Archives of Hydro-Engineering and Environmental Mechanics
Vol. 68 (2021), No. 2, pp. 103–117
DOI: 10.2478/heem-2021-0006
ISSN 1231–3726

Developing the Regression Equations to Determine the Bankfull Discharge from the Basin Characteristics

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(Received May 12, 2021; revised August 09, 2021)

Abstract

Bankfull discharge is an important criterion for flash flood warnings. In this study, the authors propose a new approach to determine the bankfull discharge for basins in Ha Giang province, Vietnam. The study combines the field survey to determine the bankfull discharge through the bankfull indicators and develop a multivariate regression equation between the bankfull discharge and the basin characteristics. The results of the study give a simple equation with 2 independent variables. They are the catchment area and the main river length. They show a strong relationship with the bankfull discharge with the R^2 indexes in developing and validating process equal to 95.3% and 92.7%, respectively. With this approach, the workload is significantly reduced. However, the accuracy and flexibility of the total discharge calculation are enhanced. This will be the foundation to reduce uncertainty in flash flood warnings.

Key words: bankfull discharge; regression equation; catchment characteristics

1. Introduction

In recent years, flash floods have caused serious consequences in Ha Giang province in particular and in Vietnam in general. Flash floods are becoming more and more complex and increasing in frequency and intensity. From 2012 to 2016, Ha Giang recorded 15 flash floods that killed 70 people, injured 82 people, and damaged 19500 houses and many crops. The damage is estimated at about 1500 billion VND (Ha Giang DARD 2017). Some flash floods have serious consequences, such as the flood that killed 7 people in July 2014 in Hoang Xu Phi district and the flood that swept

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away 3 people in September 2015. The above evidence shows that it is vital to study the solutions to reduce the impact of flash floods.

Flash flood research has been carried out for several decades. Since the late 1970s, Mogil et al (1978) has made a number of recommendations to enhance the ability to cope with flash floods. According to the summary of Braud et al (2016), hydrologic models are beginning to use in flash flood forecasting. In recent years, modern tools have been applied in flash flood research such as distribution models (Qinghua et al 2016, Nguyen et al 2016), artificial intelligence (Alipour et al 2020, Chou et al 2020, Nguyen et al 2020). One of the approaches used very commonly around the world is the flash flood warning system, which is based on the calculation of the FFG (Flash Flood Guidance) (Georgakakos 2005, Norbiato et al 2008, Schmidt et al 2007). The basis of the method is to determine the amount of rainfall within a specified period of time to cause flood at the basin outlet. The corresponding discharge at the onset of inundation is called the bankfull discharge (Leopold et al 1964). Many studies have determined this bankfull discharge value equivalent to the peak flow of the 1-to-2-year return period (Rosgen and Silvey 1996, Leopold 1994, Schmidt et al 2007, Carpenter et al 1999). There is a small amount of evidence to support the accuracy of this hypothesis. Moreover, flash floods often occur in the small catchments (Qinghua et al 2016), where there are few measurement stations installed. Sherwood and Huitger (2005) suggested that it depends on each river section, the bankfull discharge value could be given the return period of less than 1 year or more than 2 years. This hypothesis is completely grounded because the topography of the river section can have a great influence on the bankfull discharge value. Several studies (Emmett and Gordon 2001, Grant et al 1990) have found that the cycle of the bankfull discharge tends to increase as the river slope increases; it means the rivers with high gradient tend to have less frequent the bankfull flow than the ones with low gradient. As for this research, its concern is to find an approach aiming to reduce the uncertainty of determining the bankfull flow.

One solution is to determine the bankfull discharge value through topographic surveys. Bent and Waite (2013) introduced 6 signs to identify the water level corresponding to the bankfull discharge – bankfull indicators (US Department of Agriculture 1995, 2003 and 2004) also provide specific guidelines to determine the bankfull indicators. This has been done in the US such as in Florida (Blanton et al 2010), in New York (Mulvihill et al 2009), in Massachusetts (Bent and Waite 2013), in North Carolina (Doll et al 2003) or in Virginia and in Maryland (Krstolic and Chaplin 2007). But there has not been any research in Vietnam. The requirement of a large volume of survey is a limitation of this approach. In addition, the bankfull indicators are not always available or consistent.

