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Environmental Flow Assessment Using Water-Sediment Approach at the Sekampung River, Indonesia

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Abstract

Environmental issue has been considered more significant in many aspects of engineering decision-making process particularly in river management. There is an increasing effort to conserve functioning of rivers for human use as well as nature, therefore environmental flow assessment has been widely developed. This paper discusses on environmental flow assessment of the Sekampung River, particularly on its middle reach. A new analytical approach based on water-sediment equations was introduced in order to determine a minimum environmental flow at the certain cross section of a river. The result of the new method was then compared with a minimum environmental flow provided by using two hydrological based methods, namely, Tennant and Flow Duration Curve Analysis (FDCA) method. The result shows that the concerned discharge provided by the water-sediment method (3.5 m^3/s) is the smallest compare with a minimum environmental flow that is provided by both Tennant (5.7 m^3/s) and FDCA method (4.5 m^3/s). It is promising that the water-sediment method can be used as a simple approach on preliminary state of environmental flow assessment. The method involves not only water discharge but also its related sediment flow of the river in order to mitigate further ecological and morphological risks.

Keywords

Water-Sediment, Environmental Flow, River Morphology

1. Introduction

In the recent years, environmental issue has been considered more significant in many aspects of engineering

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decision-making process. It is even more considerable regarding environmental natural disaster management. Environmental flow requirements, among others, are being assessed for an increasing number of rivers worldwide. Numerous methods are used ranging from simple to complex. Not only the ecological water needs are assessed, but also the local demands of human communities along the river are taken into account.

Awareness of that a certain amount of water needs to remain flowing in the river forms a new challenge for river management as an extra demand is now competing for the scarce water resource. Internationally this awareness is reflected in the Global Dialogue on Water, Food and Environment, which has started in the wake of the Second World Water Forum of March 2002.

It has been stated that the amount of the original river flow regime required to maintain specified valued features of the river ecosystem is generally referred to the Environmental Flow Requirement (EFR) [1]. The term of in-stream flow requirements, Maintenance Flow Requirements and Ecological Flow Requirements are used as well, to emphasise the fact that water has to maintain dedicated for the river ecosystem.

Although the demands for irrigation, navigation, industries and other water users can be assessed relatively straightforward, there is still much uncertainty about how the EFR should be defined. The practice of EFR began as a commitment to ensuring a "minimum flow" in the river, often arbitrarily fixed at 10% of the main annual runoff. Further scientific evidence and experience are available that question the "minimum flow" approach and there is now a general opinion that for safeguarding essential downstream environmental conditions the dynamics of the river flow should be taken into account. However, the approach regarding a minimum environmental flow has been widely chosen due to its simplicity. Several Environmental Flow Assessment (EFA) methods have been developed over the years to acknowledge the complexity of the flow-environment relationship.

Reviews (e.g. [2]-[4]) generally identify four types of EFA methods, namely, hydrological, hydraulic rating, habitat simulation, and holistic methods, as well as combinatorial and other approaches [5] [6]. Each type of method has its own strengths and weaknesses. This raises a question about which method is appropriate in a certain context. Some methods are quantitative by nature (hydrological and hydraulic methods). They determine environmental flows based on flow records. These methods, however, leave the functions of river-ecosystem as aspects that has to be considered. In other words the method is not transparent. Other methods (holistic methods) try to include all functions of the river-ecosystem, but are usually based on expert judgement and are therefore difficult to reproduce. Hence, there is not one method that comprises all river-ecosystem functions in a quantitative way with explicit and scientifically justified links between the functions and required flows.

The scarceness of riverine environmental data makes it difficult to use such methods as habitat simulation methods [7] [8], holistic methods [9] [10] and combined methods [11]. Hydrological methods, such as the Tennant method [12] and Texas method [13], have the advantages of simple computation and easy handling, therefore it is appropriate for preliminary stage of the environmental flow assessment particularly on the basin level. However, they not only often oversimplify the actual situation of a river, but also fail to consider biological parameters and their interactions [14]. In practice, they are more appropriate for natural rivers and are generally used as a rough verification of other approaches [15]. Traditional hydraulic rating methods, such as Wetted Perimeter method [12] [15] and R2CROSS method, are readily applied due to a small data requirement, but they are unable to estimate the seasonal variations of environmental flows [15]. Therefore, a study of the most suitable method for a concerned river is necessary. The most suitable method will particularly depends on the availability of data required. A new modification method based on site condition is also required.

