yield in Sugutamu, a small urban watershed at the outskirts of Greater-Jakarta, a subsystem of the Ciliwung River in West Java, where there is neither a stream flow monitoring station nor a rainfall station. Therefore, the approach is slightly modified, namely it uses the dischargeduration curve instead of a stage duration curve. The discharge is simulated using a public domain hydrological model WinTR-55 (USDA, 1986), while the sediment rating curve is based on the field survey.

The discharge duration curve is a cumulative frequency curve that requires a continuous time series of discharges. Since WinTR-55 is a single-event rainfall-runoff model, it requires adjusment when applied on continuous-event. The adjustment will be on the Curve Number (CN), in such that it takes into account the Antecedent Moisture Condition (AMC). Variation in initial abstraction and potential water retention should also be considered, since these will affect the rainfall excess and base flow (Geetha et al., 2007). In this study only the CN variation is considered, while base flow is assumed to be constant. According to Heng and Suetsugi (2013), sediment load on alluvial rivers usually dominated by the Total Suspended Solid (TSS). This study was conducted in Sugutamu River that is located in an alluvial plain. As such the sediment rating curve constructed from field data were applied into TSS only.

The drainage area is delineated using topographic map (*Peta Rupabumi)* sheet number: 1209-421 at a scale of 1:25,000. Rainfall data from the Faculty of Engineering, Universitas Indonesia (FTUI) station is used for both calibration and simulation processes. The station is located about 6 km northwest of Sugutamu. Calibration of WinTR-55 was based on discharge measurements on five days in January 2015 and rainfall events were recorded at the FTUI station on the same days. The TSS rating curve is derived based on the same five-day field survey. The discharge duration curve is derived from a simulated discharge for the year 2014. Referring to the Schaffernak approach, a combination of the discharge duration curve and the TSS rating curve will result in annual sediment yield.

2. MATERIALS AND METHODS

2.1. Study Area

Sugutamu, a small urban watershed located about 30 km south of Jakarta is a subsystem of the Ciliwung River in West Java, Indonesia, as presented in Figure 1. The point of interest is located at a small bridge immediately upstream of the Juanda Bridge, with a total watershed area of around 12.21 km^2. The secondary data available for the study consisted of a 1:25,000 scale topographic map (*Peta Rupabumi*) and rainfall data from the FTUI rainfall station at the Faculty of Engineering Universitas Indonesia. There are manual and automatic rainfall recorders. The land use of the watershed is dominated by a residential area. The watershed delineation was carried out based on the information available on the topographical map (*Peta Rupabumi*) supported by ArcGIS in determining the physiographic parameters.

