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Original Research

Occurrence of bed load transport in the presence of stable clast☆

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ABSTRACT

It is well-versed that transport occurrence is vital for in stream rehabilitation, river restoration and installment of sediment sampler on river beds. Current practice emulates the use of continuous prediction using reach-averaged approach. However, prediction of transport occurrence entails the use of binary model through the execution of logistic regression analysis. Bed load and turbulence data were physically measured at mountainous region with divergent surface bedform in its presence. The parameterization and statistical approaches are treated in the similar fashion with multiple regression except for the test for model fit and model selection criterion. The parameters on near-bed turbulence characteristics at the entrainment threshold were assigned as independent variables containing 15 predictors. Almost 80 models were generated by selecting the best possible combination in accordance with the statistical precaution of alleviating multicollinearity issue. It is postulated that the model containing shields stress in the form of turbulent kinetic energy (TKE) at vertical direction and fractional time for second quadrant provides better estimation of potential location for greatest sediment-entrainment; hence a high possibility for transport occurrence.

1. Introduction

It is of great interest to hydraulic community to predict the sediment flux at reach scale in order to model bedrock incision, to calculate sediment routing through watershed and to determine the downstream effects of land use practices on hillslopes (Yager et al., 2007). However, observing the transport mechanism at local scale is always puzzling the past researchers due to the flow structure and presence of surface bedform (Mueller & Pitlick, 2005; Sulaiman & Sinnakaudan, 2012). Mueller and Pitlick (2005) postulated that even the fully submerged particles at gravel bed rivers tend to exceed the threshold limit of 0.06 for incipient motion criterion. This result contradicts with the previous finding that the threshold value of 0.06 will hold at constant value regardless of bed particles. The eventual finding of Mueller and Pitlick (2005) lead to a conclusion that changes in flow structure (turbulence) due to the presence of bed texture will modify transport threshold.

Current practice for predicting sediment yield emulates the reach-averaged concept where various approaches are considered such as size by size fraction (Parker, 1990), excess Shields approach (Engelund & Hansen, 1967), regression technique (Sinnakaudan et al., 2010) or stream power approach (Yang, 1972, 1984). However predicting transport occurrence at local scale is different from reach scale. Although developing continuous model at local scale is possible, the practicality of such an equation at local scale is subject for further discussion. Most practitioners are interested in "reach-scale" kind of prediction. Nevertheless, finding the transport occurrences at local scale is crucial for decision making process. Therefore, biologists need the data on the local scale behavior to determine the best spot for in-stream rehabilitation, whilst engineers acquire detail flow and transport dynamic pattern within the very-fine scale for landscape and restoration project and fluvial researchers must obtain accurate field data measurement to validate empirical equation.

Field measurement at "supply-limited" channel is significantly different from "equal mobility" channel. The same principle goes to the sampling outcome at undulating river beds and flat river

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beds. The presence of surface bedform may entrap the incoming particles; hence acting as source or sink of sediment. Deployment of pressure-difference bed load sampler such as Halley-Smith, US-BLH 84 or bed load trap is significantly affected by the presence of such surface bedform. Executing field measurement at structured bedform may require a longer period of time compared to loosely structured bedform. In addition, under normal conditions, bed load transport does not occur within the vicinity of surface bedform. Thus, it is crucial to find the possible location of greatest entrainment-transport location before installing the sediment equipment in the river bed.

There are two different ways to predict sediment transportation; reach-averaged and probability concept. The reach-averaged concept is used for continuous estimation while the probability concept is employed for binary estimation of transport occurrence. Thus far, there is no proof of any numerical equation in predicting transport rate at local scale. This is due to the nature of local scale where obtaining transport rate is insignificant; hence using reach-averaged concept is more practical in order to gain the transport average at river transect. However, it is possible to estimate the probability of transport occurrence at local scale because 'transport path' occurs at the very finer scale before converging for reach-averaged scale. Furthermore, the possible location for the greatest potential of sediment-entrainment activity is crucial to be identified for pool maintenance-process and to observe the preferential sediment deposition areas (Thompson & Wohl, 2009). The estimation of transport rate at reach scale is grouped as continuous outcome-based whereas the finding of the probability of transport occurrence at local scale is listed as categorical outcome-based due to the dichotomous end result (occur or not occur).