In the Sekampung River basin, there is a lack of river ecological data and limited hydrological data as most Indonesian rivers do. This paper discusses on preliminary study of the EFA for the Sekampung River. The river is one of the most important rivers in the Lampung Province. Having catchment area of 796 kilometre square and total length of 256 kilometre, the river supplies for more than 40.000 acre irrigation area within the province. Typical cross section of the river has 30 m of main channel width and about 250 m of floodplain length [16].

2. Research Approach

2.1. General

Thus far, only a few assessments of either the numbers of individual methodologies has been utilized for Environmental Flow Assessments in Indonesia. The emphasis in this paper is on the preliminary study of environmental flow required for river ecosystems, including their floodplains, of the Way Sekampung River. The intention of this paper is to introduce relation between magnitude and frequency of the discharge, morphological aspect and their corresponding environmental flow, in addition, comparison was also provided to have an overview what will be the reasonable discharge range of environmental flow for the Sekampung River, particularly on its middle reach.

Moreover, time series discharge data from 2001 to the year of 2010 has been analysed using several methods, namely, Tennant method [12], Flow Duration Curve Analysis (FDCA) and the new approach of the magnitude-frequency approach.

Regarding the methods, Richter [17] highlighted the Tennant (Montana) method as the second most widely used environmental flow method in North America. Since then, it has become the most commonly applied hydrological methodology worldwide. Although superficially a standard-setting approach, the method, developed in the United States by Tennant and the US Fish and Wildlife Service, differs from many other hydrological methodologies in that considerable collection of field habitat, hydraulic and biological data was involved in its development. It comprises a table linking different percentages of average or mean annual flow (AAF/MAF) to different categories of river condition, on a seasonal basis, as the recommended minimum flows. The categories of flow-related condition range from "poor or minimum" (10% AAF) to "optimum range" (60% - 100% AAF) [4]. At least twenty five countries have either applied the method as originally expounded by Tennant in 1976, in a modified form on the basis of various hydrological, geo-morphological, ecological or catchment-based criteria [11] or have simply utilized various (often arbitrarily designated) percentages or ranges of AAF. Several forms of the basic approach exist in North America particularly, and Leonard [14] provides an example of a modification of the method for use in eastern and Eastern and Southeastern United States, with the addition of specialist know- ledge of fish ecology, flow duration estimates, and a mean monthly flow index.

In this research the FDCA was also used to study probability distribution of recorded data. Using the FDCA, data was ranked and calculated its corresponding probability by using the following equation:

$$P = \left(m/n+1\right)100\% \tag{1}$$

In this paper, a new approach using analytical approach for a minimum environmental flow assessment was also formulated. The model is basically based on equations of water flow as well as sediment transport. The method is developed to provide a minimum discharge which assumed to be the main force of sediment movement at the specified river cross section. A corresponding graph was then produced based on the derived equation which related to the magnitude-frequency approach of water-sediment relationship.

2.2. Data Acquisition and Location

Data used for the environmental flow analysis of this research were collected from the discharge measurement stations (AWLR) at the downstream of the Argoguruh Weir as the measurement is conducted by the technical implementation unit (UPTD Balai Pengelola Sumber Daya Air) of the Sekampung River at Metro. Discharge data of a ten years period from 2001 to the year of 2010 consisting of 3.070 data were chosen to provide reasonable pattern of the river flow.

The Argoguruh Weir was the main concern of this paper since the weir has a prominent role to support the main irrigation area of the Sekampung River. The regulated structure is located at the meddle reach of the Sekampung River which has a total long of 256 kilometres originating from its spring in the Bukit Barisan mountain to the Eastern coast of Sumatra (Java Sea). Total annual rainfall of the river catchment ranged between 1600 mm to 2500 mm [16]. The maximum annual rainfall mostly occurred at the upstream reach of the river.

