Graz University of Technology

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Measurement of sediment transport by means of Sediment Impact Sensors (SIS) in the laboratory

Master thesis

Submitted by

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Abstract

The importance of sediment transport in hydraulic engineering and technical development of water resources is very dominant. The stability of manmade canals, water ways and bed and banks against scouring and deposition is also another field of prime interest. Moreover, one of the reasons for the wrecking of cities, roads, forests and heritage nearby rivers in high altitude region, is bedload transport. Over a long time, the alpine mountains in Austria generate disastrous flood events that results into massive damage to infrastructure and as well as mankind. These are the events that made sediment studies, basis for subject of intensive fundamental, applied and field research since 19^{th} century.

The aim of this thesis is to relate sediment transport parameters to the signals of the sensors. The test trials are conducted with the help of sediment impact sensors (SIS). These sensors provide the readings in accelerations. The test scenarios are made by combinations of the parameters that are; flume slope, water discharge, sediment size and sediment discharge. The results from the sensors are then analysed by implementing two methods, integral curve and peak counts. There are many interesting discoveries that reveal the science behind these parameters. With the help of precise study of each parameter in future, the prediction of events could be possible.

Kurzbeschreibung

Die Bedeutung des Sedimenttransports im Wasserbau und der technischen Entwicklung der Wasserressourcen ist sehr dominant. Die Stabilität von künstlich angelegten Kanälen, Wasserwegen und Sohlen und Böschungen gegen Auskolkung und Ablagerung ist ein weiteres Gebiet von vorrangigem Interesse. Darüber hinaus ist einer der Gründe für die Ablagerung von Städten, Straßen, Wäldern und dem Erbe in der Nähe von Flüssen in Hochgebirgsregionen der Geschiebetransport. Das alpine Gebirge in Österreich erzeugt über lange Zeit katastrophale Hochwasserereignisse, die zu massiven Schäden an der Infrastruktur und auch an der Menschheit führen. Diese Ereignisse haben die Sedimentuntersuchungen zum Gegenstand intensiver Grundlagen-, angewandter und Feldforschung seit dem 19.

Das Ziel dieser Arbeit ist es, Parameter des Sedimenttransports mit den Signalen der Sensoren in Beziehung zu setzen. Die Versuche werden mit Hilfe von Sedimentaufprallsensoren (SIS) durchgeführt. Diese Sensoren liefern die Messwerte in Beschleunigungen. Die Testszenarien werden durch Kombinationen der Parameter Gerinneneigung, Wasserabfluss, Sedimentgröße und Sedimentabfluss erstellt. Die Ergebnisse der Sensoren werden dann mit Hilfe von zwei Methoden analysiert: Integralkurve und Spitzenzählungen. Es gibt viele interessante Entdeckungen, die die Wissenschaft hinter diesen Parametern offenbaren. Mit Hilfe einer genauen Untersuchung jedes Parameters könnte in Zukunft die Vorhersage von Ereignissen möglich sein.

Acknowledgment

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AFFIDAVIT

I declare that I have authored this thesis independently, that I have not used other than the declared sources/resources, and that I have explicitly marked all material which has been quoted either literally or by content from the used sources. The text document uploaded to TU Graz online is identical to the present master's thesis.

Date   Signature

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1. Introduction

1.1 Motivation

In general, the importance of sediments in hydraulic engineering and in the technical development of water resources is of significant value. It is influenced by the roughness and frictional resistance in the flume. In context to sediments, the stability of bed and banks against scouring and deposition are another point of importance, particularly for manmade canals and waterways. The life span of a reservoir depends on the sediment load of the contributing natural streams. The rate of deposition of sediments determines the extent and frequency of maintenance of navigable waterways in estuaries. These are the basis, that sedimentation has been the subject of intensive fundamental, applied and field research since 19^{th} century and numerous theories, empirical formulas and semi theoretical equations have been resulted for the evaluation of sediment transport rates and the control of channel stability (Partheniades 2009).

Sedimentation is a process whereby soil particles are eroded and transported by flowing water or other transporting media and deposited as layers of solid particles in water bodies such as reservoirs and rivers. It is a complex process that varies with watershed sediment yield, rate of transportation and mode of deposition (Ezugwu 2013). Sediment deposition reduces the storage capacity and life span of reservoirs as well as river flows (Eroğlu et al. 2010). Sedimentation continues to be one of the most important threats to river eco-systems around the world. A study was done on the world’s 145 major rivers with consistency long term sediment records and the results show that about 50 % of the rivers have statistically a significantly downward flow trend due to sedimentation (Walling and Fang 2003). (Sumi and Hirose 2009) reported that the global reservoir gross storage capacity is about 6000 km^3 and annual reservoir sedimentation rates are about 31 km^3 (0.52 %). This suggests that at this sedimentation rate, the global reservoir storage capacity will be reduced to 50 % by year 2100.

One of the major reasons for destruction of cities, rivers, roads, forests and heritage in high altitude region is sediment and bedload transport. Over a decade, the alpine mountain in Austria face uncertain flood events, they result into tremendous effect to infrastructure.

To turn down the effect, there are numerous studies and techniques done to record different events and collecting the data. Later on, this data is used to project or estimate the happening in future and pre-remedies could be performed. This thesis is also based on the projects ClimCatch Klima und Energiefonds, governed by the Department of Geography and Regional Science at the University of Graz in collaboration with the Institute of Hydraulic Engineering and Water Resources Management at the Graz University of Technology.

1.2 Goals of Thesis

The aim of this thesis is to use sediment impact sensors (SIS) for monitoring sediment transport. Further, to use the signal data in different evaluation methods and produce results on basis of sediment transport parameters. Finally, to discover some scenario to predict quantitative discharge of sediments from those results.

1.3 Overview

In chapter 2, all the definitions, theories and previous studies that supports the cause of this experiment are discussed. Sediment properties and all the factors that play vital role in transportation are mentioned. Classic and modern methods for transportation measurements are discussed. Next is chapter 3, contains all the strategy that is been implemented throughout the project. Parameters of the sediment transport tests, the installation of the setup, different combinations of test scenarios, creation and handling of result data are informed. Chapter 4 highlights the whole method from conducting of tests to processing of data and further representing and evaluating the data figures. Chapter 5 of results is totally dependent upon the graphical results and evaluation of the conclusions. Finally, in chapter 6 the whole project is concluded to mention concrete findings. Moreover, suggestions for new research approaches and recommendations for improvement and more detailed study are mentioned in this chapter.

2. Theoretical Background

This chapter contains all the theoretical background that support the motive of this thesis.

2.1 Properties of Sediments

The branch of science that deals with the properties of particles considered as a unit or as a compound is called “Sedimentology”. A compound may consist of different kinds of particles varying in size, gradation and specific weight. In hydraulic engineering the size of sediments, and specific weight and the characteristic of deposited sediments are of importance (Simons and Şentürk 1992).

2.1.1 Size

Size of sediment has major influence on sediment transport in river hydraulic. Moreover, the properties such as shape and specific gravity also tends to vary with particle size. Particle size can be defined by volume, diameter, weight, fall velocity, sieve sizes. Size may be determined by callipers, by optical method, by photographic method, by sieving or by sedimentation method. In river mechanics or sedimentology, the size of single particle is not only important, but the size distribution of the sediment that forms the bed and bank of a stream or reservoir are of high concern. The “Subcommittee on Sediment Terminology of the Committee on Dynamics of Streams” of the “American Geophysical Union” has recommended the Wentworth scale that has embracing and expending size classification (Simons and Şentürk 1992). Table 2.1 shows six consecutive size classes: boulders, cobbles, gravels, sand, silts and clay.

Table 2.1: Wentworth scale for sediment size classification (Simons and Şentürk 1992)

Size in Millimeter		Class
4000-2000	....	Very large boulders
2000-1000	....	Large boulders
1000-500	....	Medium boulders
500-250	....	Small boulders
250-130	....	Large cobbles
30-64	....	Small cobbles
64-32	....	Very coarse gravel
32-16	....	Coarse gravel
16-8	....	Medium gravel
8-4	....	Fine gravel
4-2	....	Very fine gravel
2-1	2.00-1.00	Very coarse sand
1-1/2	1.00-0.50	Coarse sand
1/2-1/4	0.50-0.25	Medium sand
1/4-1/8	0.25-0.125	Fine sand
1/8-1/16	0.125-0.062	Vary fine sand
1/16-1/32	0.062-0.031	Coarse silt
1/32-1/64	0.031-0.016	Medium silt
1/64-1/128	0.016-0.008	Fine silt
1/128-1/256	0.008-0.004	Very fine silt
1/256-1/512	0.004-0.002	Coarse clay
1/512-1/1024	0.002-0.001	Medium clay
1/1024-1/2048	0.001-0.0005	Fine clay
1/2048-1/4096	0.0005-0.00024	Very fine clay

2.1.2 Shape

Generally speaking, shape refers to the overall geometric form of a particle regardless of size or composition. Particles of very different geometrical shape, but of the same volume and density may behave the same in fluids. Hence, the shape may be defined in terms of dynamic behaviour. In sediment analysis, sphericity is one of the most important shape properties proposed. It is defined as, the ratio of surface areas of a sphere of the same volume as the particle to the actual surface area of the particle. The function of this property is to indicate the relative motion between the falling particle and the fluid. Roundness is another shape property that is in contrast to sphericity. It states the ratio of average of the corners and the edges of a particle to the radius of a circle inscribed with in area of the particle.

Roundness is independent to sphericity with respect to geometry. It is noticed that compared to sphericity, roundness has less influence on hydrodynamics behaviour of particles (Simons and Şentürk 1992). Figure 2.1 shows the shape properties of a sediment.

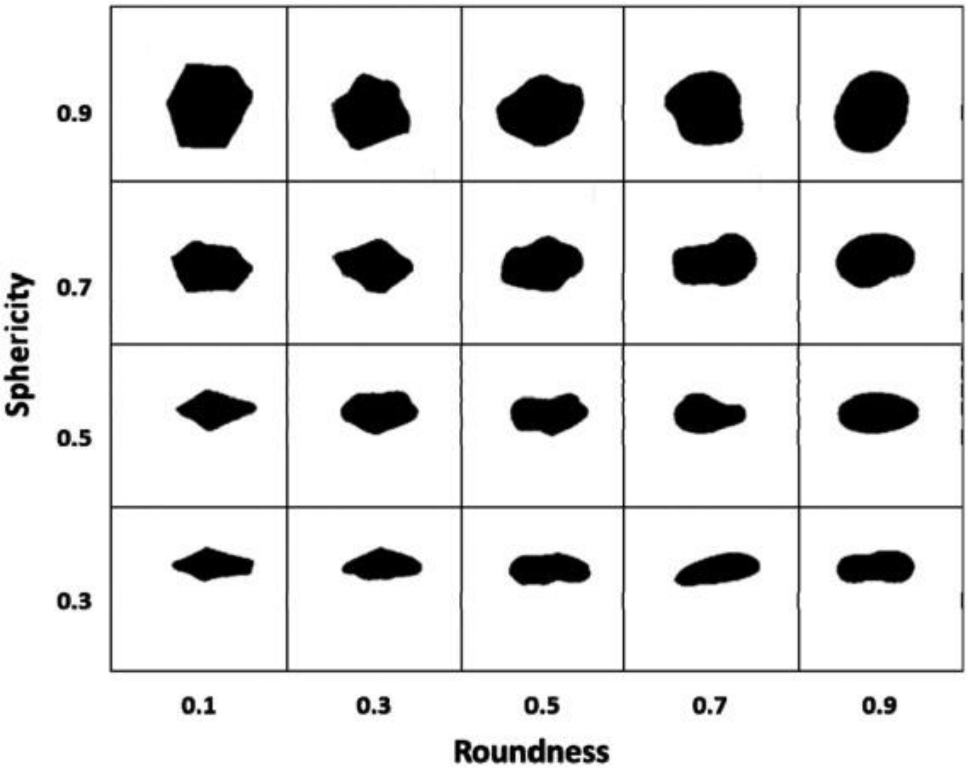

Figure 2.1: Visual chart for evaluating the roundness and sphericity of particle grains (Wang and Fan 2013)

2.1.3 Specific Weight

In general, the specific weight of sediments is different from that of whole mass flowing in the stream. When the particles are tightly packed together, they form a conglomerate such as pumice. If the particles are loose, the conglomerate is subject to consolidation and the specific weight varies with loading and time. The consolidation of sediment is an important soil mechanics problem and also point of interest to hydraulic engineers. Consolidation concepts are used to convert sediment load, determined in unites of weight, to volume of deposits in harbours, rivers, irrigation, canals, etc (Simons and Şentürk 1992).

2.2 Forms of Bed Roughness

There is a strong interrelation between the friction factor, the sediment transport rate, the geometric design assumed by the bed surface and the channel geometry due to flow in channels composed of erodible granular material. The analysis of flow in alluvial bed streams is complicated due to interconnection between the flow and bed material and the interdependency among the variables. The better analysis of different bed forms that resists the sediment transport and effects of depth, slope, viscosity, etc. on bed forms, engineer can analyse and eliminate the problems occurred while working with alluvial rivers and canals (Simons and Şentürk 1992). Following are discussed common bed forms:

- Ripples

This category of bed form is also called sand waves, ripples marks and current ripples. They are small bed form with wave length less than approximately 30 cm and height less than approximately 5cm.

- Bars

Bars are bed forms having length of the same order as the channel width or greater, and height comparable to the mean depth of the generating flow. The types of bar beds are:

a) Point bars

b) Alternate bars

c) Tributary bars

- Dunes

Dunes are bed forms smaller than bars but larger than ripples. Their profile is out of phase with the water surface profile. The longitudinal profiles of dunes are approximately triangular with fairly gentle upstream slopes and downstream slopes varying between 40° and 48°.

- Anti-dunes

Anti-dunes may develop singly or in trains. Considering a longitudinal section, anti-dunes profiles vary with flow and sediment properties from approximately a triangular to a sinusoidal shape. On one hand, the bed is coarse when the triangular shape is common. On the other hand, sinusoidal shape is formed when the bed has fine medium size sand.

- Chutes and pools

Chutes and pools occur at relatively large slopes with high velocities and high sediment discharge. These bed forms consist of large elongated mounds of sediments, which are connected by pools.

2.3 Types of Sediment Movement

In fluvial transport regime, the movement of sediment particles is in following ways:

a) Rolling or sliding on the bed, surface creep

b) Jumping into flow and then resting on the bed, saltation

c) Supported by the surrounding fluid during a significant part of its motion, suspension

Sediments are transported partially as saltation and also as suspension, when suddenly caught by turbulent flow. Sediments which are transported by surface creep or saltation and supported by the bed, are called Bed Load. Sediments which are supported and suspended by flow are called Suspended Load (Simons and Şentürk 1992). Figure 2.2 is taken from the website world rivers, described by (Šafarek 2018). It shows all types of particle movement in a river flow.

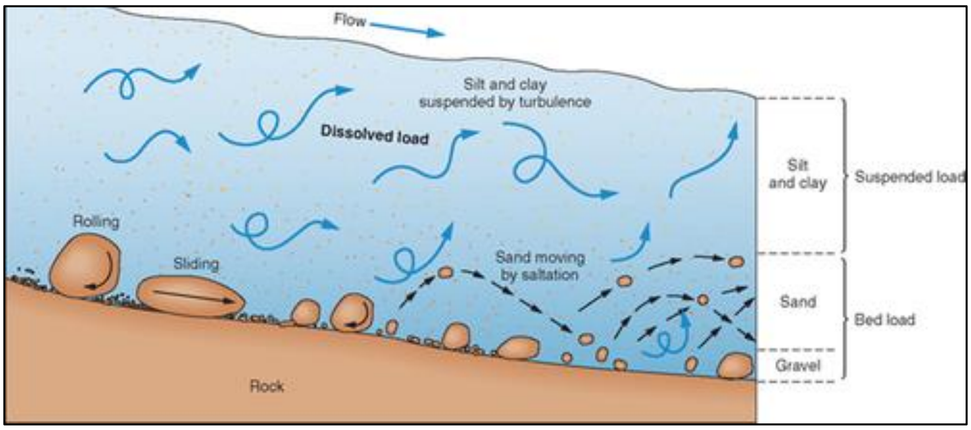

Figure 2.2: Bed load and suspended load particle movement (Šafarek 2018)

2.4 Factors Effecting Sediment Transport and Deposition

The interaction between two variable groups results into the amount of material transported or deposited in the stream under a given set of conditions. First group consist of those variables that influence the quantity and quality of the sediment brought down to that section of stream. In the second group, are the variables that influence the capacity of stream to transport the sediment.