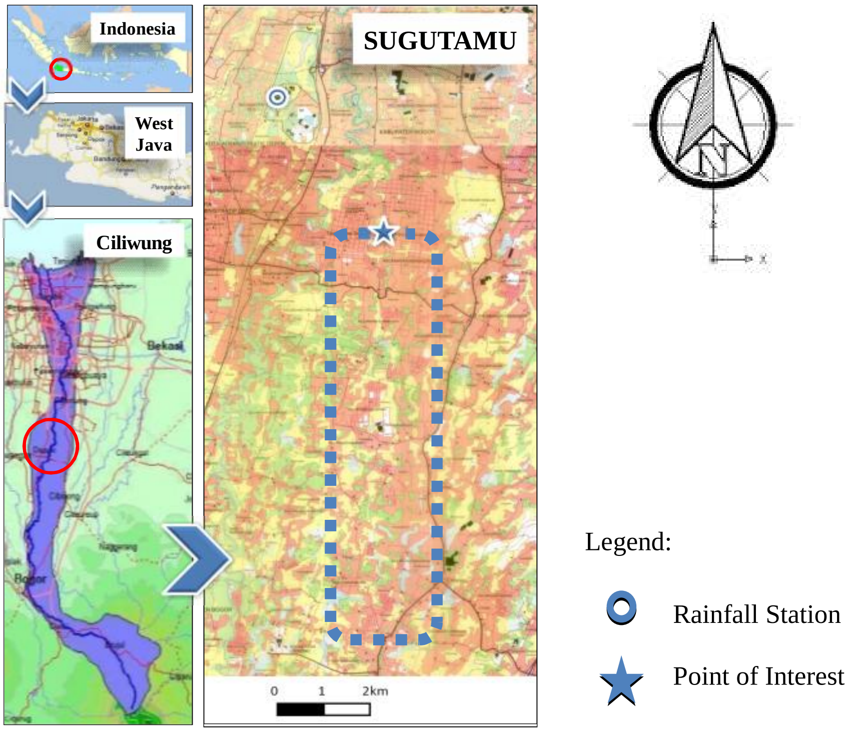

Figure 1 Location of the study area (BAKOSURTANAL, 1999)

2.2. Description of the Model

The Model is based on a Schaffernak approach as presented in Figure 2, where the sediment duration curve is derived, based on a combination of the discharge duration curve and the sediment rating curve. Time integration of the sediment duration curve gives the result of sediment yield presented as the shaded area on Figure 2. Schaffernak's original approach was actually based on a stage duration curve. In a watershed where there is no water level recorder, the stage duration curve is substituted by the discharge duration curve, which is derived from the rainfall-runoff relation using a hydrological model WinTR-55. The WinTR-55 is developed especially for a small urban watershed.

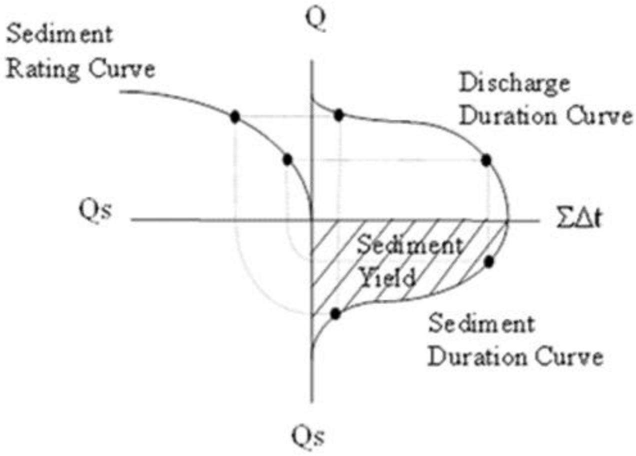

Figure 2 The Modified Schaffernak Approach for estimating sediment yield

2.3. Sediment Yield Estimation Procedure

The discharge duration curve is derived based on daily runoff simulation using an established public domain hydrological model WinTR-55, while the sediment rating curve is derived based on a field survey. The estimation procedure is then presented in Figure 3.

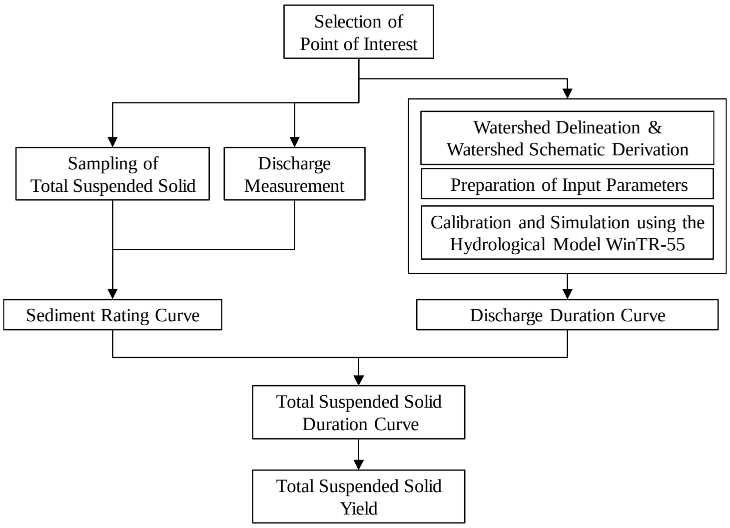

Figure 3 Sediment yield estimation procedure

Since WinTR-55 is a single-event rainfall-runoff model, the applications for a continuous-event actually require an adjustment. However, in this study only a variation of the runoff coefficient represented by Curve Number (CN) is considered. CN values vary according to the Antecedent Moisture Condition (AMC) (Geetha et al., 2007; Chow, 1988) as shown in Equations 1a and 1b.