Research site of this work is located on the down-stream site of the Argoguruh weir in the village of Metro Kibang as presented in **Figure 1**.

3. Result and Discussion

Environmental flow analysis is essential to provide knowledge of linkage between water resources use and ecological boundaries. It is also important to answer of the general question whether operation the Batutegi Dam has been affecting ecological pattern of the Way Sekampung River. Learned from the river hydrograph as presented in **Figure 2**, there is no significant changes on high flows (higher than 100 m^3/s) both on its pattern of occurrence and values. However environmental flow will also affected by how the low flow of the river behaves.

Based on recommendation stated by Tennant, an environmental flow (EF) was provided. The environmental flow was mainly driven by time series data of the daily discharge. Annual average discharge was calculated from 3070 data and the discharge of 57.3 m^3/s is defined as Annual Average Flow (AAF). The environmental flow provided is vary from 10% AAF to 60% - 100% AAF as an optimum values.

Regarding the AAF of the Sekampung River, the optimum environmental flow was then also provided as an interval of 34.3 m^3/s to AAF (57.3 m^3/s). Meanwhile the minimum discharge that has to be maintained for environmental flow in middle reach of the Sekampung River 5.73 m^3/s (10% AAF). The other environmental value as categorised by Tennant is presented in **Table 1**.

Meanwhile using FDCA method, the discharge of 32.08 m^3/s is defined as 50% of probability that can be assigned as mean value. Regarding **Figure 3** that provides probability curve of the data concerned, it is also found that to maintain the probability of 95% of the river flow then the value of 4.5 m^3/s has to be concerned. Compare to the Tennant method, the 50% of probability (32.08 m^3/s) is categorised as Outstanding (between 40% - 60% AAF). However the discharge with 95% of probability is even lower than the 10% AAF that means lower than the minimum threshold set by Tennant.

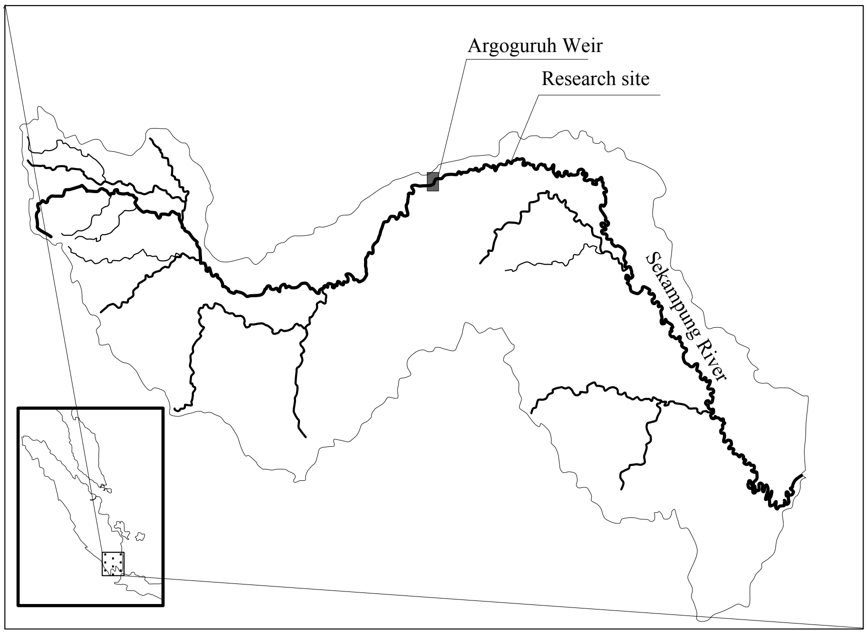

Figure 1. The Argoguruh weir at middle reach of the way Sekampung River, Indonesia.