In group 1, the variables which influence the quantity of sediments are: size, settling, velocity, specific gravity, shape, resistance to wear, state of dispersion and cohesion. Whereas, the variables influencing the quality are: geology and topography of watershed; magnitude, intensity, duration, distribution and season of rainfall; soil condition, vegetation and gazing; surface erosion and bank cutting.

According to group 2, the capacity of sediment transport is influenced by two categories of variables. One is the geometric properties or shape of stream; such as: depth. Width, form and alignment. Second is the hydraulic properties of the stream, which are: slope, roughness, hydraulic radius, discharge, velocity distribution, turbulence, tractive force, fluid properties and uniformity of discharge (Simons and Şentürk 1992).

2.5 Sediment Transport Monitoring

(Bernecker 2018) explained techniques adopted for the measurements of sediment transport in her thesis. The probability for the results of monitoring sediment transport can be numerous. Merits and de-merits are part of every system and not every approach is sufficient. To adopt a reasonable sediment transport monitoring system, aspects like the available budget or duration of measurement, river morphology or the results the system delivers should be taken into major concern. A sequence of more than one measurement system is solution in many cases. The goal of each measuring system is to match numerous requirements and to face extreme climate challenges.

The measurement systems are categorized as below:

- Direct Measuring System
    - Bed load sampler
    - Sediment traps
    - Sediment slots
- Indirect Measuring System
    - Hydrophone
    - Geophone
    - Tracing or telemetry stones
    - Sediment Impact Sensor (SIS) measurement
    - Accelerometer (MEMS)

The importance is to understand that the measurement should not disturb the sediment transport and the natural flow, or else the results will be manipulated and unrealistic. The limitation of every measuring method is different and this leads to the exploration to combine direct and indirect measuring techniques (Bernecker 2018).

2.5.1 Direct Measuring System

The technique for direct measuring system is to actively collect sediments with bed load sampler. In this measuring system the maximum transported grain size for the investigating river should be taken into consideration for dimension purposes. The use of direct measuring systems is selective and it provides an insight of sediment transport and grain size impact over a short period of time (Bernecker 2018).

2.5.2 Indirect Measuring System

Indirect methods for sediment measurement uses non-intrusive techniques to avoid the disturbance in sediment and waterflow. The difference between the two types of system is that direct measurement monitors the transport itself on one hand and indirect measurement measures the activity of transport on the other hand. The activity of indirect measuring could be divided into four measuring groups (Bernecker 2018).

- Acoustic system (sound)
- Impacts
- Noise in a field (magnetic)
- Echo (sonar)

The focus of this thesis is to use sediment impact sensor (SIS) for sediment transport measurement. Therefore, only description of SIS is given below;

- **Sediment Impact Sensor (SIS)**

Sediment impact sensors are high resolution sensors (piezo-electric technology), that are mounted on a steel plate to get a quantitative reading of bed load transport. These sensor plates are fixed into the riverbed or by installed in a concreted block in the riverbed. When sediments are flushed over the sensor an electrical voltage is generated in the core of the sensor. The magnitude of the voltage is directly proportional to the size of the particle as well as the velocity of the particle. The signal is then recorded by any minicomputer (Bernecker 2018).

- **Accuracy check of the sensor used**

The sensor used for the tests is quiet sensitive as mentioned before. To check this sensitivity, some pre-tests are performed. In these tests, the placement of the sediment sample on the conveyer belt is in such a way that there are spaces between every 50 cm sections. When the tests are conducted the resultant Figure 2.4 shows those spaces of less than 5 mm very dominantly. Figure 2.3 (left) and (right) below, proves the sensitivity of the sensor.

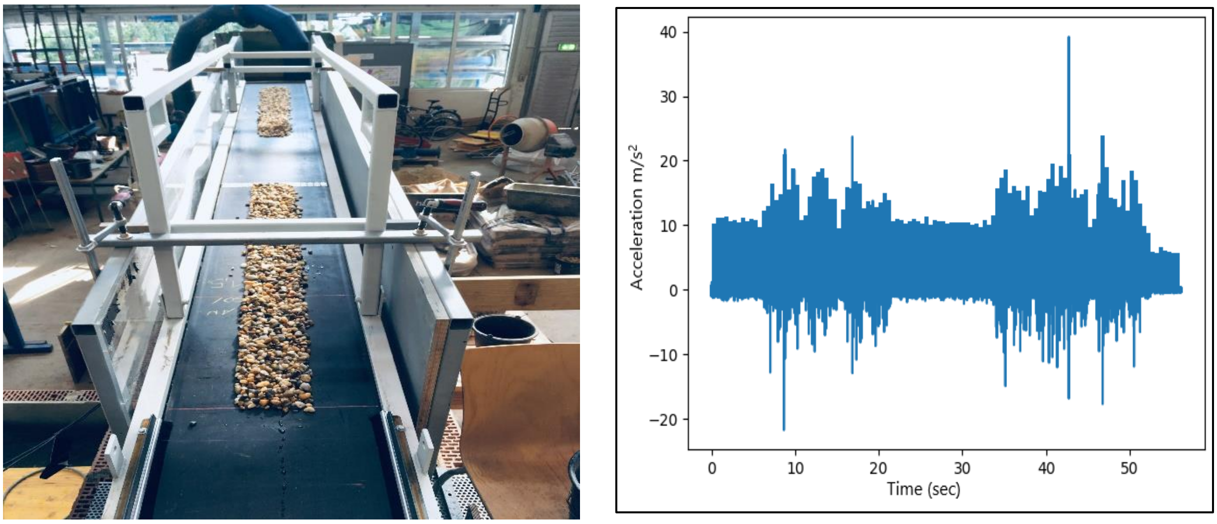

Figure 2.3: (left) Sediment arrangement to check sensor accuracy, (right) sample graphical result, to prove the sensor accuracy

3. Research Method

3.1 Experimental Parameters

To understand and predict the dynamics of sediment transport, tests are performed with a variation of parameters that play big role in transportation. A number of certain values are selected for each parameter which could mirror the real time scenario for the future studies. Following is the short description for every parameter.

3.1.1 Sediment Particle Size (Dm)

In a river outlet there are sediments of all sizes and shapes. The magnitude of sensor impact of each size and shape may vary from one another. In order to understand this difference better, three ranges of sediment sizes were selected, as shown in Figure 3.1, 3.2 and 3.3. The following are the ranges of particle size diameter:

- Dm1 = 8 mm to 16 mm
- Dm2 = 16 mm to 32 mm
- Dm3 = 32 mm to 50 mm

Figure 3.1: Particle size Dm1 = 8 to 16mm – flusskiesel bunt - Sherf GmbH

Figure 3.2: Particle size Dm2 = 16 to 32mm – flusskiesel bunt - Sherf GmbH

Figure 3.3: Particle size Dm3 = 32 to 50mm – flusskiesel bunt - Sherf GmbH

3.1.2 Bed Slope (Sl)

To observe the role of slope parameter on sediment transport, three inclinations are selected.

- 14°
- 10°
- 6°

3.1.3 Water Discharge (Qw)

The sediment transport is also dependent on the discharge or velocity of flow. This property allows particle to travel and exert force which leads to bedload transport. To observe the effect of this parameter, there are three different discharge rates selected. They are as follows:

For slope 14° and 10°

- Qw1 = 15 l/s
- Qw2 = 20 l/s
- Qw3 = 25 l/s

For the 6° slope, the inclination is so horizontal that it is nearly impossible to transport the sediments from high level to low level. So, to overcome this problem the water discharge is increased as follows:

- Qw1 = 25 l/s
- Qw2 = 30 l/s
- Qw3 = 35 l/s

3.1.4 Sediment Discharge (Qs)

This parameter can show the influence on result magnitude when interconnected with particle size. For this phenomenon, the speed of the conveyer belt which throws the sediment into the flow was limited to 0.1m/s. The length of conveyor belt is restricted to 4m, therefore three amounts of sediment discharge are calculated as follow;

- Qs1 = 3.75 kg/m * 0.1 m/s = 0.375 kg/s   Total weight = 3.75 kg/m * 4 m = 15 kg
- Qs2 = 5 kg/m * 0.1 m/s = 0.5 kg/s   Total weight = 5 kg/m * 4 m = 20 kg
- Qs3 = 6.25 kg/m * 0.1 m/s = 0.625 kg/s   Total weight = 6.25 kg/m * 4 m = 25 kg

3.2 Experimental Setup

The experimental setup consists of a flume section which has a storage tank on upper level as a water supply and a retaining tank to reload the water. This flume is installed at a designated inclination. The structure is made up of metal diaphragm. The side walls are made of transparent plastic sheet to observe the flow depth and sediment transport. The base is made of wooden board protected with veneer

At the centre of the flume, two accelerometer sensors, each of them placed one after the other, are installed in a concrete block to detect the impact of the sediment, shown in Figure 3.4 (a). Next to the lower level of flume, a platform is built where laptop is installed that collects the data generated from the sensors during test. Parallel to the top of the flume, a conveyer belt is installed that will carry the sediments to the top level of the channel and will eventually drop it into the flow. Figure 3.4 (b) and (c) shows a 3D diagram of the whole system.

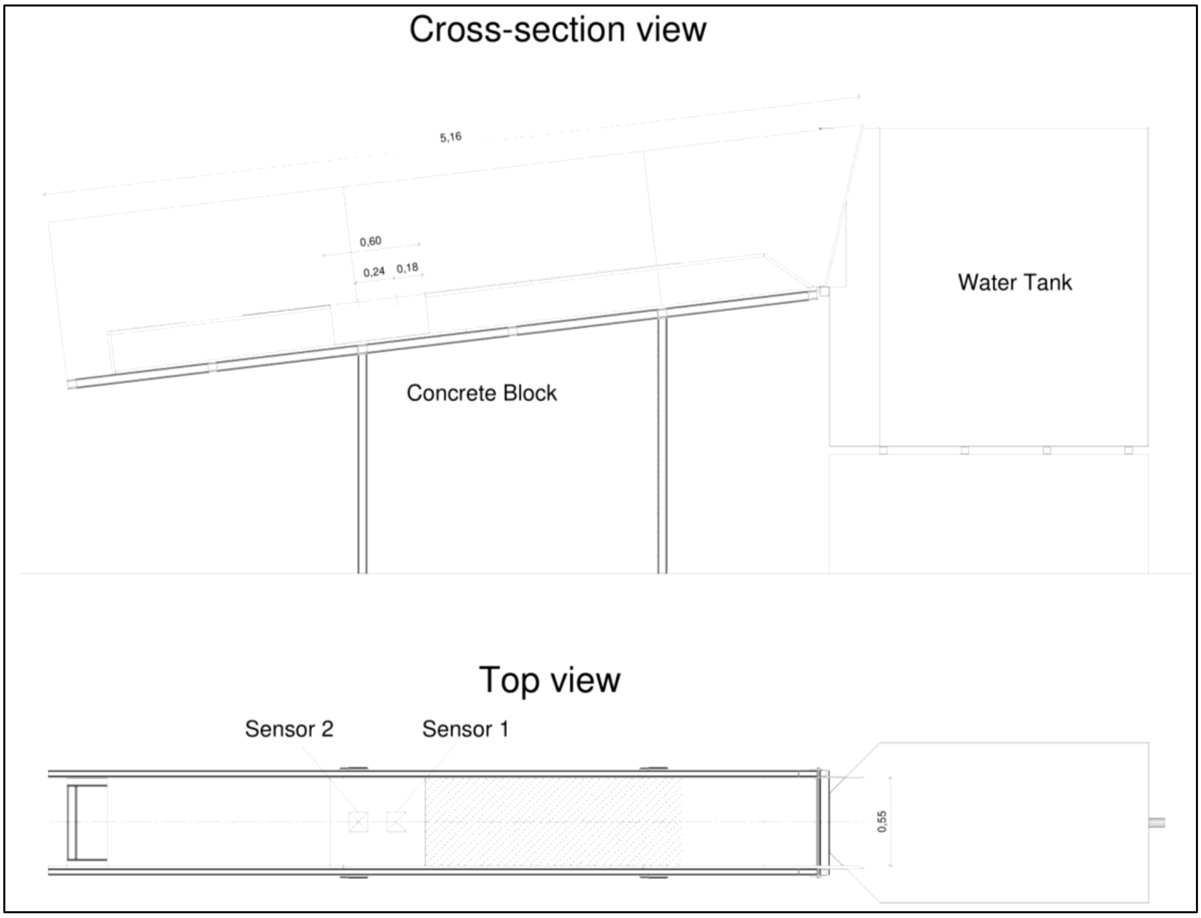

Figure 3.4(a): Sketch of cross section and top view of the flume, the dimensions are also displayed in meter (m)

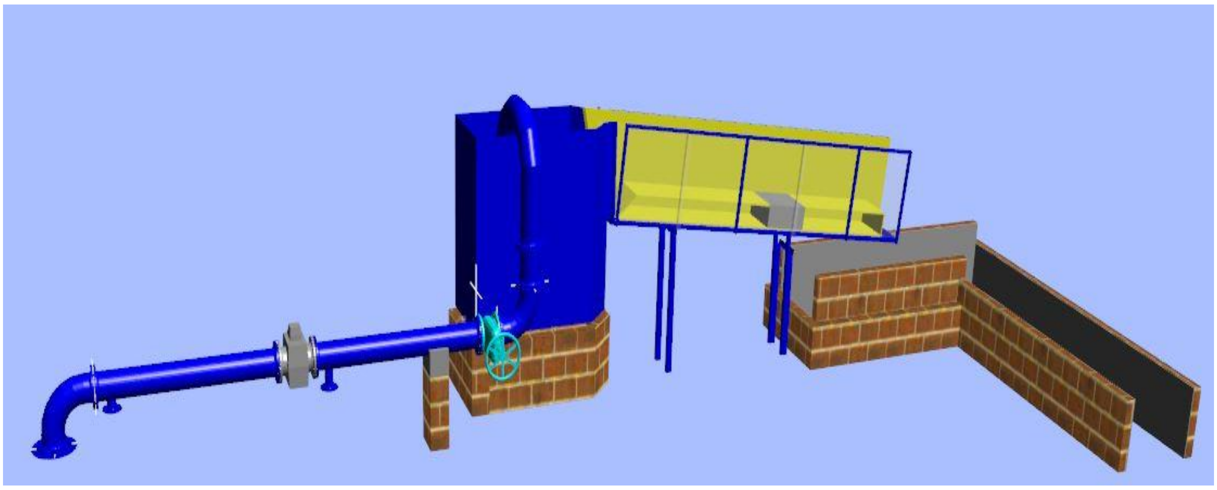

Figure 3.4(b): 3D side view of the whole flume system

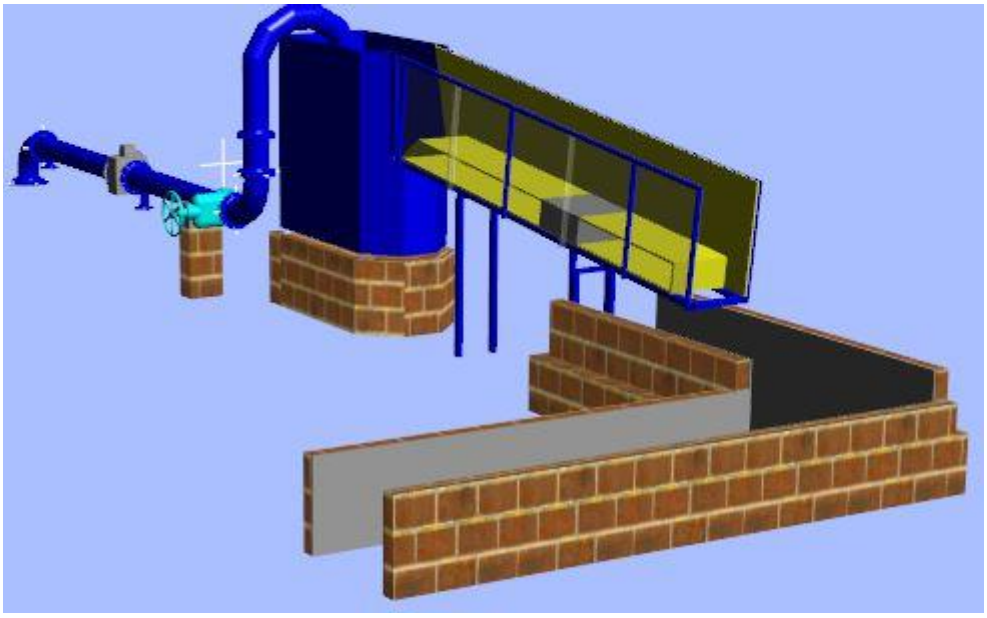

Figure 3.4(c): Front 3D view of the flume system

One of the basic problems in the prediction of sediment transport is to define the bed roughness. This is because sediment transport is strongly dependent on bed roughness, whereas the bed roughness in turn depends on the sediment transport generated by the bed forms migrating over the bed (van Rijn 2007)**.** Therefore, to create real time scenario, a polymeric sheet with uniform embossed roughness is installed in the flume bed. This generates the toppling and rolling effect to the sediment samples, rather than mere sliding. Figure 3.5 shows a detail of the bed roughness material used in the flume.