Carpenter et al (1999) proposed a method of calculating the bankfull discharge based on the relationship with the channel geometry and roughness features. In this study, the authors consider that the survey process would not be feasible for a huge workload. Therefore, it is necessary to develop a multivariate regression equation between bankfull discharge and basin characteristics. The construction of a multivariate regression equation between basin characteristics and different frequency design floods has been carried out by many studies. Lumia et al (2006) constructed the equations between the flood peak at corresponding different frequencies and basin characteristics for 6 regions of New York. A similar approach is applied in Ahearn (2004). Basin characteristics (e.g., area, slope…) or river section (e.g., length, slope…) can be easily determined by using GIS tools. Therefore, if considering the bankfull discharge as also a flow value corresponding to an assumed frequency, this is a possible approach.

The above analysis shows that the bankfull discharge is an effective indicator for flash flood warnings. The determination of the bankfull discharge through bankfull indicators can reflect the local characteristics of the study area. However, this approach requires a huge workload. In order to minimize the workload, the correlation between the bankfull discharge and the more easily measurable factors can be defined. Furthermore, this gives the user more flexibility when calculations can be done at all desired locations in the catchment. Especially in the mountainous sites which are impossible to reach. The purpose of this study is developing the multivariate regression equation between the bankfull discharge and the catchment characteristics. The research was conducted in several basins in Ha Giang province, Vietnam.

2. Methodology

2.1. Study Site

The studied areas are 3 small catchments. The areas of Nam Ly, Na Nhung and Song Ma are 92.72 km^2, 41.46 km^2, and 106.15, respectively (see Fig. 1). These basins are in Xin Man, Hoang Xu Phi and Vi Xuyen district, respectively. These catchments were selected based on similar conditions and surveyability. These are rural districts in the northeastern region of Vietnam, where is affected by natural disasters each year. These slope of basins are very steep with the average slope of the Nam Ly catchment being 64.9% and of the Na Nhung being 60.3%. While the slope value in Song Ma catchment is 55.78% In addition, this is the center of the rainy area with the average annual rainfall from 2000 to 2400 mm/year, the rainfall can be up to 4000 mm/year in Bac Quang. These are favorable factors constituting flash floods.

2.2. Research Methods

According to the study of Bent and Waite (2013) or Blanton et al (2010), the signs for identifying the level of bankfull discharge can be listed as follows: (1) the level of the active floodplain, (2) depositional features, (3) the level where riverbank slope changes, (4) the level where grain material changes, (5) the highest ground level of undercut on the riverbank, (6) the level where vegetation is changed (e.g. from a non-vegetated area to an area with vegetation). In addition, in some documents, it is