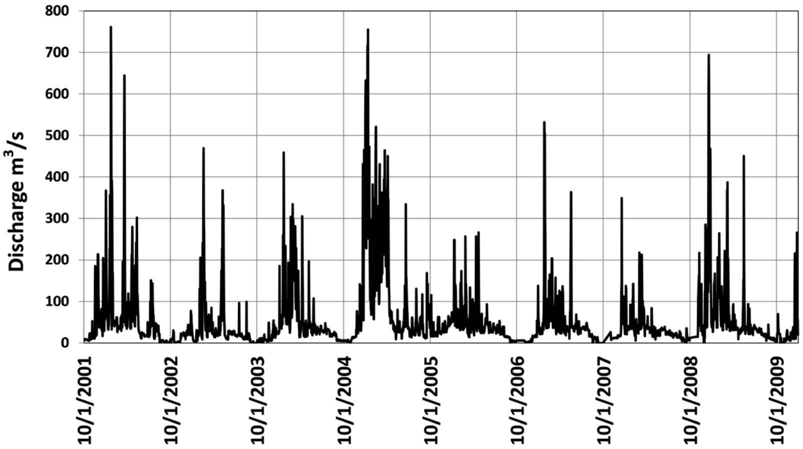

Figure 2. Discharge of the way Sekampung Rivet at Argoguruh weir.

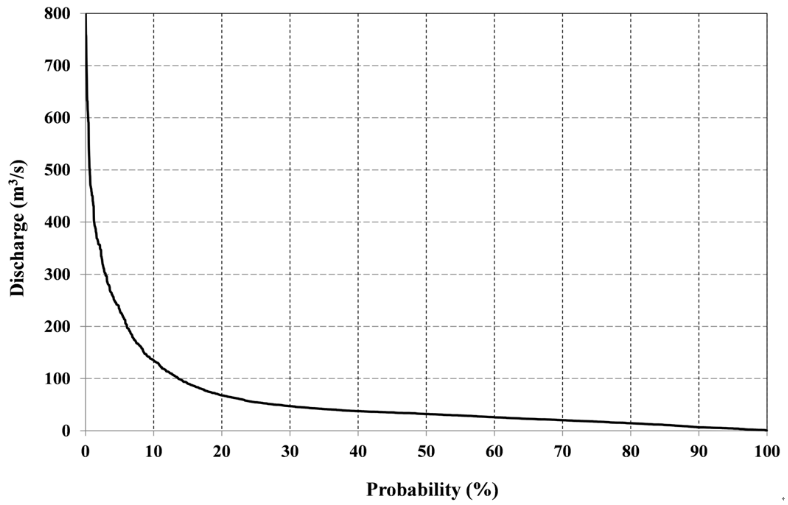

Figure 3. Flow duration curve of the way Sekampung River at Argoguruh weir.

Table 1. Environmental flow for middle reach of the Sekampung River.

Description of discharges	Recommended base flow regime (%)		Discharge (m^3/s)	
	Oct.-Mar.	Apr.-Sept.	Oct.-Mar.	Apr.-Sept.
Average annual flow	100% average flow		57.306	
Flushing or maximum	200% average flow		114.611	
Optimum range	60% - 100% average flow		34.383 - 57.306	
Outstanding	40%	60%	22.922	34.383
Excellent	30%	50%	17.192	28.653
Good	20%	40%	11.461	22.922
Fair or degrading	10%	30%	5.731	17.192
Poor or minimum	10%	10%	5.731	5.731
Severe degradation	10% average flow to zero flow		5.731 - 0	

A new analytical approach of water-sediment that based on magnitude-frequency method is intended to provide more simple method and reasonable value of environmental flow since the ecological variables of the river are not only depended on the flow pattern but also on the bed-load sediment rate. In this water-sediment approach, resultant of the magnitude of river discharge and their corresponding frequency, which is related to frequent discharge, will represent the most prominent flow available in the river. Although value and duration of the high flow is also important, the most dominant discharge provides positive correlation to the shape of river's cross section. Meanwhile the minimum value of water-sediment curve is related to the dominant ecological pattern of the river. Since the minimum environmental flow is the main concern then the minimum value of water-sediment of the river is represent the point of concern.