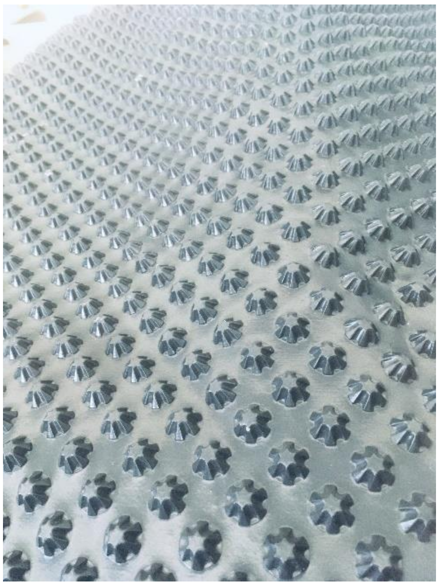

Figure 3.5: Bed roughness material

3.3 Experiments

In order to evaluate the impact of every parameter of sediment transport and to observe their impact on each other, a total number of 81 experimental tests are performed by making combination between all the parameters. The tests are arranged in the Tables 3.1, 3.2 and 3.3 given below:

Table 3.1: Sediment transport tests for Slope 14°, with all combinations of the other parameters

S.No.	Parameter1	Parameter2	Parameter3	Parameter4
1	Slope 14°	Qw1	Dm1	Qs1
2	Slope 14°	Qw1	Dm1	Qs2
3	Slope 14°	Qw1	Dm1	Qs3
4	Slope 14°	Qw1	Dm2	Qs1
5	Slope 14°	Qw1	Dm2	Qs2
6	Slope 14°	Qw1	Dm2	Qs3
7	Slope 14°	Qw1	Dm3	Qs1
8	Slope 14°	Qw1	Dm3	Qs2
9	Slope 14°	Qw2	Dm3	Qs3
10	Slope 14°	Qw2	Dm1	Qs1
11	Slope 14°	Qw2	Dm1	Qs2
12	Slope 14°	Qw2	Dm1	Qs3
13	Slope 14°	Qw2	Dm2	Qs1
14	Slope 14°	Qw2	Dm2	Qs2
15	Slope 14°	Qw2	Dm2	Qs3
16	Slope 14°	Qw2	Dm3	Qs1
17	Slope 14°	Qw2	Dm3	Qs2
18	Slope 14°	Qw2	Dm3	Qs3
19	Slope 14°	Qw3	Dm1	Qs1
20	Slope 14°	Qw3	Dm1	Qs2
21	Slope 14°	Qw3	Dm1	Qs3
22	Slope 14°	Qw3	Dm2	Qs1
23	Slope 14°	Qw3	Dm2	Qs2
24	Slope 14°	Qw3	Dm2	Qs3
25	Slope 14°	Qw3	Dm3	Qs1
26	Slope 14°	Qw3	Dm3	Qs2
27	Slope 14°	Qw3	Dm3	Qs3

Table 3.2: Sediment transport tests for Slope 10%, with all combinations of the other parameters

S.No.	Parameter1	Parameter2	Parameter3	Parameter4
28	Slope 10°	Qw1	Dm1	Qs1
29	Slope 10°	Qw1	Dm1	Qs2
30	Slope 10°	Qw1	Dm1	Qs3
31	Slope 10°	Qw1	Dm2	Qs1
32	Slope 10°	Qw1	Dm2	Qs2
33	Slope 10°	Qw1	Dm2	Qs3
34	Slope 10°	Qw1	Dm3	Qs1
35	Slope 10°	Qw1	Dm3	Qs2
36	Slope 10°	Qw2	Dm3	Qs3
37	Slope 10°	Qw2	Dm1	Qs1
38	Slope 10°	Qw2	Dm1	Qs2
39	Slope 10°	Qw2	Dm1	Qs3
40	Slope 10°	Qw2	Dm2	Qs1
41	Slope 10°	Qw2	Dm2	Qs2
42	Slope 10°	Qw2	Dm2	Qs3
43	Slope 10°	Qw2	Dm3	Qs1
44	Slope 10°	Qw2	Dm3	Qs2
45	Slope 10°	Qw2	Dm3	Qs3
46	Slope 10°	Qw3	Dm1	Qs1
47	Slope 10°	Qw3	Dm1	Qs2
48	Slope 10°	Qw3	Dm1	Qs3
49	Slope 10°	Qw3	Dm2	Qs1
50	Slope 10°	Qw3	Dm2	Qs2
51	Slope 10°	Qw3	Dm2	Qs3
52	Slope 10°	Qw3	Dm3	Qs1
53	Slope 10°	Qw3	Dm3	Qs2
54	Slope 10°	Qw3	Dm3	Qs3

Table 3.3: Sediment transport tests for Slope 6%, with all combinations of the other parameters

S.No.	Parameter1	Parameter2	Parameter3	Parameter4
55	Slope 6°	Qw1	Dm1	Qs1
56	Slope 6°	Qw1	Dm1	Qs2
57	Slope 6°	Qw1	Dm1	Qs3
58	Slope 6°	Qw1	Dm2	Qs1
59	Slope 6°	Qw1	Dm2	Qs2
60	Slope 6°	Qw1	Dm2	Qs3
61	Slope 6°	Qw1	Dm3	Qs1
62	Slope 6°	Qw1	Dm3	Qs2
63	Slope 6°	Qw2	Dm3	Qs3
64	Slope 6°	Qw2	Dm1	Qs1
65	Slope 6°	Qw2	Dm1	Qs2
66	Slope 6°	Qw2	Dm1	Qs3
67	Slope 6°	Qw2	Dm2	Qs1
68	Slope 6°	Qw2	Dm2	Qs2
69	Slope 6°	Qw2	Dm2	Qs3
70	Slope 6°	Qw2	Dm3	Qs1
71	Slope 6°	Qw2	Dm3	Qs2
72	Slope 6°	Qw2	Dm3	Qs3
73	Slope 6°	Qw3	Dm1	Qs1
74	Slope 6°	Qw3	Dm1	Qs2
75	Slope 6°	Qw3	Dm1	Qs3
76	Slope 6°	Qw3	Dm2	Qs1
77	Slope 6°	Qw3	Dm2	Qs2
78	Slope 6°	Qw3	Dm2	Qs3
79	Slope 6°	Qw3	Dm3	Qs1
80	Slope 6°	Qw3	Dm3	Qs2
81	Slope 6°	Qw3	Dm3	Qs3

3.4 Data Collection and Result Files

A laptop is installed and connected to sensors with the help of USB chords near the lower level of the flume. The command to run the sensor to collect the data, and the turn on/off button for conveyor belt to transfer the sediments into the flow, are operated simultaneously. To control the data generation, a frequency of 3200 Hz is chosen. The result files are generated in csv (comma separated files). After every test, the result files are generated and saved in the given folder.

4. Methodology

4.1 Preparing, Loading and Retaining of Sediments

To conduct the tests, the samples are supposed to be loaded and recollected. To make this easier, a sieved bucket is installed on the down-stream side to retain the sediment samples. The sediments are arranged in a way in which the same amount of batch is used per unit length of the belt. This is done so to ensure the uniform flow of sediments throughout the test.

4.2 Preparation of Test Parameters

- Water discharge: there is a valve near the tank, and it is used to regulate and control the flow in the section. In order to increase or decrease the flow, this valve is adjusted to maintain the discharge in l/s. The discharge is observed in a Magnetic inductive flow meter (MID), as shown in Figure 4.1.

Figure 4.1: Digital meter (MID), to display water discharge Qw

- Slope: Changing slope is time consuming. For this reason, the tests are arranged in such a way that we do not need to change the slope after every few tests. This process needs a crane to lift the whole structure and cut down the bottom vertical support bars to achieve the required slope. The slope is then checked by using a digital level, as shown in Figure 4.2 (a) and (b).

Figure 4.2(a): Digital level at the bottom of flume, to check the required slope

Figure 4.2(b): Maintaining the slope Sl = 10°

- Particle size: The sediment bags are already classified into required size range, i.e. 8-16 mm, 16-32 mm and 32-50 mm.
- Sediment discharge: The length of conveyer belt is 4m and there is marking on every 50cm. The total weight of sediment is divided into 8 sections of half meter and the required weight/50cm is then measures in a bucket on a scale. The content of the bucket is then finally distributed over the whole section equally.

4.3 Data Processing and Representing

After the tests are conducted, the data files are processed in the Python code. As the frequency of readings per second is too high, this results into hundred thousand reading in a minute. That is why it is easier to handle it with Python. Moreover, from the data file, the impact value of acceleration in z-direction is taken into account because it gives the evidence of the direct hit on the sensor. Also, this study is limited to 1-direction impact. The following paragraph gives a short description about the different phases and filter functions, used to represent the result graphically.

Python Programming

In this software part of the project, the data is filtered and enhanced to produce reasonable outcomes. The following key filters and resampling are used for data enhancement;

- Wavelet Filter: It is popular tool for computational analysis of harmonics. In both, the temporal domain and as well as frequency domain, wavelet provides localization. Multiresolution analysis is one of the main features. The sparse representation property of wavelet filter is key to the good performance in applications such as data compression and denoising (Lee et al. 2019).
- Butterworth Filter: Water flow generates noise signal and too many low frequencies, to cut-off these low frequencies a Butterworth filter is used. The task of this filter is also to bring the graph base line to zero.
- Resampling of measurement: Indicated earlier, signals are un-even over the time span. To bring these signals to uniformity, Resampling of measurements is done.
- Normalization of inclination: The sensors are installed parallel to the bed. This means, the normal line of the sensor is same as the system inclination. The correction is done by multiplying the cosine of the angle with the z-direction readings.

4.4 Methods of Graphical Representation

According to a research (Rickenmann et al. 2014), there are a few points to be considered to make meaningful results. Firstly, sum of impulse values is found to correlate reasonably well with bedload mass and volume transported. Secondly, flume experiments indicate that the amplitude of the signal and the number of impulses depends on the size of the particle transported over the plates. Thirdly, the integral of the signal might be expected to provide a combined measure related to both the number of impulses and the strength of the signal.

Following the reference above, the enhanced and filtered sediment transport data is represented graphically. There are two methods that are adopted to present the graphical result for a single test. The two methods are as follows:

- Method 1: Integral Under curve

In this method, the area under a certain curve is measured by integral method. The limit of the integration is the intervals of time that are selected. In our case, that limit is 1 second. This means that the average area is calculated within an interval of a second. The average value is the co-relation between the number of frequent impacts and the magnitude of impacts. This method depends upon the particle size as well as particle discharge. Figure 4.3 (Joe 2018) is the basic example to understand this mathematical approach.

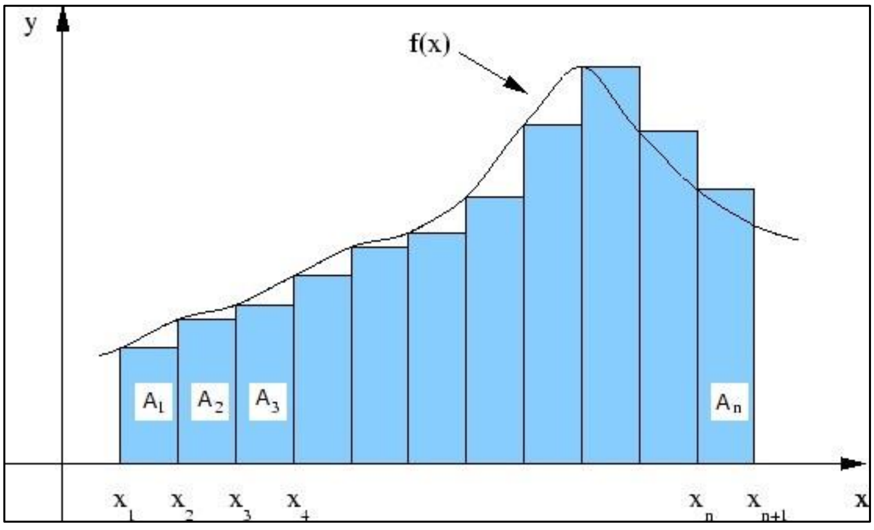

Figure 4.3: Sample example for integral curve, average area for n intervals (Joe 2018)

- Method 2: Total peak counts

As shown in Figure 4.4 (Gabe 2016), when the resultant graph is generated, then every positive and negative rise in the pathway is counted as single peak. At the end, all the peaks are summed up and the total is displayed.

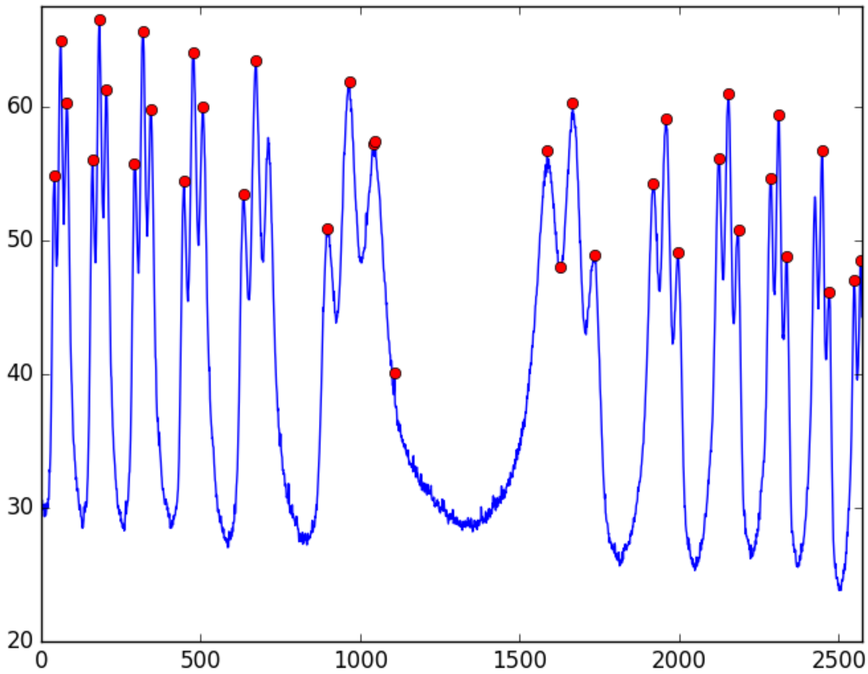

Figure 4.4: Sample example for peak counts (Gabe 2016)

4.5 Result Analysis Approaches

This chapter deals with the base for the final outcome of the whole test scenario. The understanding of this section of the book is of high importance. There are two sensors used to collect the data from each test. Each sensor data is processed for 2 methods, this means that total of 324 graphical results from the 81 tests are made. There are total 4 parameters that play part in a test. It is very challenging to evaluate some concrete theory or any hypothesis, considering all aspect at same time. To overcome this problem, a strategy is made.

The position of the four parameters that are used to represent a test result, is associated as four groups of information. Table 4.1 shows their names and placement as well;

Table 4.1: name and placement of the four group of information

Position 1	Position 2	Position 3	Position 4
System	**Session**	**Period**	**Variable**
Slope	Qw	Dm	Qs
14°	15 l/s	8-16 mm	0375 kg/s

- The System: This groups stays constant throughout the whole structure. The system is independent group, this is because the evaluation is tricky and it has many complex variables which cannot be considered simultaneously.
- The Session: It is a sub-group of the system. Each system contains 3 sessions, shown in Figure 4.5. Every session consists of 9 result values. The evaluation of the sessions is done by taking an average of all the results of each session and are then compared analytically. It can be said that session analysis is the cumulative analysis of a parameter with similar combination of periods and variables.