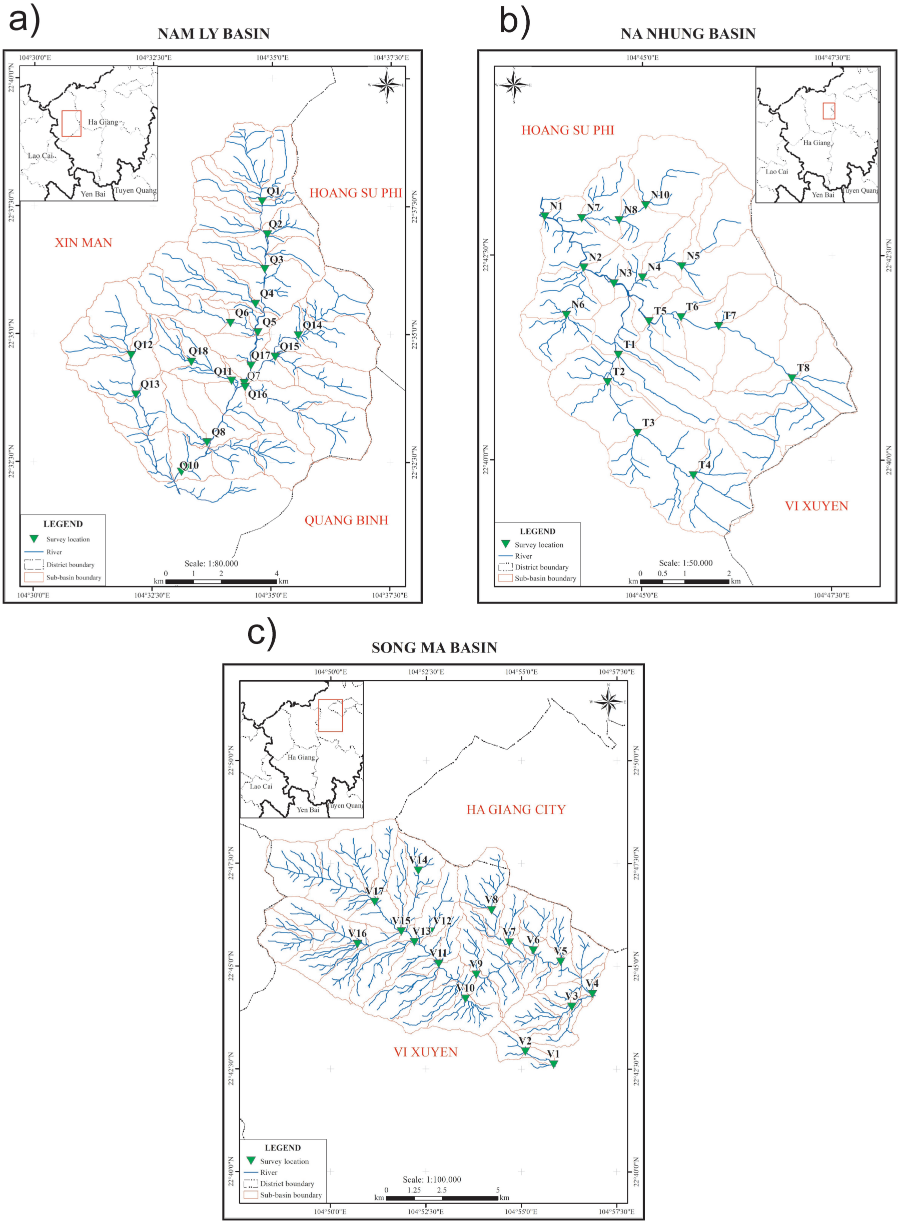

Fig. 1. Research area: a) Nam Ly b) Na Nhung c) Song Ma

possible to rely on discolored marks or stains, sand on the rock (7) to determine the level of bankfull discharge.

To conduct a survey in the surveyed sites, it is needed to satisfy some specific conditions. In order to ensure representation across the catchment, it necessary to be evenly distributed across the catchment in the surveyed sites. However, these sites need to be convenient for travel and survey. The sites that were prioritized for the survey were those located in residential areas, the infrastructure which is located close to the riverbanks. In addition, these sites need to exist at least one bankfull identifying sign. At each location, the cross-sectional and longitudinal surveys of the river section were conducted. In addition, the elevation of bankfull indicator was determined during this period.

The study established a rating curve between the discharge and water level corresponding to each surveyed site. The Manning formula (Chow 1959) was used to construct a curve $Q = f(Z)$

$$Q = \frac{1}{n} A R^{2/3} \sqrt{S}, \tag{1}$$

where:

Q – discharge (m^3/s),
n – Manning’s roughness coefficient,
R – hydraulic radius (m),
A – channel cross section area y (m^2),
S – hydraulic slope (–).

In this study, the values of A and R could be determined via channel geometry; S was assumed to equal the river gradient measured at the surveyed site. To determine the roughness of each corresponding river section, we applied the instructions of Barnes (1969). The research also comprised observations of water level and discharge 2 times at dry and flood season respectively. These values were used to verify the rating curve.

According to Bent and Waite (2013), the bankfull discharge is not only influenced by the catchment area but also affected by factors such as land use, hydro-meteorological conditions, or river system characteristics. In this study, due to the small area, the difference in precipitation can be ignored. Therefore, meteorological conditions are not considered in this study. Lumia et al (2006) gave 14 input variables to build the correlations between the bankfull discharges and different frequencies of flood discharge. Based on the study of Benson (1962) about the factors influencing the flood peak, in this study, the authors give some input variables that can be calculated from the available data in Vietnam. The data includes the 1/10000 topographic document of the study area issued by the Ministry of Natural Resources and Environment. Land cover data and land type data were collected for the calculation. Fig. 2 shows the topographic and land use maps of the study area. Topographic data are used to define catchment characteristics, such as area (F), catchment slope (S_{lv}), average catchment elevation (Z_{tb}), length of the main river (L_c), the slope of the main river (S_s). For the effect of the land cover factor, it is necessary to quantify the land cover data and land type data. Through the CN index (Mishra and Singh 2003, Mishra et al 2007) calculates amount of losses for different types of land cover and soil. In this study, the *CN* index was used to define the land cover impact.