$$CN_I = \frac{CN_{II}}{2.3 - 0.013 CN_{II}} \tag{1a}$$

$$CN_{III} = \frac{CN_{II}}{0.43 + 0.0057 CN_{II}} \tag{1b}$$

The CN_{II} for each sub-area is defined as composite CN_{II}, which applies for each land use area on the sub-watershed as a weighted factor. The CN_{II} table can be found in (Chow, 1988). Where, CN_{II} applies for normal antecedent moisture condition (AMC II), while CN_I applies for dry conditions (AMC I) and CN_{III} applies for wet conditions (AMC III). CN_{II} is a function of soil type and land use as recommended by the Soil Conservation Service (Chow, 1988). It depends on the season, how the magnitude of AMC is affected by the magnitude of $ANTRF_t$, that is a total five-day antecedent rainfall $P_{(t-1)}$ up to $P_{(t-5)}$, (See Equation 2 and Table 1). The dormant season is commonly from 1 June to 31 October, while the growing season is from 1 November to 31 May the following year. The time of concentration, T_c is computed based on the procedures described in (USDA, 1990).

$$ANTRF_t = P_{(t-1)} + P_{(t-2)} + P_{(t-3)} + P_{(t-4)} + P_{(t-5)} \tag{2}$$

Table 1 Antecedent Moisture Condition (AMC)

AMC	Total five-day antecedent rainfall (cm)	
	Dormant season	Growing season
I	Less than 1.3	Less than 3.6
II	1.3 to 2.8	3.6 to 5.3
III	More than 2.8	More than 5.3

3. RESULTS AND DISCUSSION

3.1. The Watershed Characteristics

The land use of Sugutamu Watershed is dominated by residential area (See Figure 4). For computational purposes using WinTR-55, the Sugutamu Watershed is divided into three sub-areas and two reaches as presented in Figure 5. The sub-area and reach parameters are presented in Tables 2a and 2b, respectively.