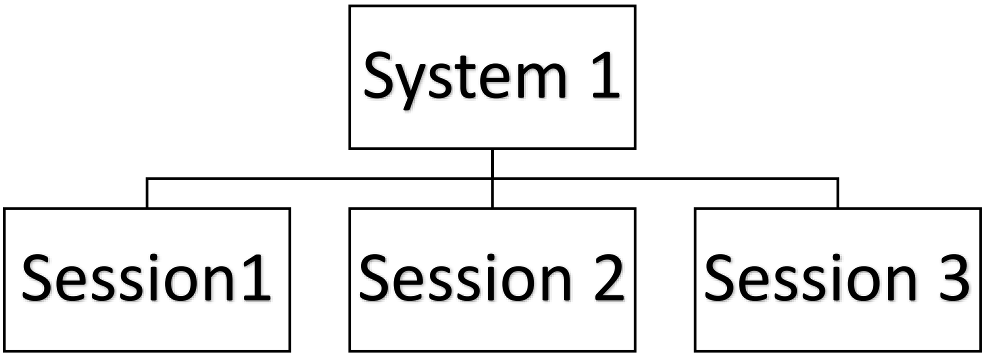

Figure 4.5: Sub-division of a system into three sessions

- The Period: It is the subgroup of a session. There are three periods in a session, which are represented graphically. These three lines segments are constructed because the arrangement of variables under them is uniform. The analysis of the result values from method 1 and method 2 is done by observing the pathway or trajectory of these line with respect to each other. For example: whether the lines are rising or falling or show random behaviour from left to right, shows the influence of the parameter on sediment transport results. To make this scenario more visible, the average of all three variables under each period is also displayed in the figures. The following Figure 4.6 is an example for the demonstration of a period analysis.

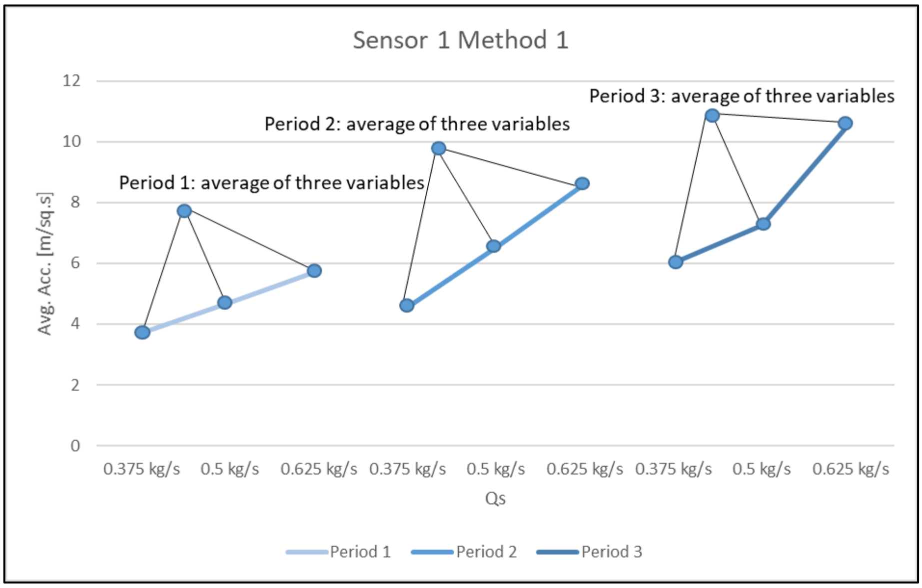

Figure 4.6: Three lines represent three periods of a parameter in a session of water discharge Qw

- The Variable: The period is further sub-divided into three variables. The variable is the last position in the group representation. It is also evaluated graphically. A single line segment in a figure is consist of three variables. The path within a period, show the behaviour of the variable. Figure 4.7 is the modification of same Figure 4.6, that shows the climb in the figure when the parameter is placed as variable, i.e. within the period.

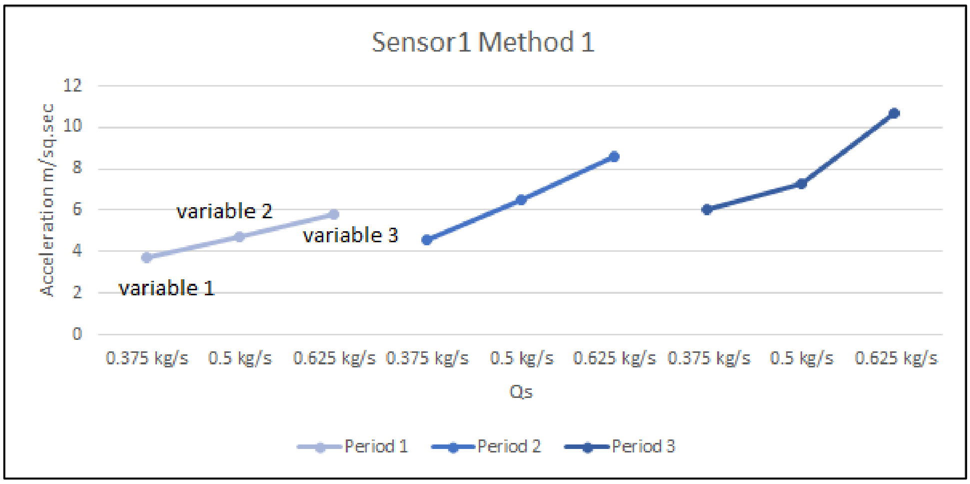

Figure 4.7: Three points in a period represent variables. there are 9 variables in a session

5. Results

5.1 Final Raw Results

After obtaining all the graphs of 81 tests and for both the sensors, we received end results for both the methods of each test. Table 5.1 and 5.2 are the results for method 1 and 2 of sensor 1. On the other hand, table 5.3 and 5.4 are results for method 1 and 2 of sensor 2.

Table 5.1: Results of method 1 and 2 for sensor 1

SENSOR 1						
Measurement	Slope	Qw	Dm	Qs	Method 1	Method 2
1	1	1	1	1	5.435	592
2	1	1	1	2	6.155	632
3	1	1	1	3	6.724	722
4	1	1	2	1	7.593	895
5	1	1	2	2	9.693	971
6	1	1	2	3	9.741	982
7	1	1	3	1	4.583	391
8	1	1	3	2	7.297	583
9	1	1	3	3	17.636	1237
10	1	2	1	1	4.45	475
11	1	2	1	2	5.183	506
12	1	2	1	3	5.838	587
13	1	2	2	1	5.503	609
14	1	2	2	2	7.186	772
15	1	2	2	3	7.813	834
16	1	2	3	1	5.233	356
17	1	2	3	2	5.51	415
18	1	2	3	3	11.084	723
19	1	3	1	1	3.711	364
20	1	3	1	2	4.711	491
21	1	3	1	3	5.769	549
22	1	3	2	1	4.544	477
23	1	3	2	2	6.524	608
24	1	3	2	3	8.608	883
25	1	3	3	1	6.013	422
26	1	3	3	2	7.264	465
27	1	3	3	3	10.648	555
28	2	1	1	1	5.001	576
29	2	1	1	2	7.869	1093
30	2	1	1	3	8.583	913
31	2	1	2	1	7.929	805
32	2	1	2	2	10.151	1286
33	2	1	2	3	11.482	1437
34	2	1	3	1	5.196	429
35	2	1	3	2	8.866	653

Table 5.2: Results of method 1 and 2 for sensor 1

Measurement	Slope	Qw	Dm	Qs	Method 1	Method 2
36	2	1	3	3	12.133	967
37	2	2	1	1	5.942	596
38	2	2	1	2	5.471	563
39	2	2	1	3	7.708	939
40	2	2	2	1	8.08	723
41	2	2	2	2	6.84	698
42	2	2	2	3	8.945	1140
43	2	2	3	1	10.291	632
44	2	2	3	2	9.33	732
45	2	2	3	3	9.233	661
46	2	3	1	1	4.639	546
47	2	3	1	2	6.055	702
48	2	3	1	3	6.994	804
49	2	3	2	1	6.568	642
50	2	3	2	2	6.727	714
51	2	3	2	3	6.744	714
52	2	3	3	1	6.138	617
53	2	3	3	2	7.777	534
54	2	3	3	3	11.48	638
55	3	1	1	1	4.711	449
56	3	1	1	2	4.407	449
57	3	1	1	3	4.595	706
58	3	1	2	1	5.056	606
59	3	1	2	2	7.125	829
60	3	1	2	3	7.178	803
61	3	1	3	1	4.925	408
62	3	1	3	2	8.134	614
63	3	1	3	3	8.061	539
64	3	2	1	1	3.246	348
65	3	2	1	2	4.194	387
66	3	2	1	3	4.823	495
67	3	2	2	1	4.499	502
68	3	2	2	2	4.39	542
69	3	2	2	3	7	880
70	3	2	3	1	7.813	455
71	3	2	3	2	5.946	369
72	3	2	3	3	8.817	649
73	3	3	1	1	3.473	414
74	3	3	1	2	4.178	429
75	3	3	1	3	4.958	552
76	3	3	2	1	3.801	426
77	3	3	2	2	4.645	618
78	3	3	2	3	5.424	728
79	3	3	3	1	4.303	337
80	3	3	3	2	11.076	593
81	3	3	3	3	9.17	651

Table 5.3: Results of method 1 and 2 for sensor 2

SENSOR2						
Measurement	Slope	Qw	Dm	Qs	Method 1	Method 2
1	1	1	1	1	3.25	353
2	1	1	1	2	4.891	627
3	1	1	1	3	6.222	741
4	1	1	2	1	4.651	518
5	1	1	2	2	6.805	865
6	1	1	2	3	6.995	1005
7	1	1	3	1	5.771	360
8	1	1	3	2	6.189	578
9	1	1	3	3	10.281	838
10	1	2	1	1	3.131	420
11	1	2	1	2	4.792	643
12	1	2	1	3	4.505	577
13	1	2	2	1	3.535	443
14	1	2	2	2	5.368	595
15	1	2	2	3	6.378	777
16	1	2	3	1	3.953	362
17	1	2	3	2	4.702	444
18	1	2	3	3	8.819	633
19	1	3	1	1	2.995	326
20	1	3	1	2	3.669	359
21	1	3	1	3	4.441	559
22	1	3	2	1	2.281	314
23	1	3	2	2	4.009	546
24	1	3	2	3	4.965	646
25	1	3	3	1	6.394	395
26	1	3	3	2	4.633	434
27	1	3	3	3	6.01	522
28	2	1	1	1	5.486	744
29	2	1	1	2	5.391	760
30	2	1	1	3	6.49	821
31	2	1	2	1	7.196	747
32	2	1	2	2	7.471	990
33	2	1	2	3	8.916	1237
34	2	1	3	1	3.975	411
35	2	1	3	2	5.25	522
36	2	1	3	3	9.288	776
37	2	2	1	1	3.973	521
38	2	2	1	2	4.528	581
39	2	2	1	3	5.137	704
40	2	2	2	1	4.826	536

Table 5.4: Results of method 1 and 2 for sensor 2

Measurement	Slope	Qw	Dm	Qs	Method 1	Method 2
41	2	2	2	2	4.909	670
42	2	2	2	3	6.202	832
43	2	2	3	1	5.688	443
44	2	2	3	2	6.313	528
45	2	2	3	3	8.893	731
46	2	3	1	1	3.713	471
47	2	3	1	2	3.917	507
48	2	3	1	3	4.57	646
49	2	3	2	1	4.613	692
50	2	3	2	2	5.319	753
51	2	3	2	3	4.319	612
52	2	3	3	1	4.978	580
53	2	3	3	2	7.905	548
54	2	3	3	3	9.252	726
55	3	1	1	1	1.316	167
56	3	1	1	2	3.157	321
57	3	1	1	3	3.498	477
58	3	1	2	1	2.565	320
59	3	1	2	2	3.595	503
60	3	1	2	3	4.113	553
61	3	1	3	1	3.936	301
62	3	1	3	2	3.617	404
63	3	1	3	3	7.996	658
64	3	2	1	1	3.034	306
65	3	2	1	2	2.624	279
66	3	2	1	3	2.974	272
67	3	2	2	1	3.453	460
68	3	2	2	2	3.706	532
69	3	2	2	3	4.488	694
70	3	2	3	1	3.617	295
71	3	2	3	2	3.796	410
72	3	2	3	3	6.752	584
73	3	3	1	1	1.52	197
74	3	3	1	2	2.805	259
75	3	3	1	3	4.234	400
76	3	3	2	1	2.68	352
77	3	3	2	2	2.114	319
78	3	3	2	3	3.576	485
79	3	3	3	1	3.317	272
80	3	3	3	2	4.552	353
81	3	3	3	3	6.523	548

5.2 Results of Method 1

According to method 1 i.e. integral under curve, the graphs for all the 81 test cases for the 2 sensors are constructed. There are some discoveries from method 1 graphical representation of the raw results. This leads one to understand the fact hidden behind the single impact associated to the parameters governing it. The description below shows the information behind every line in the figures;

cs	Total average value of the test
(blue)	Orignal signal of sensor
(orange)	Average of signals at specific time interval
(green)	Total average of signals at certain time

5.2.1 Sensor 1

Figures 5.1 and 5.2 are the examples with same slope, water discharge and particle discharge but with different particle size. The figures show that, irrespective of the particle sizes, the magnitude of the average integral is almost the same (≈6m/s^2). Having same results of the sensors makes it difficult to predict the sediment particles size, but with the help of graphical representation, it is clear that the magnitude range is higher with larger particle. In these figures the magnitude for small particle ranges between 20 – 40, whereas for medium size it rises to 50 to 100+.

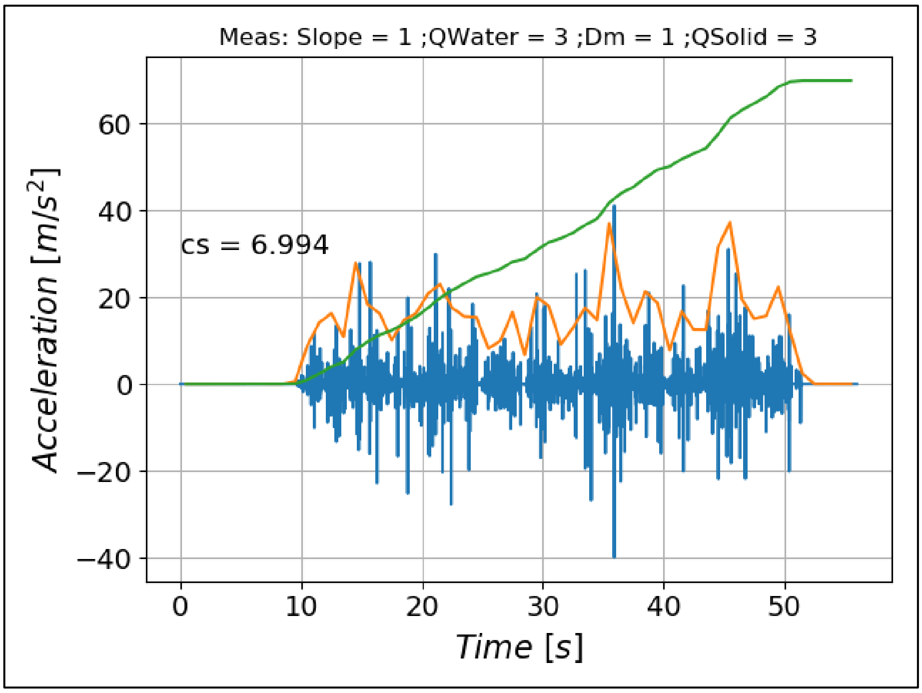

Figure 5.1: Result graph of method 1 for sensor 1, with parameter combination: Sl1.Qw3.Dm1.Qs3

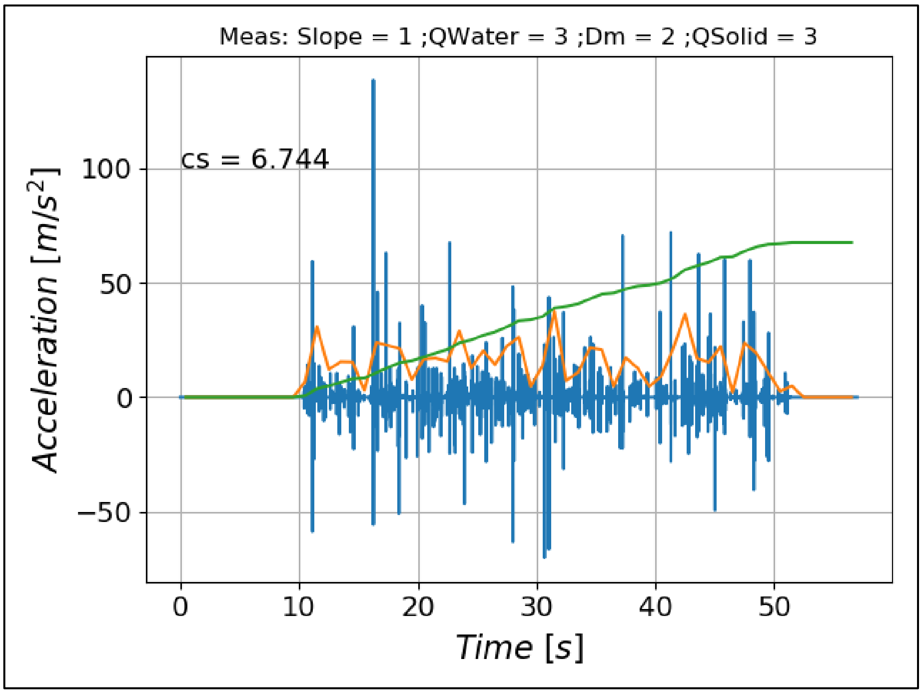

Figure 5.2: Result graph of method 1 for sensor 1, with parameter combination: Sl1.Qw3.Dm2.Qs3

Figure 5.3 and 5.4 also elaborate the same explanation given earlier. Both particles have same average integral values. Yet, both could be differentiated with the help of signal magnitude. The particle small has magnitude ranging between 20 – 60. However, the magnitude of medium size particle is between 40 – 100+.