2. Theoretical and statistical considerations

2.1. Selecting explanatory variables at local scale

Near bed turbulence characteristics at the entrainment threshold will be used to distinguish the occurrence of bed load transport at local scale. At the basic level, the presence of local bed structure will modify the flow field; hence provide condition for selective entrainment of grains (Kramer & Papanicolaou, 2005; Papanicolaou et al., 2003, 2004; Strom & Papanicolaou, 2009). Table 1 depicts the possible explanatory variables that affect the occurrence of transport at local scale. The main reason for selecting those parameters lies on the convincing results by Thompson and Wohl (2009) and Dey et al. (2011). Pattern of turbulent kinetic energy (TKE) and extreme instantaneous velocities (EIV) at moderate and high flows may provide a better estimation of locations of greatest sediment-entrainment potential than cross-sectional or time-averaged values of flow or shear stress (Thompson & Wohl, 2009). Dey et al. (2011) postulated that the departure of streamwise velocity from log law distribution is far greater for immobile bed than the entrainment-threshold bed. In addition, they conclude that Reynolds stress, quadrant analysis, bursting duration and TKE are the major factors associated with immobile bed and entrainment-threshold bed. Sulaiman et al. (2013) reveal the effect of local scale bed shear stress on the pulsating nature of transport rate. One to one relationship between local bed shear and transport rates exposes the pattern of singularity and weak correlation amongst them. Thus, the occurrence of bed load transport can be deduced as:

$$\begin{aligned} C = f(&EIV, RSq\_Q2, RSq\_Q4, TSq\_Q2, TSq\_Q4, R, \mathrm{I}_e, \mathrm{I}_s, \tilde{u}, F_{ku}, F_{kw}, \\ &\text{Shields\_loglaw}, \text{Shields\_Reynolds extrap}, \text{Shields\_TKE}, \\ &\text{Shields\_TKEw}') \end{aligned} \tag{1}$$

where C is the binary variable for which $C=1$ represents the occurrence of bed load transport and $C=0$ depicts otherwise. The meaning of those notations can be inferred from Table 1. To alleviate the site specificity, all independent variables must be expressed in dimensionless form. Meanwhile, the dependent variable was inferred from the actual field measurement by assigning "0" if there is no transport occurrence and "1" for otherwise. The later model will simulate the occurrence using the probability concept where the cut-off value for transport occurrence is set to 0.5.

2.2. Mathematical expression for selected predictor

Mean and turbulent flow statistics contain useful information for most of the stream processes such as transport of sediment and nutrient, distribution of fish and aquatic habitat and river design (Robert, 2004). The separation of velocity and turbulent components are formalized through the Reynolds decomposition:

$$u' = \hat{u} - \overline{u} \tag{2}$$

where u'=fluctuating velocity, $\hat{u}$=instantaneous velocity and $\overline{u}$=time-averaged velocity. The deviations (fluctuations) from the mean velocity represent the second order of statistical moments of velocity. The average magnitude of the deviation from the mean reveals the 'intensity' of the turbulence for each velocity component. The standard deviation of the velocity distribution or root-mean-square (RMS) is best to describe turbulence intensity. RMS is

Table 1
Explanatory variables for logistic regression analysis.

No	Parameters	Notation	Investigators
1	Extreme instantaneous velocity	EIV	Thompson and Wohl (2009)
2	Contribution to Reynolds stress for quadrant 2	RSq_Q2	Sukhodolov et al. (1998)
3	Contribution to Reynolds stress for quadrant 4	RSq_Q4	Sukhodolov et al. (1998)
4	Fractional time for quadrant 2	TSq_Q2	Sukhodolov et al. (1998)
5	Fractional time for quadrant 4	TSq_Q4	Sukhodolov et al. (1998)
6	Normalized turbulent intensity/correlation coefficient	R	Nelson et al. (1995)
7	Conditional-averaged pattern (w'component)	I_e	Sukhodolov et al. (1998)
8	Conditional-averaged pattern (u'component)	I_s	Sukhodolov et al. (1998)
9	Normalized streamwise flow	$\tilde{u}$	Dey et al. (2011)
10	Normalized TKE	F_{ku}	Dey et al. (2011)
11	Normalized TKE for vertical direction	F_{kw}	Dey et al. (2011)
12	Local shields stress using loglaw approach	Shields_loglaw	Biron et al. (2004), Sulaiman et al. (2013)
13	Local shields stress using Reynolds extrapolation	Shields_Reynolds extrap.	Biron et al. (2004), Sulaiman et al. (2013)
14	Local shields stress using TKE approach	Shields_TKE	Biron et al. (2004), Sulaiman et al. (2013)
15	Local shields stress using TKE for vertical direction approach	Shields_TKEw'	Biron et al. (2004), Sulaiman et al. (2013)