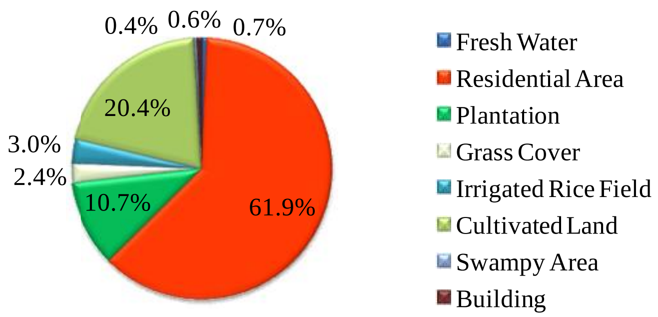

Figure 4 Sugutamu land use distribution

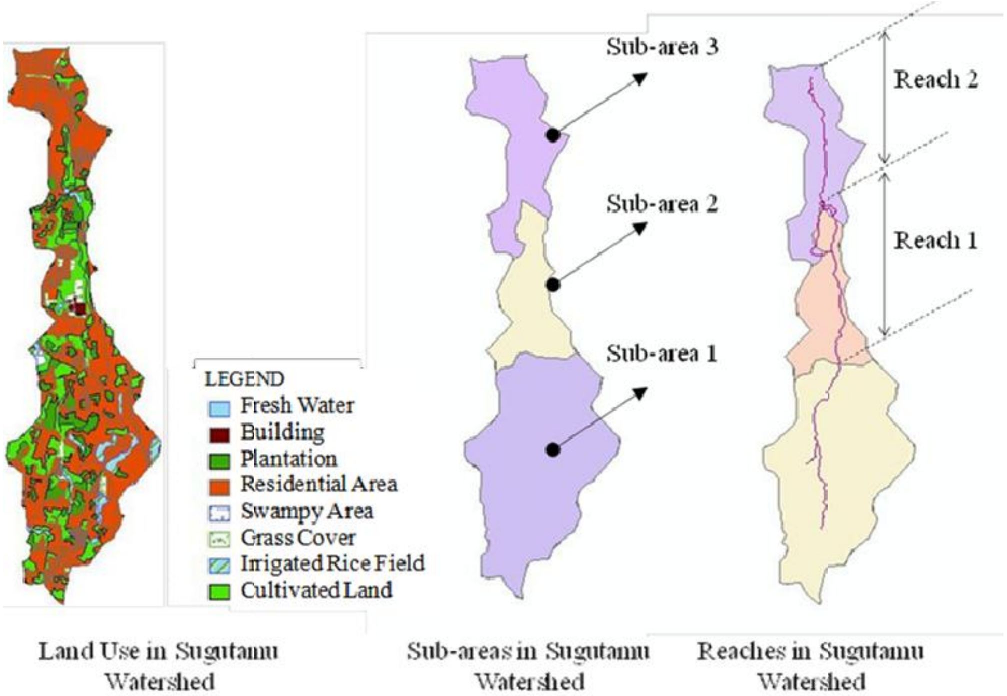

Figure 5 Sugutamu Watershed characteristics

Table 2a Sub-area parameters

Sub-area Parameters	Area 1	Area 2	Area 3
Drainage area (km^2)	7.00	2.21	3.00
Runoff Curve Number	84	82	84
Time of Concentration (hrs)	2.20	2.28	2.00
Receiving Reach Number	Reach 1	Reach 2	Outlet

Table 2b Reach parameters

Reach Parameters	Reach 1	Reach 2
Receiving Reach	Reach 2	Outlet
Reach Type	Channel	Channel
Reach Length (m)	2,903	2,957

3.2. Calibration

The hydrological model WinTR-55 was calibrated based on a five-day field survey in January 2015 and rainfall data at the FTUI Rainfall Station. The field survey results are presented in Table 3, while daily rainfall, ANTRF-5D and AMC are presented in Table 4.

Table 3 Discharge measurement

Date	V_{mean} (m/s)	Wetted Area (m^2)	Discharge (cms)
13 Jan 2015	0.38	4.73	1.81
15 Jan 2015	0.24	3.78	0.90
16 Jan 2015	0.46	5.16	2.36
20 Jan 2015	0.21	3.37	0.71
21 Jan 2015	0.20	3.42	0.70

Table 4 Rainfall characteristics and AMC

Date	FTUI Rainfall Station		
	P_t (mm)	ANTRF-5D (mm)	AMC
13 Jan 2015	32.3	51.5	II
15 Jan 2015	8.5	86.6	III
16 Jan 2015	7.3	95.1	III
20 Jan 2015	1.1	42.0	II
21 Jan 2015	9.4	34.6	I

The daily rainfall distribution is based on the record of automatic rainfall recorder at FTUI. The calibration for 13 and 15 January 2015 events are presented in Figures 6a and 6b, respectively. The most probable reason that the calibration for other events was unsuccessful is, there was very light rainfall and the AMC were equal to I and II, respectively (20 and 21 January 2015), or the rainfall data at FTUI does not fully represent the rainfall spatial variability in the Sugutamu Watershed (16 January 2015 event). In the case that the minimum discharge during the field survey amounted to 0.7 cms, it can be considered as the base flow, then the WinTR-55 has proved to be moderately representative of the rainfall-runoff relation in the Sugutamu Watershed.

Measurement results of the Total Suspended Solid (TSS) measurement for deriving the sediment rating curve are presented in Table 5. The TSS Rating Curve can be represented by a power trend line as depicted in Figure 7.