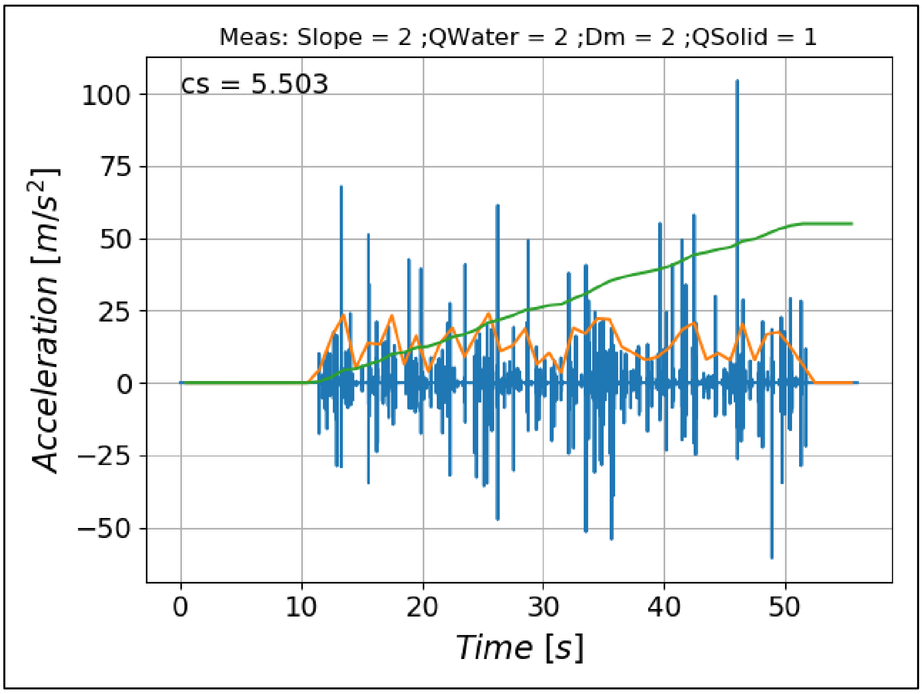

Figure 5.3: Result graph of method 1 for sensor 1, with parameter combination: Sl2.Qw2.Dm2.Qs1

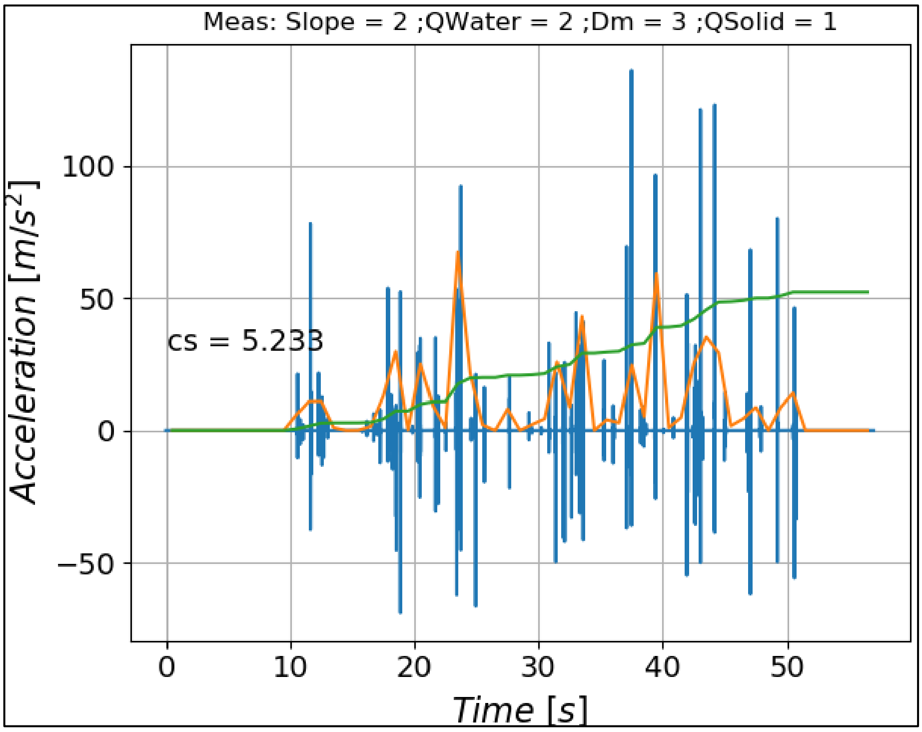

Figure 5.4: Result graph of method 1 for sensor 1, with parameter combination: Sl2.Qw2.Dm3.Qs1

In Figure 5.5.and 5.6, the highest magnitude for the small particle size Dm1 is 65 and the larger particle Dm3 has the highest magnitude of 100+.

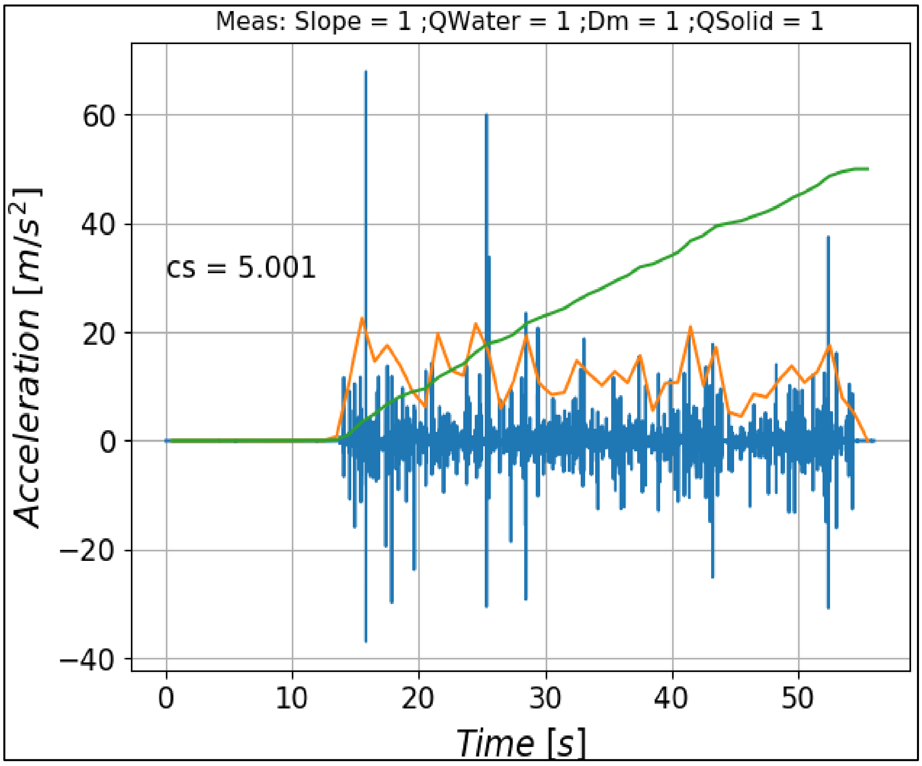

Figure 5.5: Result graph of method 1 for sensor 1, with parameter combination: Sl1.Qw1.Dm1.Qs1

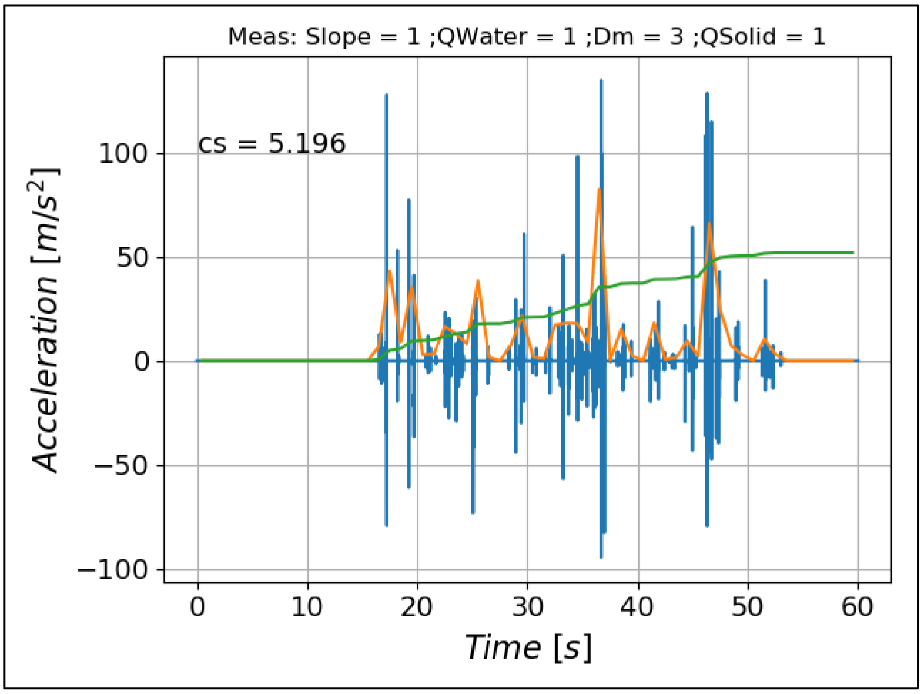

Figure 5.6: Result graph of method 1 for sensor 1, with parameter combination: Sl1.Qw1.Dm3.Qs1

5.2.2 Sensor 2

To counter check the scenario, the results from sensor 2 are also taken into consideration. Figures 5.7, 5.8 shown below are clear examples;

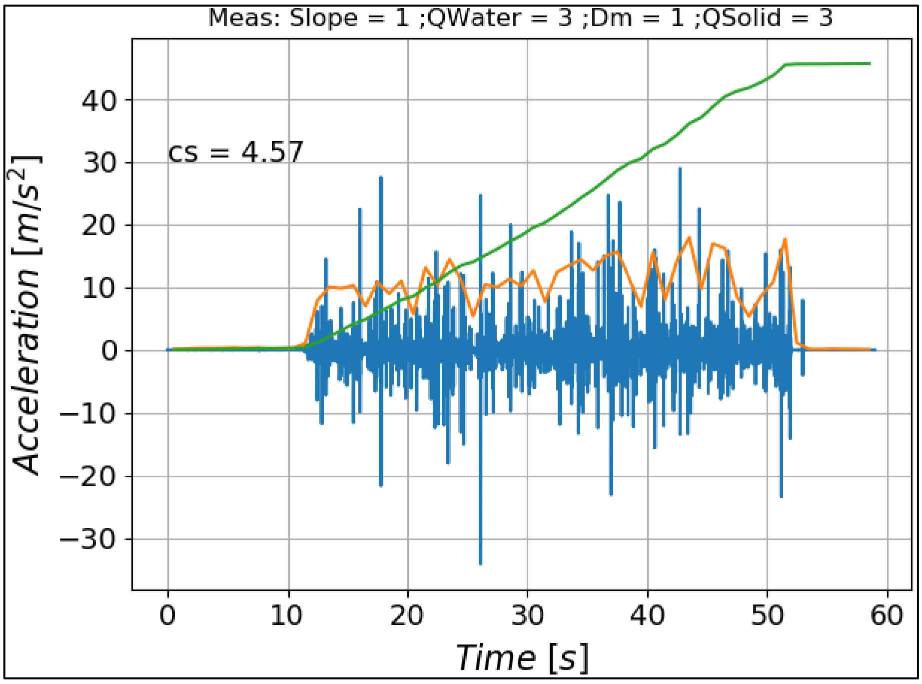

Figure 5.7: Result graph of method 1 for sensor 2, with parameter combination: Sl1.Qw3.Dm1.Qs3

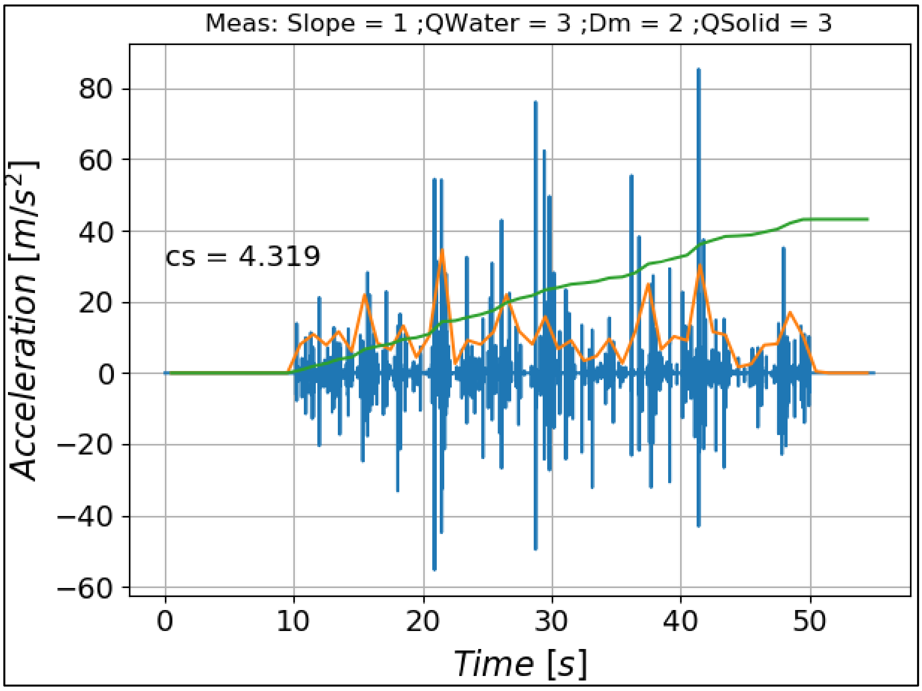

Figure 5.8: Result graph of method 1 for sensor 2, with parameter combination: Sl1.Qw3.Dm2.Qs3

The average integral values for Figure 5.7 and 5.8 are almost similar. Nevertheless, the magnitudes of the impact are totally different. By keeping the other parameters fixed and just changing the sediment grain size, the amplitude for smaller particle Dm1 ranges between 10 – 30. On the other hand, the medium size particle ranges 20 – 80. Followed by Figure 5.9-5.12, this hypothesis is proved by all particle sizes and almost every tests.