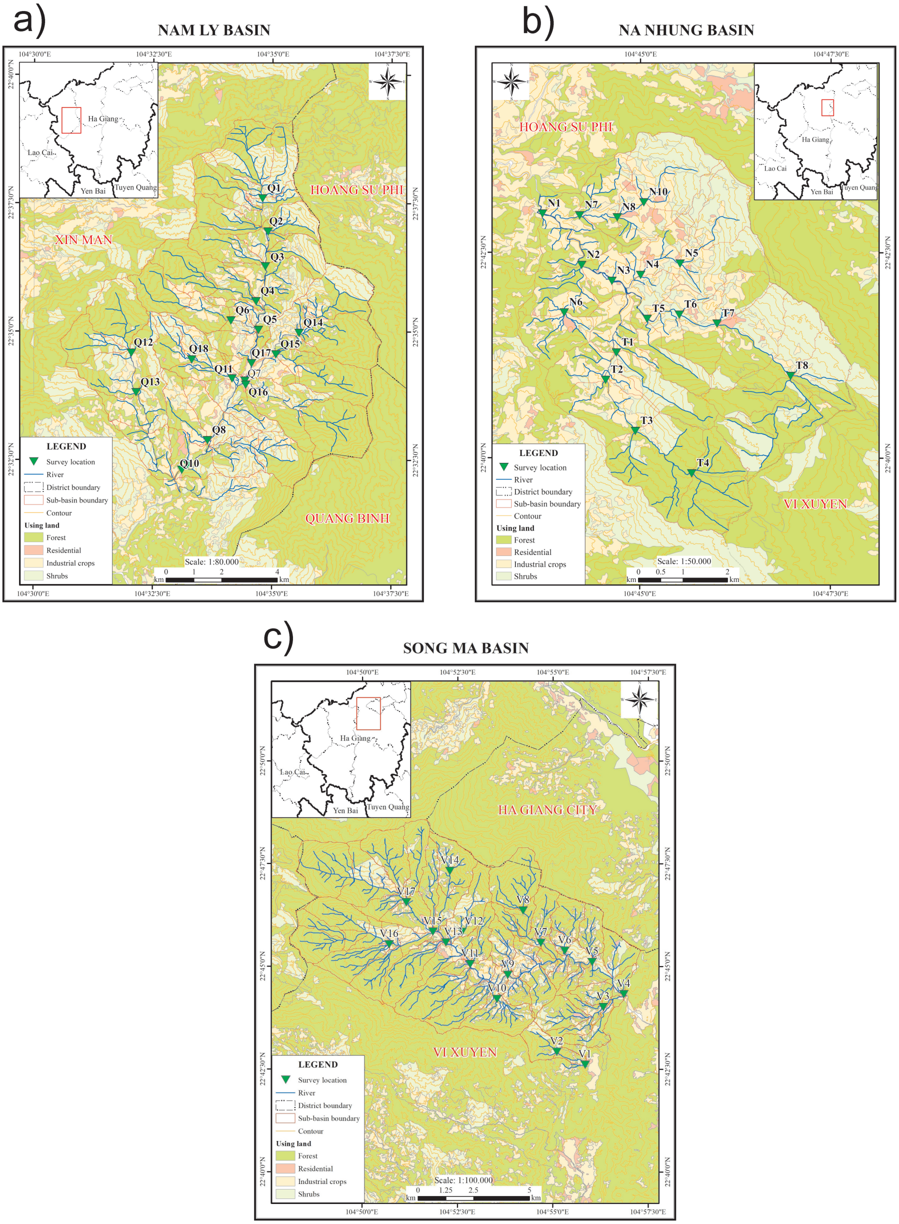

Fig. 2. Topography and Land Cover data : a) Nam Ly b) Na Nhung c) Song Ma

The research basins are divided into sub-basins to determine bankfull discharge at the outlet of each sub-basin. The selected outlet locations are usually residential areas, or where flash floods have occurred. GIS tools are used to calculate catchment characteristics. At each outlet, as the flow accumulates from the upstream to the catchment outlet, catchment characteristics were averaged from the upstream until to this outlet. After the data between the bankfull discharge which determined through the survey and the catchment characteristics were synthesized, the correlation equation is constructed. Due to the limited data, the equation was developed based on the data of Nam Ly and Na Nhung. Meanwhile the data of Song Ma were used for validaton.