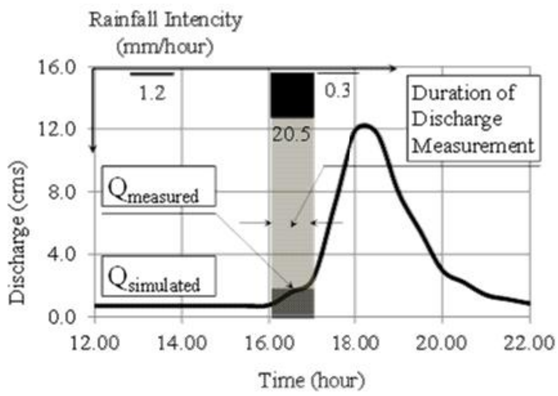

Figure 6a Calibration of 13 January 2015 event

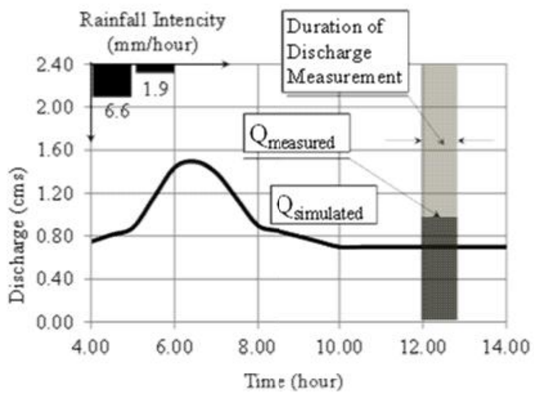

Figure 6b Calibration of 15 January 2015 event

Table 5 Discharge and TSS measurement

Date	Discharge (cms)	TSS (ton/day)
13 Jan 2015	1.81	2.32
15 Jan 2015	0.90	0.32
16 Jan 2015	2.36	3.58
20 Jan 2015	0.71	0.32
21 Jan 2015	0.70	0.56

Calibration of WinTR-55 was based on field survey results conducted on 13, 15, 16, 20 and 21 January 2015, and rainfall event recorded at FTUI rainfall station on the same days. The calibration results of 13 and 15 January 2015 were convincing in that WinTR-55 proved to be moderately representing the rainfall-runoff relation in the Sugutamu Watershed. The Total Suspended Solid (TSS) rating curve was also derived from the same five-day field survey.

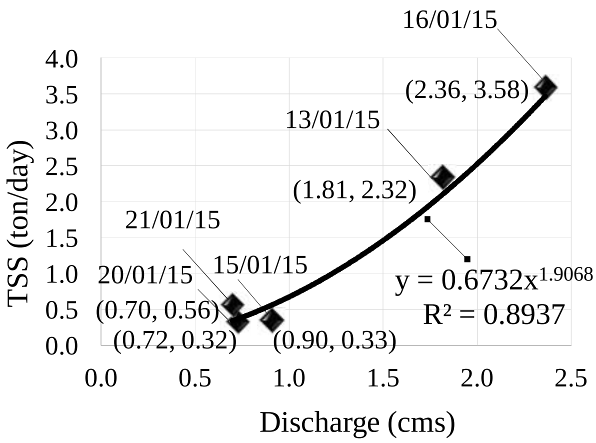

Figure 7 Sediment rating curve at upstream of Juanda Bridge, Sugutamu Watershed

3.3. Simulation Results

The discharge simulation is carried out based on year 2014 daily rainfall data recorded at the FTUI station. The different distribution pattern for daily rainfall <50 mm and daily rainfall >50 mm are applied. There are 126 rainy days, consisting of 44 days with AMC-I, 18 days with AMC II and 64 days with AMC-III, respectively. Only 70 rainfall days resulted in direct runoff.

The resulted hydrographs were averaged daily, and a constant base flow of 0.70 cms throughout the whole year is assumed. The discharge duration curve is composed based on the simulation result. The discharge duration curve is converted into the TSS duration curve using the sediment rating curve as depicted in Figure 7. The configuration of the three curves, according to modified Schaffernak approach (Figure 2), is presented in Figure 8.