Discharge has been widely used as a tool to study morphological aspect of a river [18]. For example, among number of researchers, Wilkerson and Parker [19] stated that bankfull discharge tends to have a significant relation with morphological changes of a river. Number of researchers [19] [20] defines a bankfull discharge as a function of river's geometry namely: wetted perimeter, top width and particle diameter of the river-bed (D_{50}). Wahono [21] state that discharges of higher than the dominant discharge will provide significant effects on the morphology changes of a river-bed.

Jansen within [22] described there are four basic assumptions as a tools to arrive in one dimensional analytical approach of river morphology those are:

1. Momentum equation of water movement:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+g\frac{\partial h}{\partial x}+g\frac{\partial z}{\partial x}=-g\frac{u|u|}{C^2 h} \tag{2}$$

which can be expressed as Chezy equation of water flow within steady and uniform flow

$$Q = BCh^{3/2}i^{1/2} \quad (3)$$

2. Continuity equation of water:

$$\frac{\partial a}{\partial t} + u\frac{\partial h}{\partial x} + h\frac{\partial u}{\partial x} = 0 \quad (4)$$

3. Sediment continuity:

$$\frac{\partial z}{\partial t} + \frac{\partial s}{\partial x} = 0 \quad (5)$$

4. Sediment transport predictor:

$$s = mu^n \quad (6)$$

which m and n are coefficients. Klaassen at [23] provides equation of sediment predictor as the following:

$$s = D^{-P}mu^n \quad (7)$$

By combining those equations, Equations (6) and (7), and introducing B as river width, then the equation will be as the following:

$$(S = s \cdot B): S = BD^{-P}mu^n = BD^{-P}mC^n(hi)^{n/2} \quad (8)$$

When Chezy equation is used to represent velocity: $u = C(hi)^{\frac{1}{2}}$ where C is Chezy coefficient and h is the water flow depth.

Moreover, a relation among variables within alluvial system can be written as:

$$SD :: Qi \quad (9)$$

By integrating Equations (8) and (9) it can be provided an equation that not only based on the qualitative approach as Equation (9). With S = sediment discharge (m^3/s), Q = water discharge (m^3/s), D = diameter of river-bed's grain size (m) and i = energy gradient (m/m). It will come to the following equation:

$$SD^pB^{\frac{n-3}{3}} :: mC^{\frac{2n}{3}}Q^{\frac{n}{3}}i^{\frac{n}{3}} \quad (10)$$

That can be expressed as:

$$SD^pB^{\frac{n-3}{3}} :: Q^{\frac{n}{3}}i^{\frac{n}{3}} \quad (11)$$

By assuming :: is "proportional to" and replacing n and p using predictor of Engelund-Hansen, Klaassen [23] reported that n and p are replaced by 5 and 1 respectively, then Equation (11) can be expressed as the following:

$$SD^1B^{\frac{2}{3}} :: Q^{\frac{5}{3}}i^{\frac{5}{3}} \quad (12)$$

in case of D, B and i are assumed to be constant then sediment rate (S) will be proportional to discharge and its frequency of occurrence (F)

$$S :: F_iQ^{\frac{5}{3}} \quad (13)$$

Using Equation (13), it can be provided the relationship between probability of the discharge-sediment and average discharge Q as presented in **Figure 4**. This figure is also known as magnitude-frequency approach of sediment-water relationship. The graph shows that discharge of 38 m^3/s is the represent dominant discharge of the concerned river reach and it is also can be seen that discharge of about 3.5 m^3/s as the lowest discharge on the graph represents the minimum environmental flow of the concerned site.

Using the water-sediment method that represents magnitude-frequency of water as well as its corresponding sediment flow, frequency diagram of the entire data was provided as presented in **Figure 4**. It has to be noted