3. Results and Discussion

Based on our survey, the results showed that indicator (I) – the level of the active floodplain, is the clearest and most accurate indication of bankfull water level. If this sign appears, the study would choose bankfull water level altitude without concerning other signs. Fig. 3 shows river cross-section Q14 with active floodplain as the bankfull indicator. However, for rivers in mountainous areas like the study area, this indicator does not always exist. Fig. 4 shows an example of a possible bankfull indicator (II) – point bar, as well as indicator (VI) – changes in vegetation on the bank, at cross-section Q5.

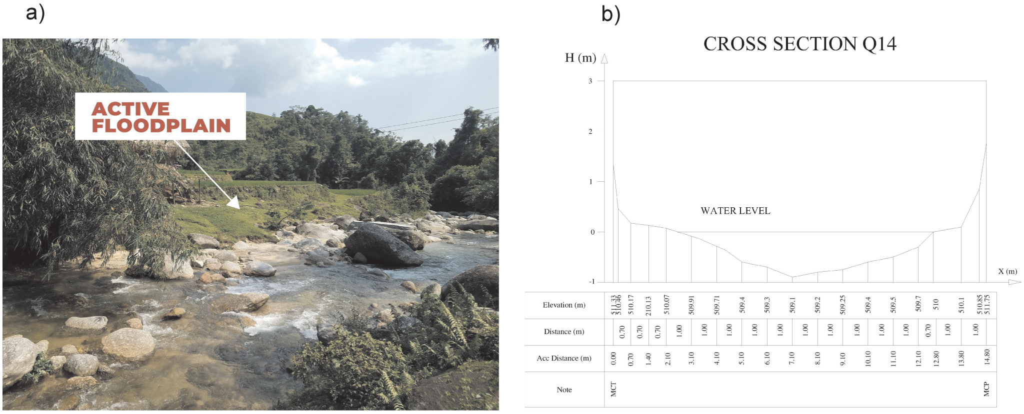

Fig. 3. The bankfull indicator (1): a) field survey picture b) measured cross section

During the research process, some sites may witness several indicators, moreover, they are not consistent with each other. This was also mentioned by McCandless (2003). Another difficulty faced by the research is the ambiguity of the indicators. Especially indicators (III), (IV), and (VI) when the level of these indicators often fluctuates within a range. In contrast, indicators (V) and (7VII) are very clear. In this study, the authors selected the most common level in the case where there are many indicators. Fig. 5 shows the rating curve $Q = f(Z)$ corresponding to two sections Q14 and Q5. These rating curves were found to be consistent with the observed values. Based on the bankfull water level, the corresponding bankfull discharge was also determined. This process is performed for all locations.

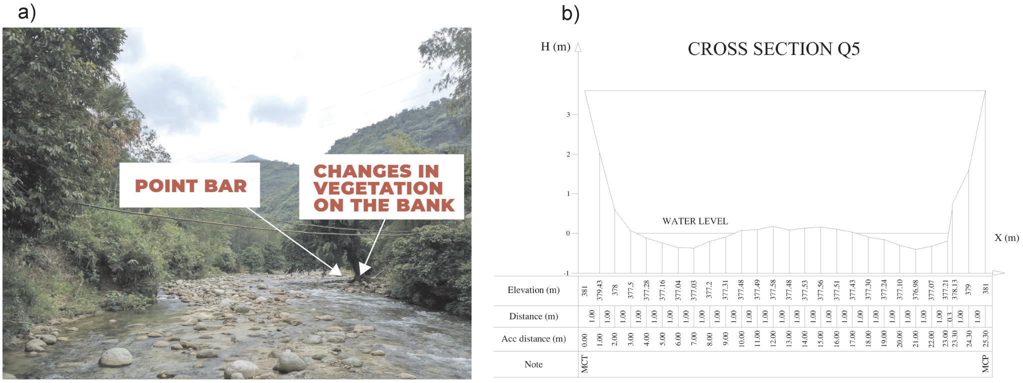

Fig. 4. The bankfull indicator (2) and (6): a) field survey picture b) measured cross section