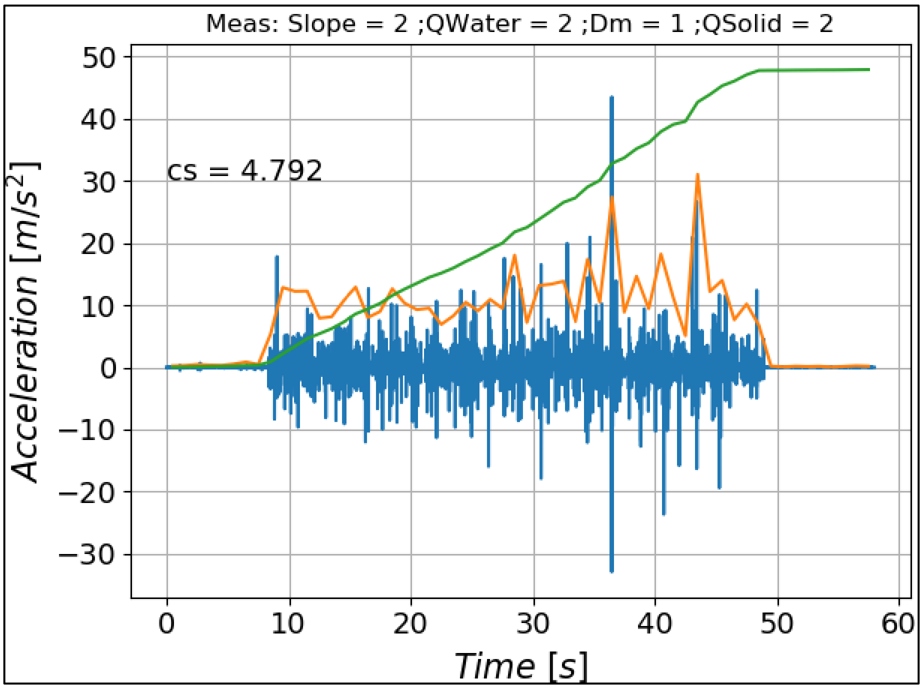

Figure 5.9: Result graph of method 1 for sensor 2, with parameter combination: Sl2.Qw2.Dm1.Qs2

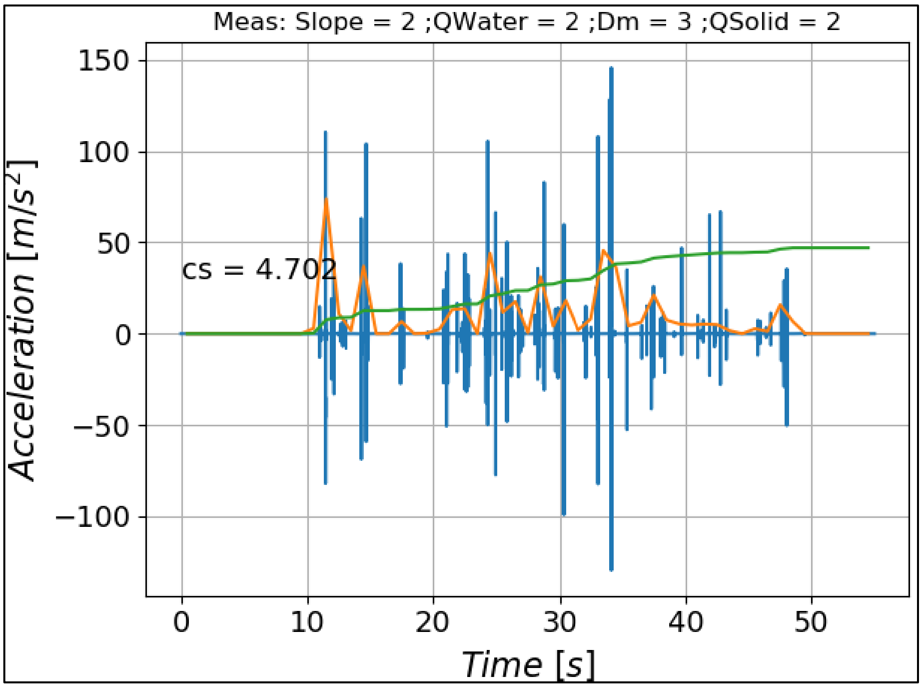

Figure 5.10: Result graph of method 1 for sensor 2, with parameter combination: Sl2.Qw2.Dm3.Qs2

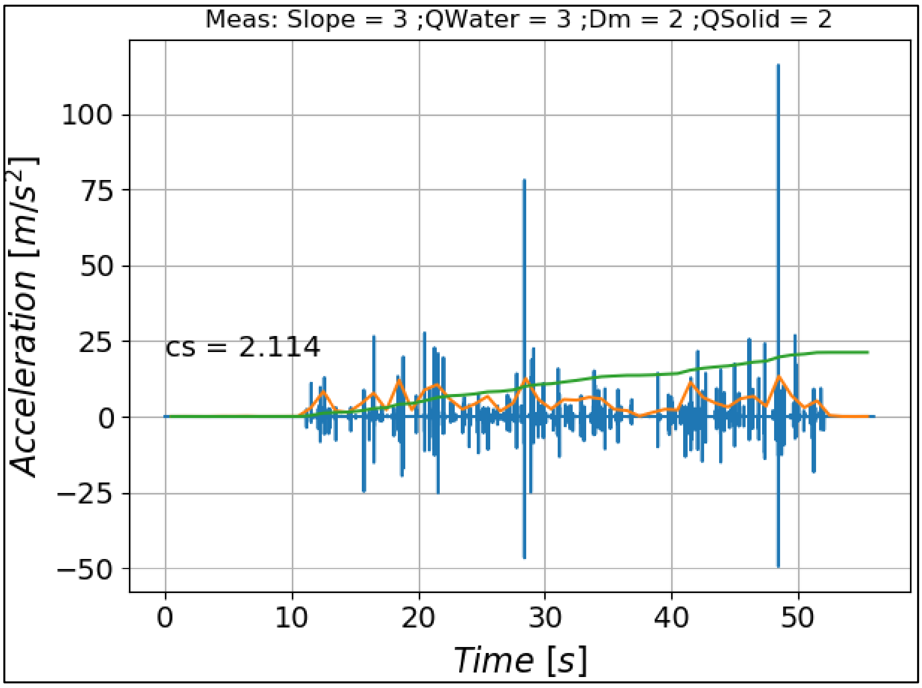

Figure 5.11: Result graph of method 1 for sensor 2, with parameter combination: Sl3.Qw3.Dm2.Qs2

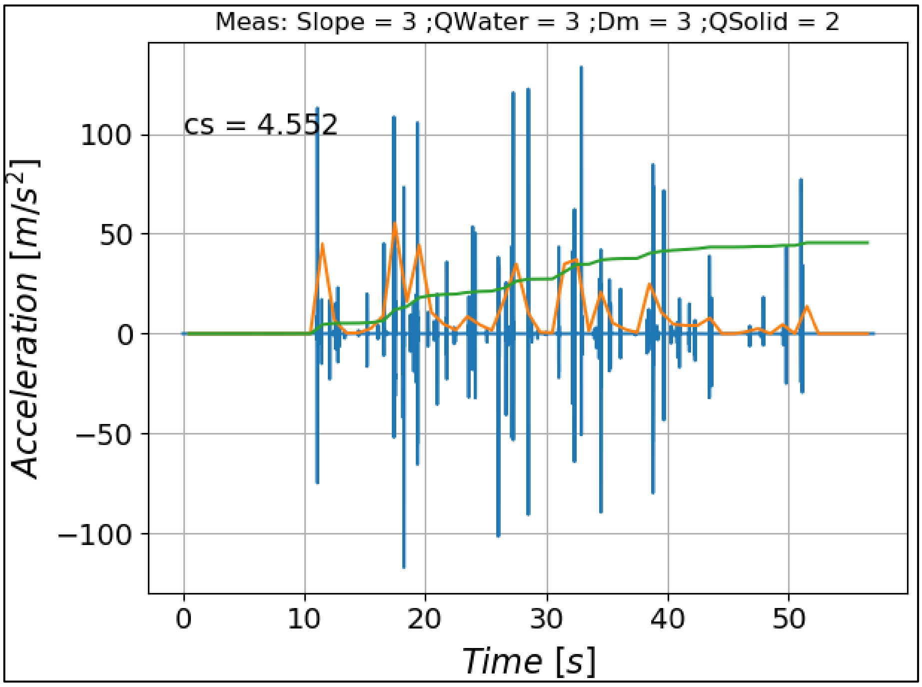

Figure 5.12: Result graph of method 1 for sensor 2, with parameter combination: Sl3.Qw3.Dm3.Qs2

5.3 Result Method 2

Method 2 is about the sum of all peak counts in a test. It is observed that throughout the procedure, as the sediment discharge Qs is increased the number of peak counts also increases. While the remaining parameters are kept constant. As proof, Figures 5.13 – 5.18 from sensor 1 and 2 are shown as follow;

5.3.1 Sensor 1

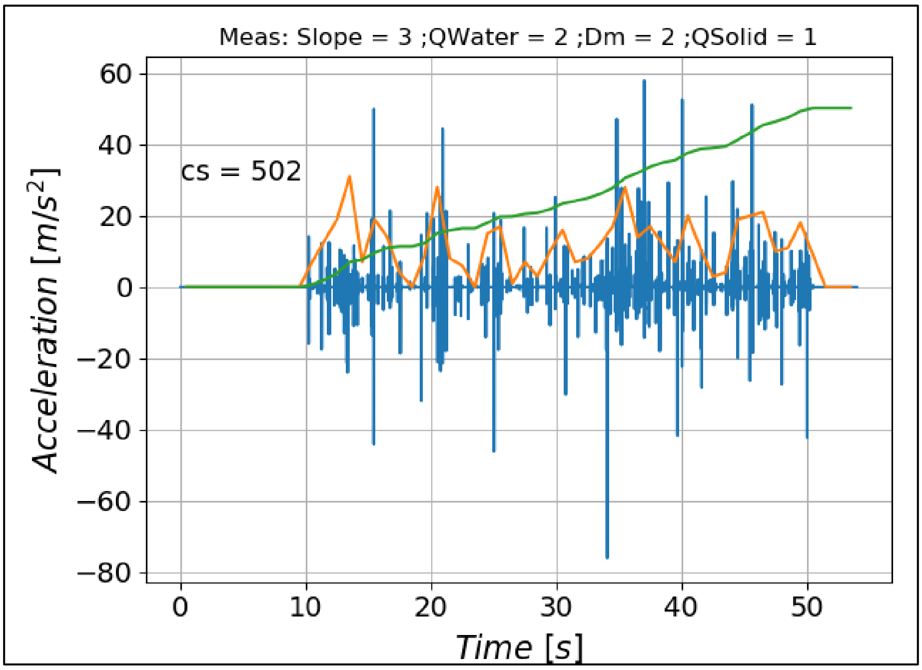

Figure 5.13: Result graph of method 2 for sensor 1, with parameter combination: Sl3.Qw2.Dm2.Qs1

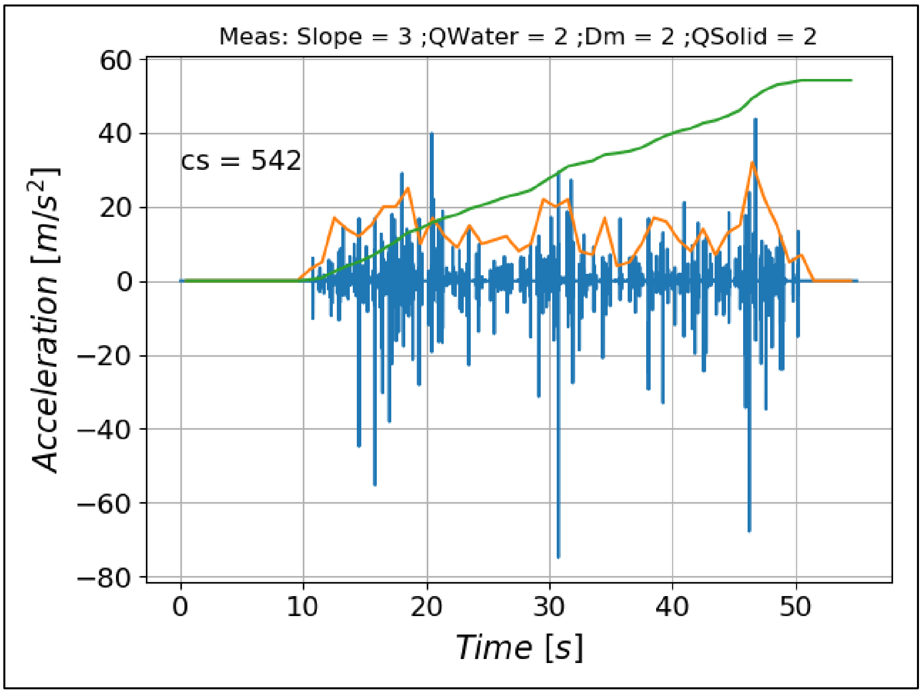

Figure 5.14: Result graph of method 2 for sensor 1, with parameter combination: Sl3.Qw2.Dm2.Qs2

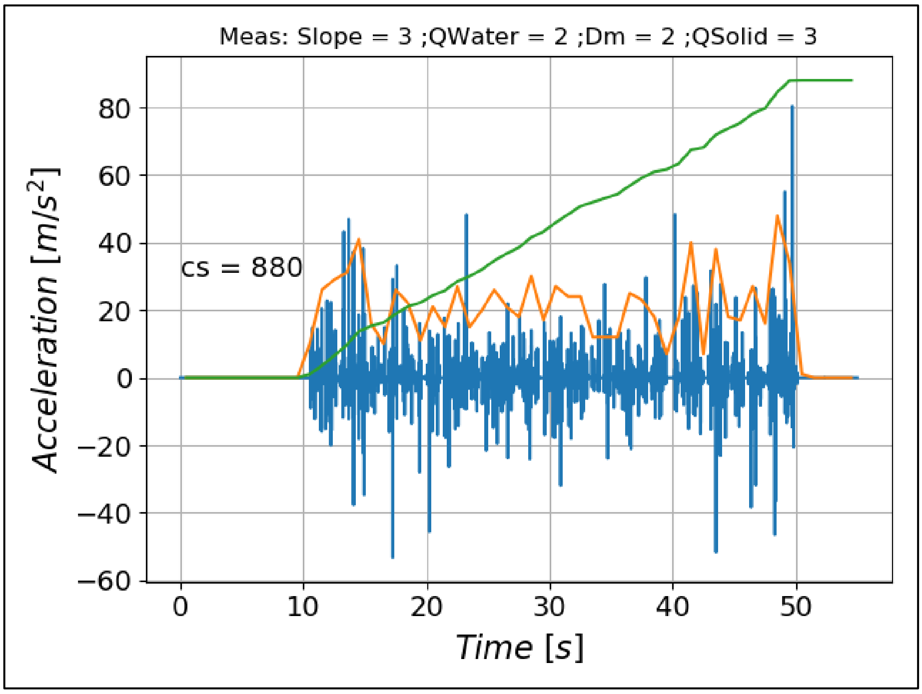

Figure 5.15: Result graph of method 2 for sensor 1, with parameter combination: Sl3.Qw2.Dm2.Qs3

5.3.2 Sensor 2

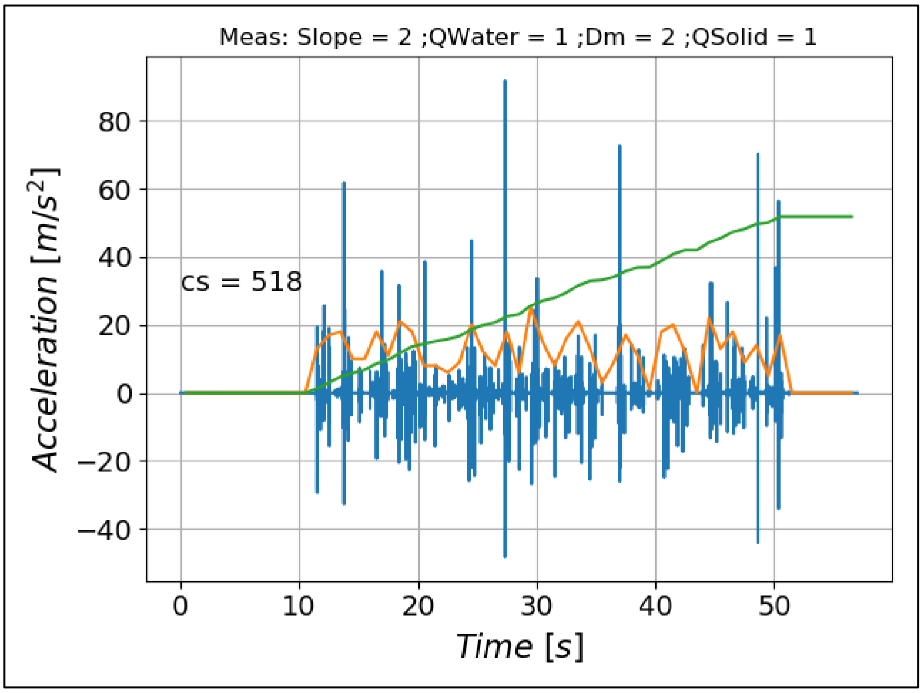

Figure 5.16: Result graph of method 2 for sensor 2, with parameter combination: Sl2.Qw1.Dm2.Qs1