The sediment yield is represented by shaded area. The application of a modified Schaffernak approach in the Sugutamu Watershed for the year 2014 was also based on daily rainfall data from the FTUI rainfall station as presented in Figure 8 that resulted in an annual TSS Yield of 1,325 tons/year or 108.52 tons/km^2/year, which is still acceptable for a watershed dominated by

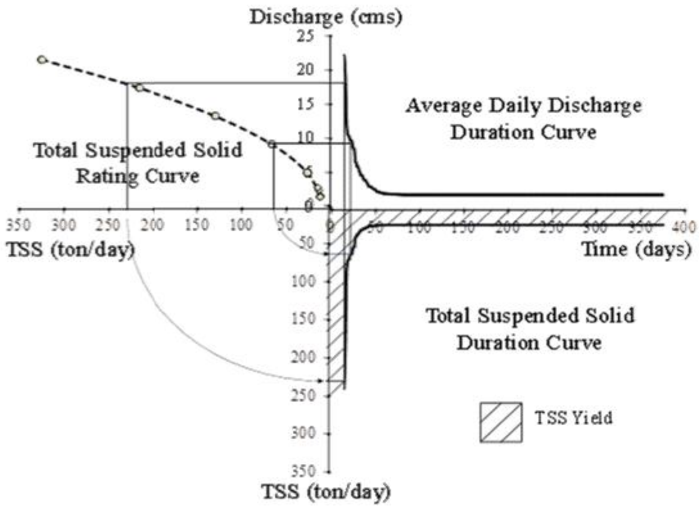

Figure 8 The result of Modified Schaffernak Approach application for estimating the TSS Yield in the Sugutamu Watershed

A residential area is shown on Figure 9. This figure illustrates that the result is comparable to the results of other studies conducted by Webb et al. (2001), Curran-Cournane, et al. (2013), Ndomba (2013), and Wolman (1967). According to Wolman (1967), if the entire area has been developed, sediment yields should be expected to decline to values as low as or lower than prior to the farming era.

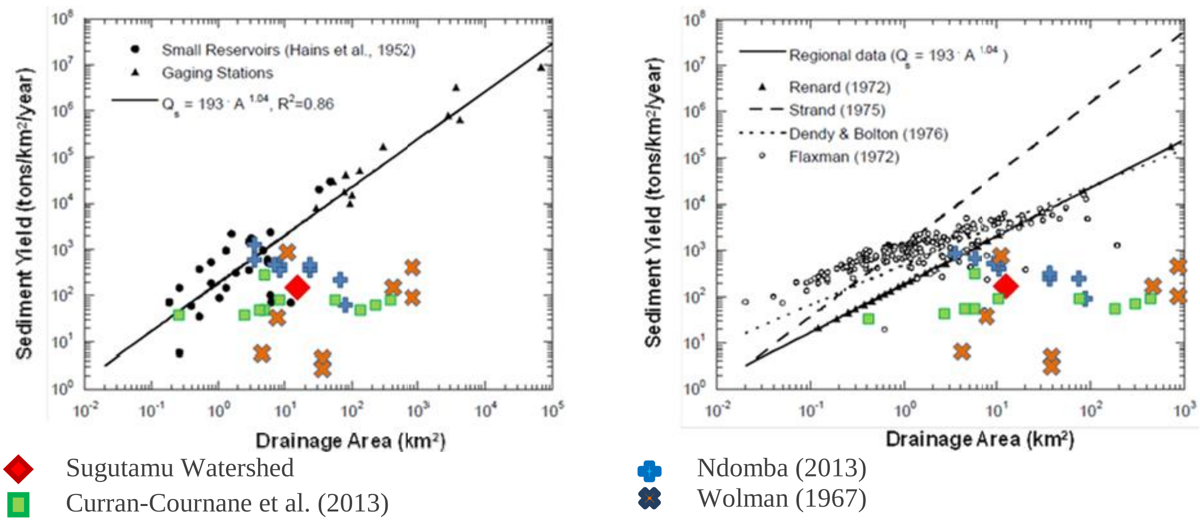

Figure 9 The result of Modified Schaffernak Approach compared to the sediment yield quantification (Webb et al, 2001;Curran-Cournane, et al., 2013;Ndomba, 2013; Wolman, 1967)

4. CONCLUSION

The result showed that the TSS yield from a small urban ungauged watershed is possible to be quantified using a modified Schaffernak approach in combination with the WinTR-55 application. Further research is still needed, in order to validate the applicability of the approach in predicting suspended sediment yield in ungauged watersheds, especially in places on Java, which have similar conditions to Sugutamu.

5. ACKNOWLEDGEMENT

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