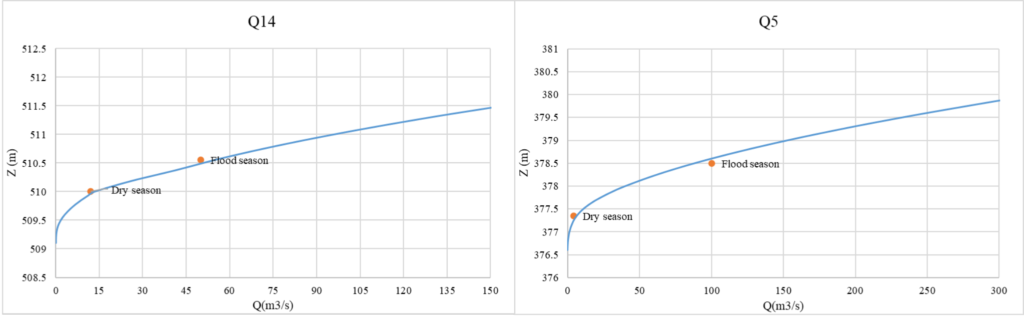

Fig. 5. Rating curve $Q = f(Z)$: a) cross-sections Q14, b) cross-sections Q5

Basing on the above criteria described in the methodology section, 48 sites have been surveyed in 3 catchments. The survey site is determined as shown in Fig. 1. Detailed coordinates and the corresponding identification of the methods are shown in Table 1. Table 1 also shows the bankfull water level and the bankfull discharge values.

In studies of Bent and Waite (2013); Fernandez (2017); Lumia et al (2006), the base 10 log-transformation function (equation 2) is used to describe the relationship between the dependent variables and the independent variables. This has been mentioned in research by Carpenter et al (1999). The transforming of data makes the regression procedure become simpler. In this study, the same form of the equation is applied in all regression functions.

$$\log_{10} y = a + \sum_{1}^{n} b_i \log_{10} x_i, \tag{2}$$

where:

n – the total number of independent variable x; i go from 1 to n,

Table 1. Survey location and bankfull indcator

No.	Name	Longitude	Latitude	Indicator	Bankfull water level (m)	Bankfull discharge (m^3/s)
1	Q1	104.580	22.627	(I,VII)	817.44	41.55
2	Q2	104.582	22.616	(I,VII)	653.30	27.78
3	Q3	104.581	22.605	(I,VI)	532.65	78.66
4	Q4	104.578	22.593	(I,VII)	464.60	36.87
5	Q5	104.579	22.584	(II,VI)	378.75	117.17
6	Q6	104.569	22.587	(VI)	623.50	37.37
7	Q7	104.574	22.567	(III)	367.73	130.02
8	Q8	104.561	22.548	(III,VI,VII)	290.50	31.04
9	Q9	104.552	22.538	(VI)	279.40	163.8
10	Q11	104.569	22.568	(VI)	385.65	35.43
11	Q12	104.534	22.576	(IV,VI)	757.63	45.18
12	Q13	104.536	22.564	(VI,VII)	603.80	57.78
13	Q14	104.593	22.583	(I)	510.56	52.73
14	Q15	104.585	22.576	(VI)	470.75	71.01
15	Q16	104.574	22.566	(VI,VII)	366.60	60.11
16	Q17	104.576	22.573	(I,VI)	410.80	122.45
17	Q18	104.555	22.574	(VII)	830.75	22.79
18	T1	104.745	22.688	(I,VI)	970.80	80.48
19	T2	104.742	22.682	(V)	1044.80	65.93
20	T3	104.749	22.672	(VI)	938.00	48.87
21	T4	104.761	22.664	(VI)	1350.50	31.89
22	T5	104.752	22.695	(VI,VII)	737.86	91.56
23	T6	104.759	22.696	(VII)	827.80	80.43
24	T7	104.767	22.694	(VI,VII)	980.73	60.47
25	T8	104.783	22.683	(VI)	1128.75	31.77
26	N1	104.729	22.716	(III)	571.20	140.79
27	N2	104.737	22.706	(VII)	651.13	132.98
28	N3	104.744	22.703	(I)	651.19	128.28
29	N4	104.750	22.704	(III)	717.45	43.49
30	N5	104.759	22.706	(III,VI)	837.70	35.42
31	N6	104.733	22.696	(III)	780.80	24.86
32	N7	104.737	22.716	(III)	610.75	52.46
33	N8	104.745	22.715	(I)	683.70	31.77
34	N10	104.751	22.718	(III,VI)	825.86	28.85
35	V1	104.931	22.710	(IV,VI)	371.40	39.38
36	V2	104.918	22.715	(I,VI)	690.70	23.75
37	V3	104.939	22.734	(VI)	261.00	28.10
38	V4	104.948	22.739	(I)	100.70	292.82
39	V5	104.934	22.752	(I,IV,VII)	151.30	197.71
40	V6	104.922	22.756	(IV)	350.60	14.29
41	V7	104.911	22.759	(VI)	421.10	40.30
42	V8	104.904	22.772	(VII)	941.40	55.27
43	V9	104.897	22.746	(I,IV)	290.50	154.16
44	V10	104.892	22.736	(IV,VI)	421.00	45.93
45	V11	104.881	22.750	(I,IV)	371.20	171.01
46	V15	104.864	22.764	(I,VI)	521.00	150.65
47	V16	104.845	22.758	(IV,VI)	721.40	87.41
48	V17	104.853	22.775	(I)	690.90	67.01

y – dependent variable,
a, b – coefficients.