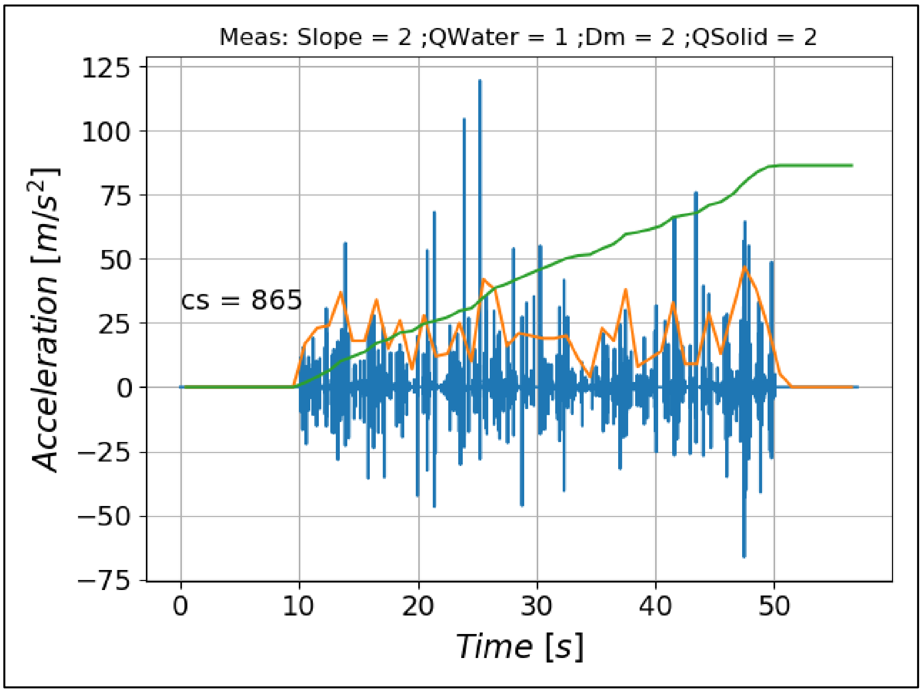

Figure 5.17: Result graph of method 2 for sensor 2, with parameter combination: Sl2.Qw1.Dm2.Qs2

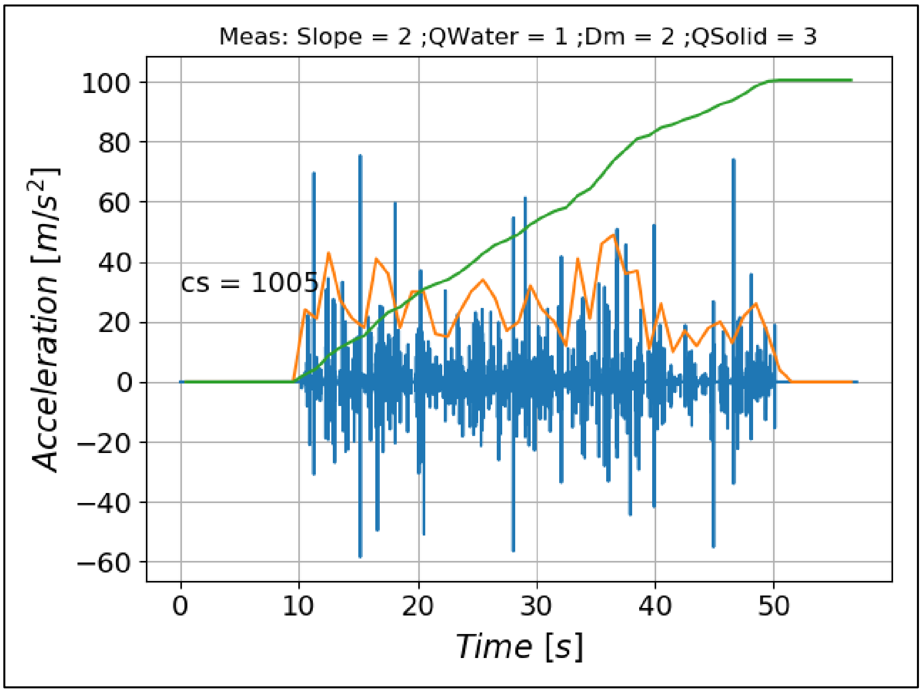

Figure 5.18: Result graph of method 2 for sensor 2, with parameter combination: Sl2.Qw1.Dm2.Qs3

In the above figures, the slope of the section, water discharge and particle size are kept constant. With the increase in sediment discharge Qs in each test there is an increase in the peak counts. This regime is followed in most of the cases as well as both the sensors.

5.4 Analysis of Results: Individual Parameter

The results analysis is done as explained in chapter 4. Therefore, every parameter has been evaluated individually. For every parameter, the analysis is made by placing them on every position of the session, period and variable. Following which, the graphical representation proves the influence of every parameter throughout the process.

5.4.1 Analysis of Water Discharge Qw

Water discharge has a vital role in sediment bedload transport. Therefore, the analysis for water discharge is done as follows;

5.4.1.1 As Session

According to Table 5.5, there are three sessions of water discharge Qw in every system of slope. It is observed that the arrangement of remaining parameters (i.e. period and variables) is same in every session which allows us to take an average of the whole session. In this way the average of every session is placed in a table to find out the outcome.

Table 5.5: three sessions of Water Discharge Qw in a system of Slope.

System	Session	Period	Variable
Slope 14°	**Qw1**	Dm1	Qs1
Slope 14°	**Qw1**	Dm1	Qs2
Slope 14°	**Qw1**	Dm1	Qs3
Slope 14°	**Qw1**	Dm2	Qs1
Slope 14°	**Qw1**	Dm2	Qs2
Slope 14°	**Qw1**	Dm2	Qs3
Slope 14°	**Qw1**	Dm3	Qs1
Slope 14°	**Qw1**	Dm3	Qs2
Slope 14°	**Qw1**	Dm3	Qs3
Slope 14°	**Qw2**	Dm1	Qs1
Slope 14°	**Qw2**	Dm1	Qs2
Slope 14°	**Qw2**	Dm1	Qs3
Slope 14°	**Qw2**	Dm2	Qs1
Slope 14°	**Qw2**	Dm2	Qs2
Slope 14°	**Qw2**	Dm2	Qs3
Slope 14°	**Qw2**	Dm3	Qs1
Slope 14°	**Qw2**	Dm3	Qs2
Slope 14°	**Qw2**	Dm3	Qs3
Slope 14°	**Qw3**	Dm1	Qs1
Slope 14°	**Qw3**	Dm1	Qs2
Slope 14°	**Qw3**	Dm1	Qs3
Slope 14°	**Qw3**	Dm2	Qs1
Slope 14°	**Qw3**	Dm2	Qs2
Slope 14°	**Qw3**	Dm2	Qs3
Slope 14°	**Qw3**	Dm3	Qs1
Slope 14°	**Qw3**	Dm3	Qs2
Slope 14°	**Qw3**	Dm3	Qs3

Table 5.6 - 5.9 shows the average values from two sensors and for both methods. The rows that are shaded blue, show a track that is repeated in most of the tests. It is observed that as the discharge Qw increases in every session, there is a decrease in average values along the rows.

Table 5.6: Session of water discharge Qw of sensor 1 for method 1

	Sensor 1 Method 1		
	Avg. at Qw1	**Avg. at Qw2**	**Avg. at Qw3**
Slope 1 = 14°	8.317	6.422	6.421
Slope 2 = 10°	8.579	7.982	7.014
Slope 3 = 6°	6.021	5.636	5.670

Table 5.7: Session of water discharge Qw of sensor 1 for method 2

	Sensor 1 Method 2		
	Avg. at Qw1	**Avg. at Qw2**	**Avg. at Qw3**
Slope 1 = 14°	778.333	586.333	534.889
Slope 2 = 10°	906.556	742.667	656.778
Slope 3 = 6°	600.333	514.111	527.556

Table 5.8: Session of water discharge Qw of sensor 2 for method

	Sensor 2 Method 1		
	Avg. at Qw1	**Avg. at Qw2**	**Avg. at Qw3**
Slope 1 = 14°	6.117	5.020	4.377
Slope 2 = 10°	6.607	5.608	5.398
Slope 3 = 6°	3.755	3.827	3.480

Table 5.9: Session of water discharge Qw of sensor 2 for method

	Sensor 2 Method 2		
	Avg. at Qw1	**Avg. at Qw2**	**Avg. at Qw3**
Slope 1 = 14°	653.889	543.778	455.667
Slope 2 = 10°	778.667	616.222	615.000
Slope 3 = 6°	411.556	425.778	353.889

What is interesting is that this regime is followed in Slope 1 and Slope 2. However, Slope 3 which is the most gradual slope, does not show the same track. There could be certain assumptions made for this finding:

i. The values for slope 3 are totally random, which means it's hard to track the sediment transport in gradual slopes.

ii. The saltation movement of particles can cause the sediments to jump over the sensors and completely missing them. This can be the reason for random values on slope 3 with all kind of water discharge.

5.4.1.2 As Period

System	Session	Period	Variable
Slope	Dm	**Qw**	Qs

To analyse the water discharge on the basis of period, all the figures for both the methods are displayed. In these figures, there are three segments of lines. Each segment represents period of water discharge. 1st line is Qw1, 2nd is Qw2 and 3rd is Qw3 respectively. When these lines are observed, it is understandable that every time the new period is started, the preceding line is higher than the succeeding line. This shows, the average value for every period decreases with the increase in water discharge. The following Figure 5.19 – 5.23 shows the phenomenon for method 1;

- **Method 1**

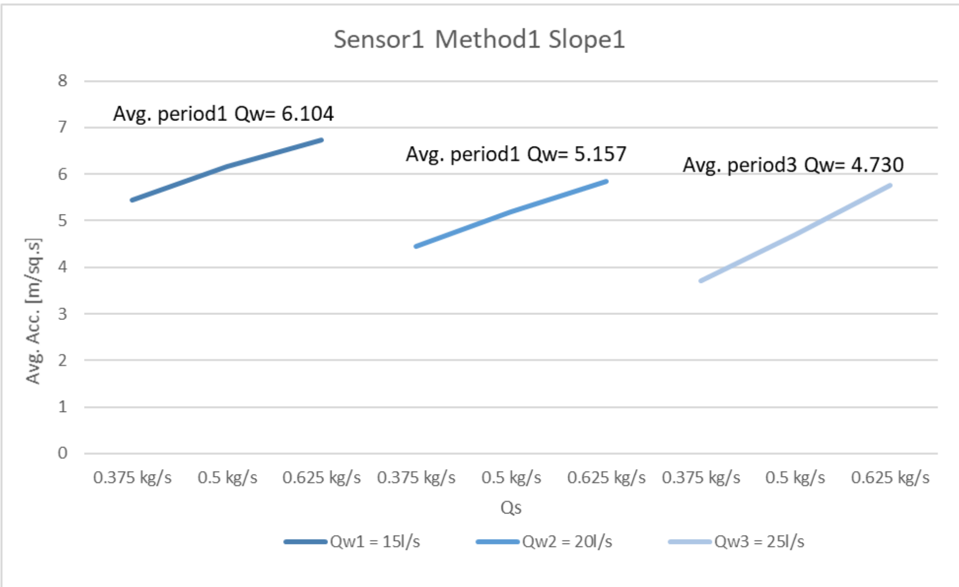

Figure 5.19: Plotting result of sensor1 method1 and slope1, with three periods of water discharge

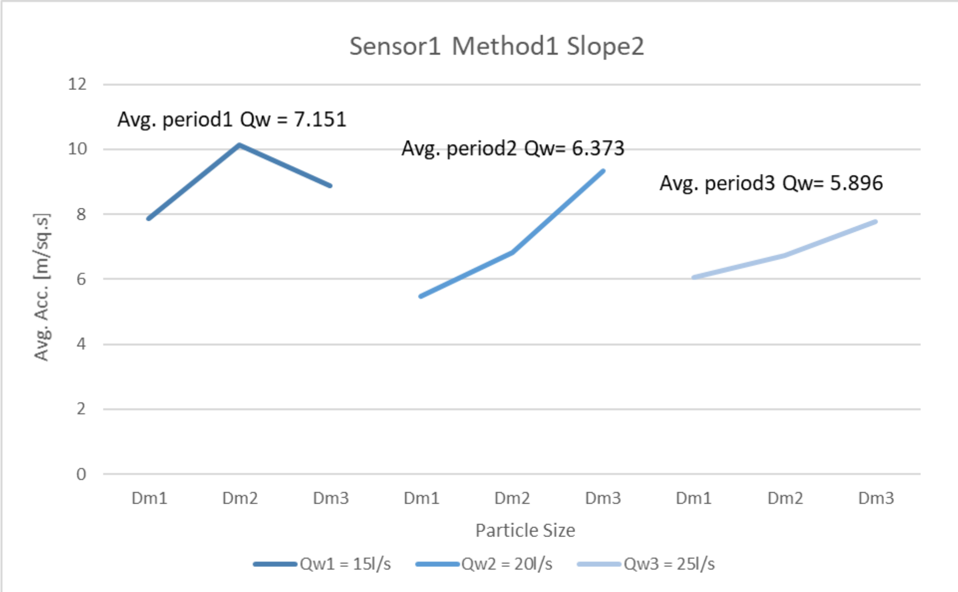

Figure 5.20: Plotting result of sensor1 method1 and slope2, with three periods of water discharge

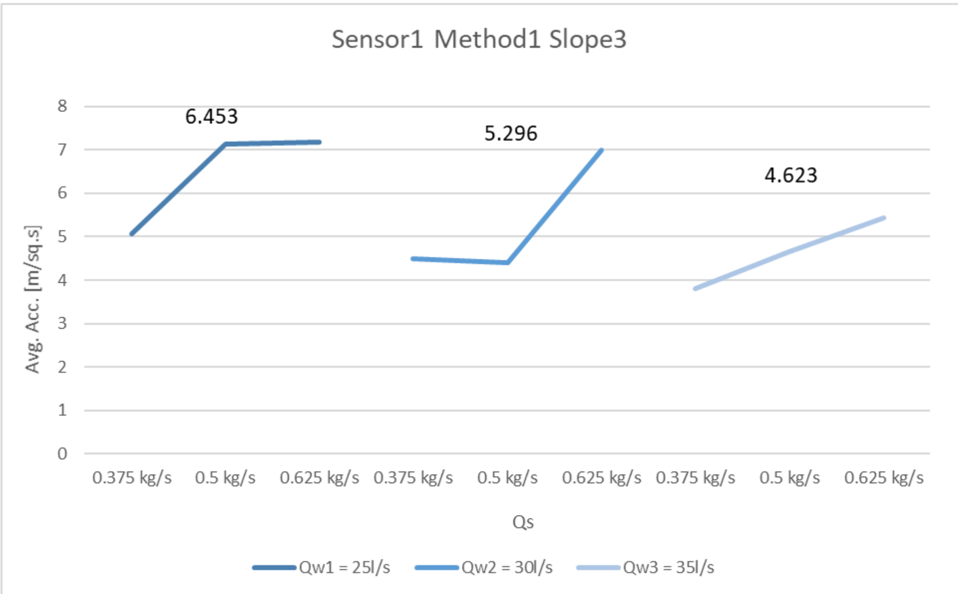

Figure 5.21: Plotting result of sensor1 method1 and slope3, with three periods of water discharge

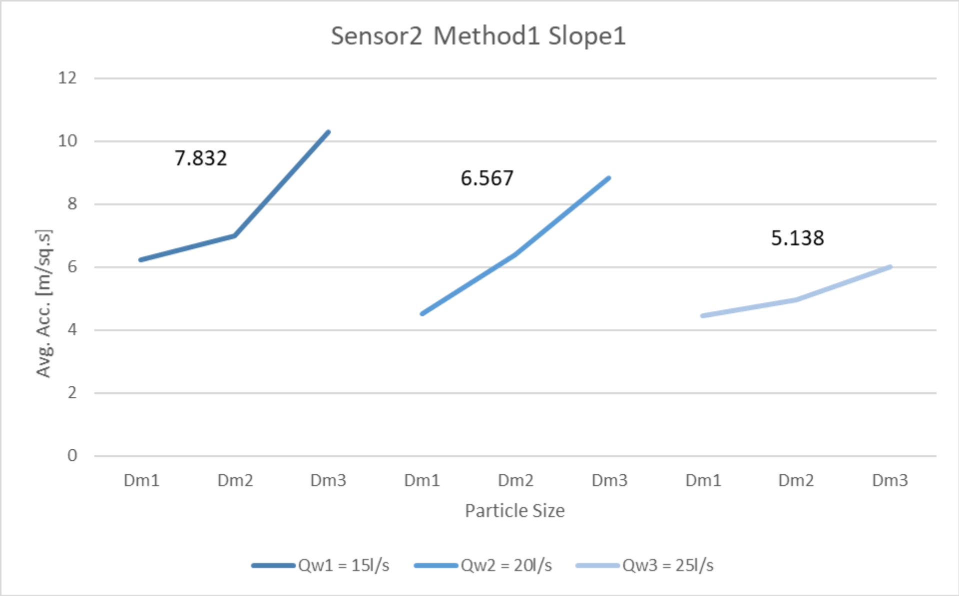

Figure 5.22: Plotting result of sensor2 method1 and slope1, with three periods of water discharge