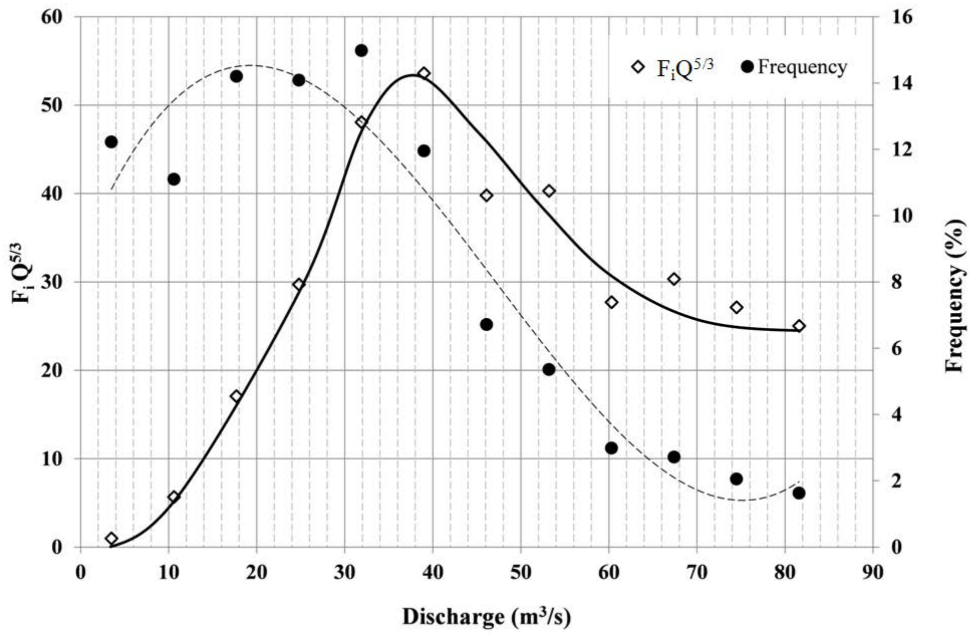

Figure 4. Magnitude-frequency of the Sekampung River.

that applicability of the method is limited to the condition of ideal sediment transport.

Discharge data between 0 m^3/s and 100 m^3/s classified into thirteen consecutive equal intervals and also calculated its corresponding frequencies. It is found that discharge of 20 m^3/s has the highest frequency (peak of the curve) and identified as the frequent discharge (Qf) which also corresponding to a 38 m^3/s discharge called the dominant discharge (Qd). Meanwhile the main concern of a minimum environmental flow is adjusted from the minimum value of the water-sediment graph. From **Figure 4**, it can be learned that value of the minimum water-sediment is represented by the smallest value of the curve representing Equation (13). Based on **Figure 4**, the value is provided as 3.5 m^3/s. The minimum environmental flow of 3.5 m^3/s is about 10% of the dominant discharge which is 38 m^3/s. The percentage will however tend to be depended on the cross section characteristic of the river.

Compare to the Tennant method, the result of the water-sediment method (3.5 m^3/s) is categorised as severe class or equivalent to a range of 10% to 0% AAF. Meanwhile, regarding the FDCA method, the value of defined environmental flow has a probability of about 95% or equal to 95% dependable discharge.

4. Conclusions

A preliminary study of environmental flow of the Sekampung River was conducted using number of methods including a new method called water-sediment method and it was concluded that the optimum environmental flow regarding Tennant method was an interval from 34.3 m^3/s to AAF (57.3 m^3/s). Meanwhile, according to the Tennant method, the poor or minimum category of discharge that has to be maintained in the middle reach of the Sekampung River is 5.73 m^3/s (10% AAF).

Using the water-sediment method, it is found that discharge of 20 m^3/s is identified as the frequent discharge. It also provides discharge of 38 m^3/s as the dominant discharge of the river site. Meanwhile the discharge of 3.5 m^3/s is classified as a minimum environmental flow.

Compare with the Tennant method, the discharge of 3.5 m^3/s is categorised as the lowest criteria (less than 10% AFF). Meanwhile 20 m^3/s is categorised as outstanding class or equivalent to a range of 40% to 60% AAF.

Regarding the FDCA method, the value of 3.5 m^3/s has a probability of 95%. Therefore, after comparing all concerned methods, the result from the new method called water-sediment is more likely close to the minimum discharge set by Tennant, and 95% of dependable discharge regarding the FDCA method.

Further developments of the method by taking into account both ecological aspect and parameters regarding sediment's initiation of motion have to be performed for a more comprehension approach.

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