For the regression function, the simplest is the univariate regression function. However, the multivariate regression equation can explain more sources of impact on the dependent variable than the univariate regression equation. Multivariate regression technique provides a measure of the accuracy of an equation, a measure of the influence of each independent variable in the equation. The choices of univariate or multivariable equations, and independent variables, have been analyzed and evaluated based on the best fit result to the observed data as well as the feasibility of determining the independent variables. In this study, both univariate regression and multivariate regression were applied to determine the regression equation for the study area. Univariate regression is applied for the catchment area (Equation 3), while multivariate regression is constructed for a combination of the catchment area and other factors. The catchment area is the priority selection because the catchment area is the area that collects rainfall which accumulates the flow at the river outlet. Therefore, it will determine the value of flow rate at the outlet. Therefore, in the study of Bent and Waite (2013) or Fernandez (2017), the area is the only dependent variable included in the regression equation

$$Q_{bf} = 18.676F^{0.530}. \tag{3}$$

The other factor influencing the bankfull discharge can be the river slope. This is consistent with the conclusion of Benson (1962). For two rivers with the same catchment area but with significantly different river slopes, a river with greater gradient may have greater bankfull discharge. Table 2 shows the correlation coefficient between the bankfull discharge with all variables. The results show that bankfull discharge has a good correlation with the basin area and the river length with correlation indexes equal to 0.97 and 0.95 respectively. It is worth discussing these interesting facts revealed by the correlation index between the bankfull discharge and the river slope. A popular explanation of negative value (−0.73) in this case is that the average river slope descends when the catchment extends to downstream. However, this value is close to −1. It means that the river slope has a high correlation with the bankfull discharge. This leads to the construction of the equations which are combinations of these 3 variables. These are shown in equations 5, 6 and 7 in Table 2. The research also developed a relationship between the bankfull discharge and all variables (Equations 4). Table 3 shows the multivariate correlation equations and evaluation criteria for the above cases.

$$Q_{bf} = 11.275F^{0.350}L_c^{0.202}S_{lv}^{0.437}S_s^{-0.211}Z_{tb}^{0.255}CN^{-0.326}, \tag{4}$$

$$Q_{bf} = 16.124F^{0.493}S_s^{-0.121}, \tag{5}$$

$$Q_{bf} = 17.661F^{0.424}L_c^{0.197}, \tag{6}$$

$$Q_{bf} = 16.019F^{0.424}S_s^{-0.092}L_c^{0.146}. \tag{7}$$

Table 2. Influence of the independent variables on the bankfull discharge

	Q_{bf}	S_{lv}	Z_{tb}	S_s	CN	F	L_c
Q_{bf}	1						
S_{lv}	0.13	1					
Z_{tb}	0.10	0.02	1				
S_s	−0.73	0.33	0.15	1			
C_N	0.15	0.14	0.14	−0.16	1		
F	0.97	0.15	0.07	−0.70	0.14	1	
L_c	0.94	0.09	−0.02	−0.74	0.18	0.95	1

Table 3. Multivariate correlation equation for bankfull runoff from catchment characteristics

Equation	Standard error (m^3/s)	Adjusted R2 (%)
3	13.2	94.8
4	12.2	96.3
5	12.8	95.3
6	12.8	95.3
7	12.7	95.5

The form of the equation 3 shows a strong correlation between the catchment area and bankfull discharge with adjusted R^2 = 94.8%. However, the value of standard error is high (13.2 m^3/s). This value varies from 50% to 10% of the bankfull discharge value depending on the area of the sub-basins. The results are slightly better when we applied multivariate regression equations. The equation that gives the best result is Equation 4 for which adjusted R2 and standard error is equal to 96.3% and 12.2 m^3/s, respectively. This equation uses a lot of independent variables, so it is important to note the workload when using it. The similar result show in Equation 7. In the remaining equations, the simpler form was used. Equation 5 and Equation 6 have same the statistical values (adjusted R^2 = 95.3% and standard error = 12.8 m^3/s). However, determining the river slope will be more complicated than determining the river length. Because the bathymetry of the riverbed is often underwater, the accuracy of calculation from the topographic map is not high. With only topographic data, possibly available on the Internet (free Digital Elevation Model – DEM such as STMR), the river length can be identified quickly with good accuracy. As a result, equation IV is the recommended equation due to its convenience.

The equation 6 using data of Song Ma catchment was applied to validate. The results are shown in Fig. 6 and Table 4. As one can see, there is a good correlation between the observed and calculated bankfull discharge with adjusted R2 and standard error equal to 92.7% and 22.34 m^3/s, respectively. This equation has been applied in flash flood warning systems for Nam Ly and Na Nhung areas. The primary results are very promising for some flash floods in the 2020 floods (Tran et al 2021).

Nevertheless, because of the lack of data resources, the research faces certain limitations as well. The development of rating curves $Q = f(Z)$ which were based

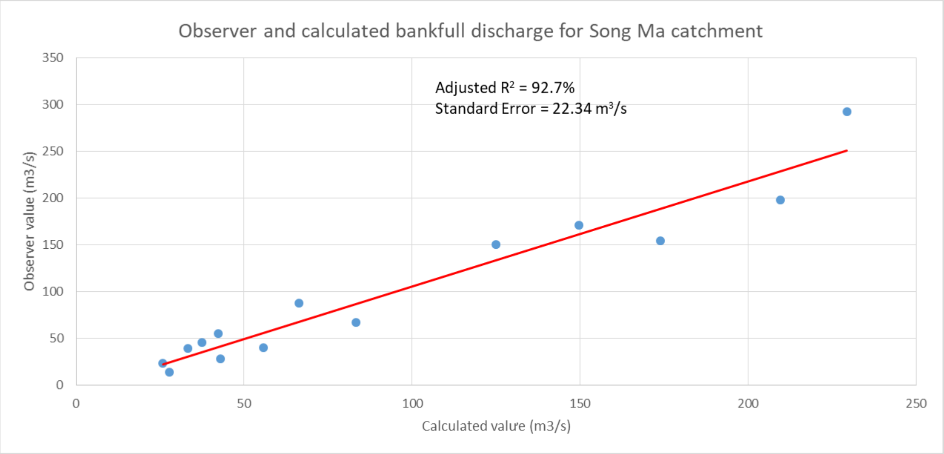

Fig. 6. Observed and calculated bankfull discharge for Song Ma catchment

Table 4. Observed and calculated bankfull discharge for Song Ma catchment

No.	Name	Calculated value (m^3/s)	Observed value (m^3/s)
1	V1	33.35	39.38
2	V2	25.86	23.75
3	V3	42.99	28.10
4	V4	229.36	292.82
5	V5	209.62	197.71
6	V6	27.83	14.29
7	V7	55.82	40.30
8	V8	42.29	55.27
9	V9	173.81	154.16
10	V10	37.45	45.93
11	V11	149.65	171.01
12	V15	125.05	150.65
13	V16	66.29	87.41
14	V17	83.30	67.01

on 2 observed values, is not highly reliable. However, to solve this problem, the discharge value needs to be measured at different water levels for more accurate results. In addition, the indicator survey process depends massively on the subjectivity of the investigator. Hence, the investigation requires experts to carry out. Another limitation is the small number of survey locations in the research. More survey locations are required to develop correlation equations that provide more accurate results.

4. Conclusions

What this study has contributed to the determination of the bankfull discharge lie in two main points. The first thing is using the bankfull indicators to determine bankfull discharge. This is the first time bankfull indicators is applied in Ha Giang, Vietnam.

It shows potential results for this studied area. Moreover, the survey data should minimize uncertainties compared to traditional methods. Secondly, this paper has successfully chosen and adapted the most suitable equation to determine the bankfull discharge from the basin characteristics for researched areas. The multivariate regression equation between the bankfull discharge and independent variables, including catchment area and main river length, has been suggested for researched areas. These are basin characteristics that can be quickly estimated from topography data. This equation has been defined based on data of two basins Nam Ly and Na Nhung, and validated by data from Song Ma basin. In future research, more investigations are needed to apply and test the presented approach for other basins.

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