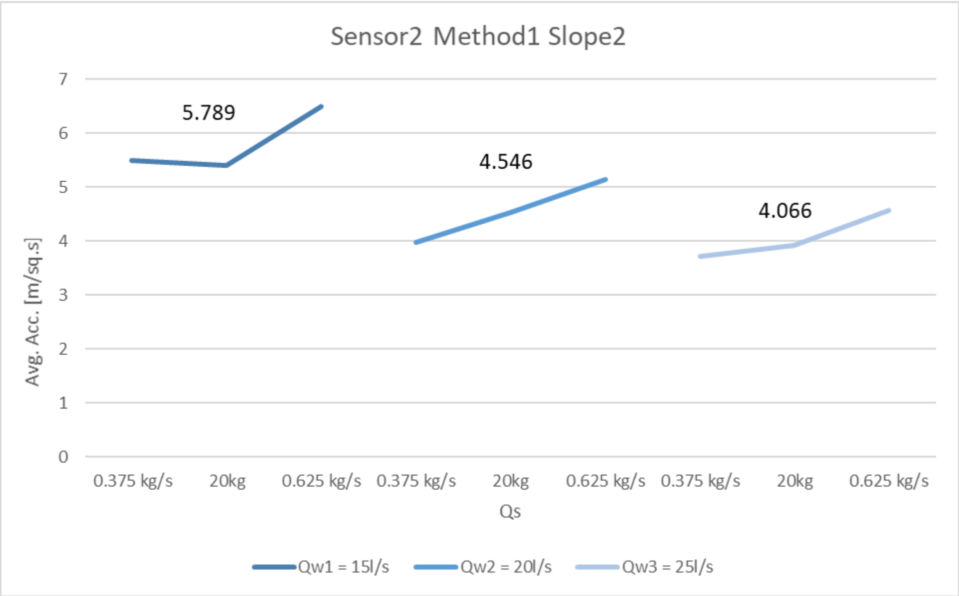

Figure 5.23: Plotting result of sensor2 method1 and slope2, with three periods of water discharge

- **Method 2**

Followed by method 1, method 2 also represents the same logic for water discharge influence on peak counts. The lowering of line segment along the figure shows that there are lesser number of peaks counted with the increment in water discharge. Moreover, every line segment has three variable points, that shows the track of a variable within the period. For now, our concentration is only to track the movement between the periods, independent of variables. Figure 5.24 – 5.29 represent the analysis for method 2;

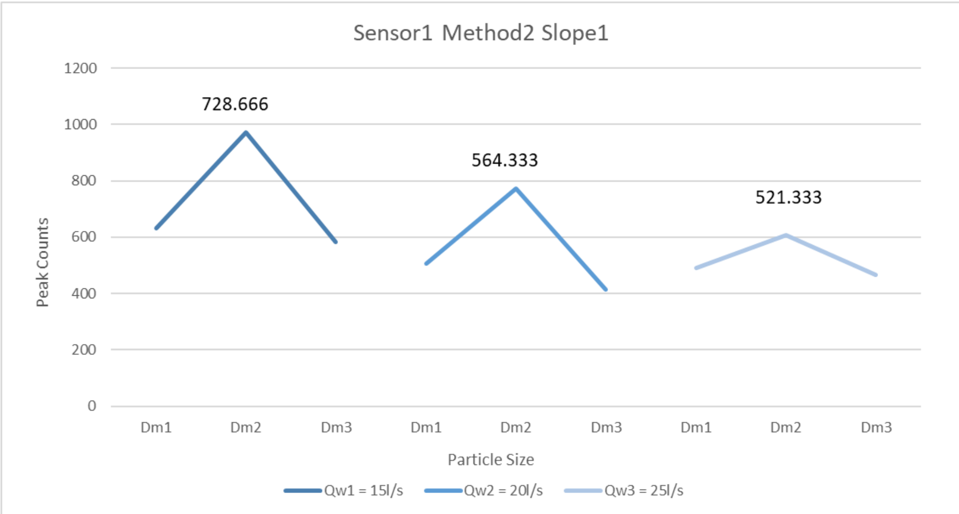

Figure 5.24: Plotting result of sensor1 method2 and slope1, with three periods of water discharge

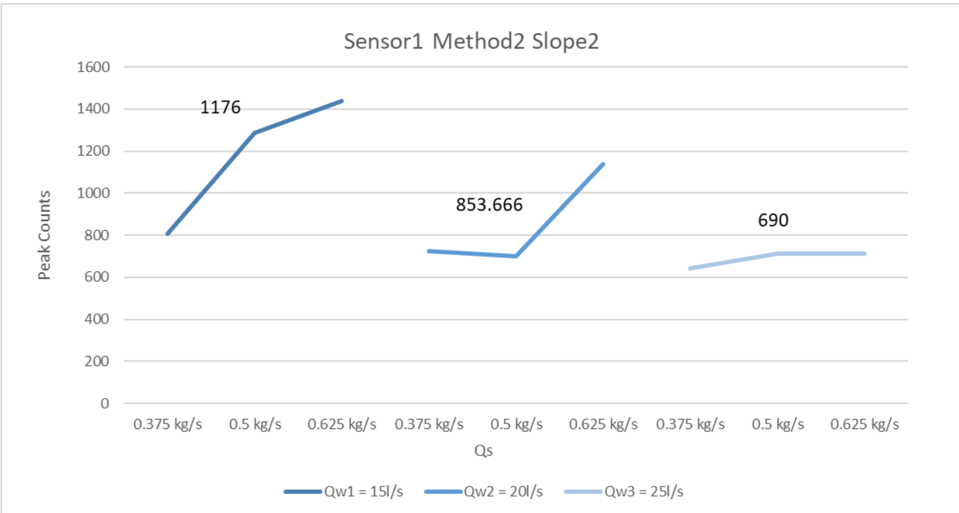

Figure 5.25: Plotting result of sensor2 method1 and slope2, with three periods of water discharge

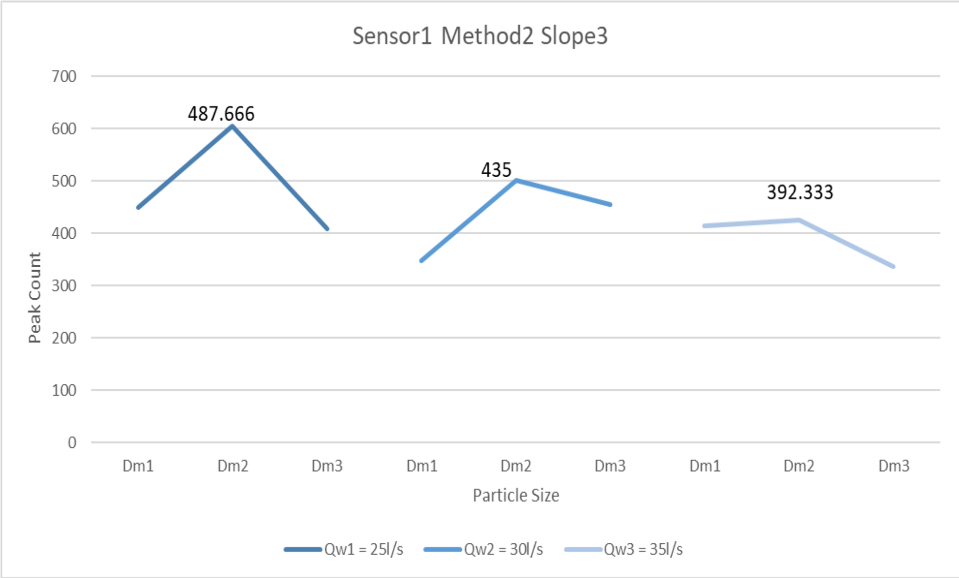

Figure 5.26: Plotting result of sensor1 method2 and slope3, with three periods of water discharge

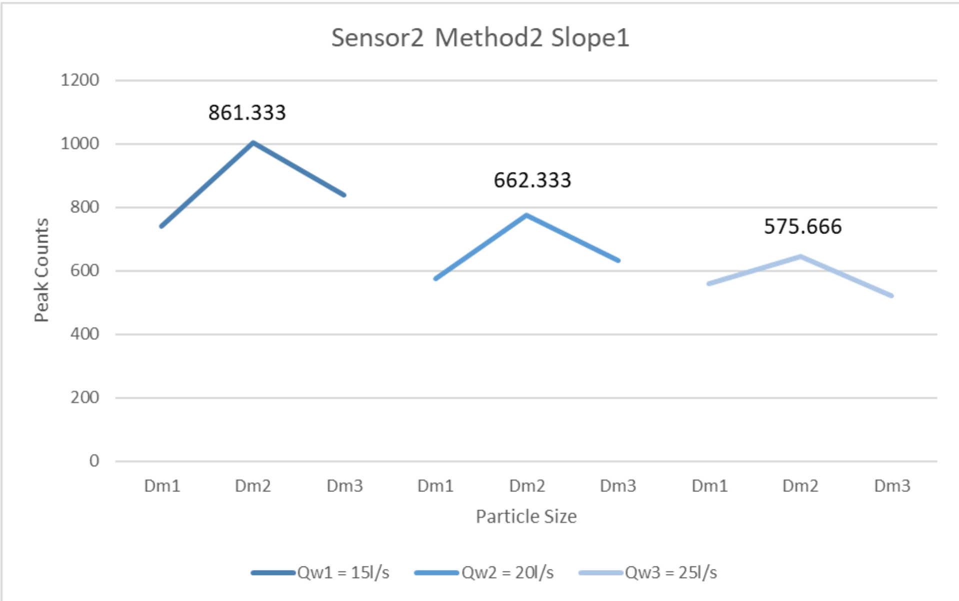

Figure 5.27: Plotting result of sensor2 method2 and slope1, with three periods of water discharge

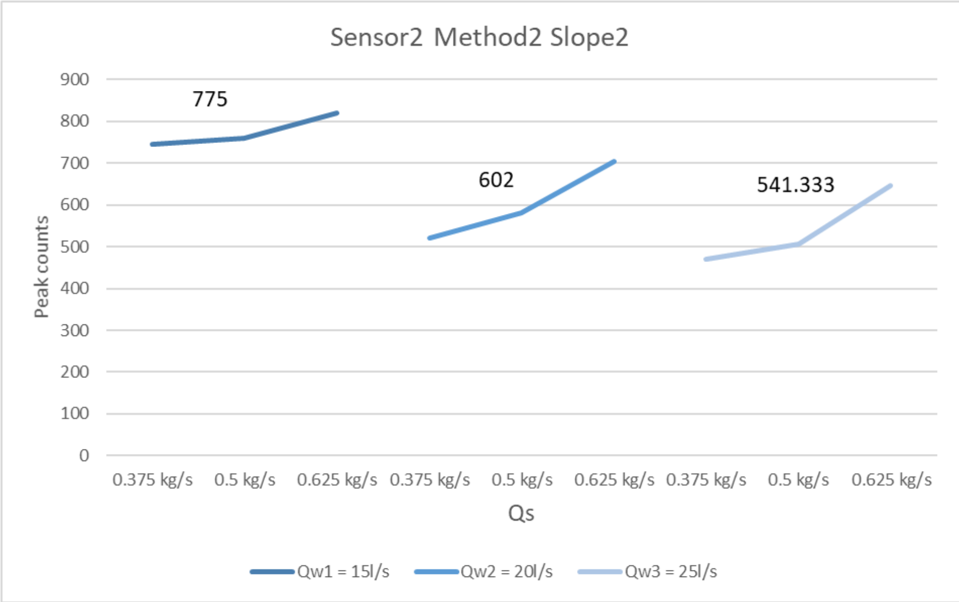

Figure 5.28: Plotting result of sensor2 method2 and slope2, with three periods of water discharge

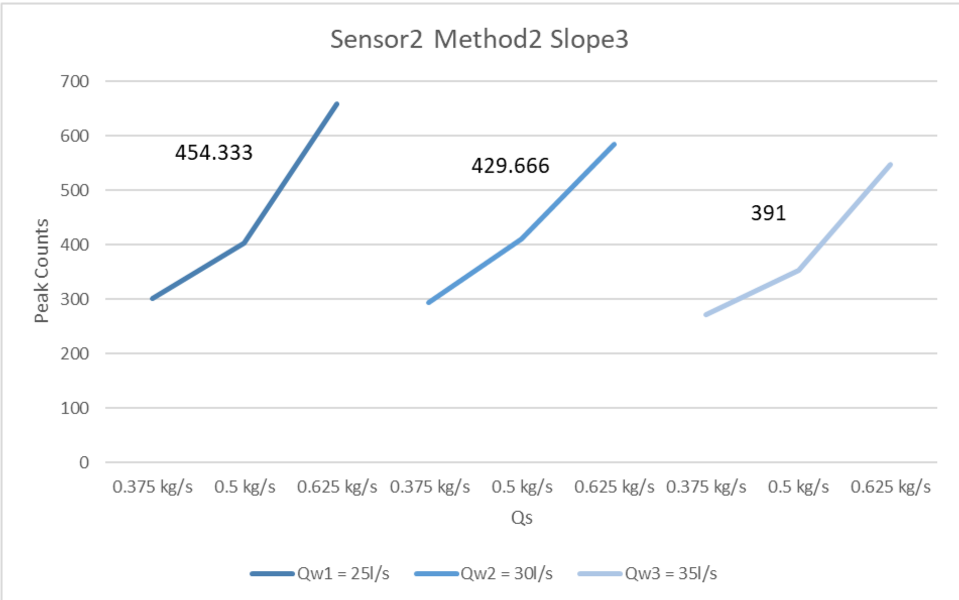

Figure 5.29: Plotting result of sensor2 method2 and slope3, with three periods of water discharge

5.4.1.3 As Variable

System	Session	Period	Variable
Slope	Dm	Qs	**Qw**

In this part of the analysis, the water discharge is evaluated as a variable. In this stage of analysis, the parameter is evaluated individually. The effect of parameter on sediment transport is observed directly by these three points in every period. It is now evident that the role of water discharge is inversely proportional to the bed load transportation. In every period, the digits fall down with rise in discharge.

- **Method 1**

The result pathway of water discharge in slope 3 for both the sensors and both methods do not show any significance. Therefore, it is hard to say that effect of discharge on sediment transport shall also be same in the gradual slopes. Figure 5.30 – 5.33 show the example;

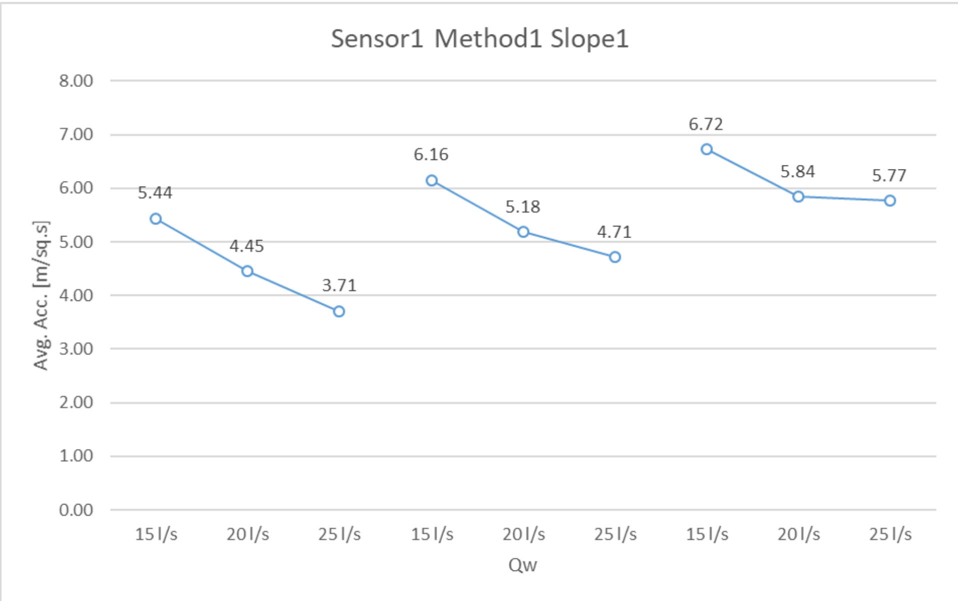

Figure 5.30: Plotting result of sensor1 method1 and slope1, with three variables of water discharge

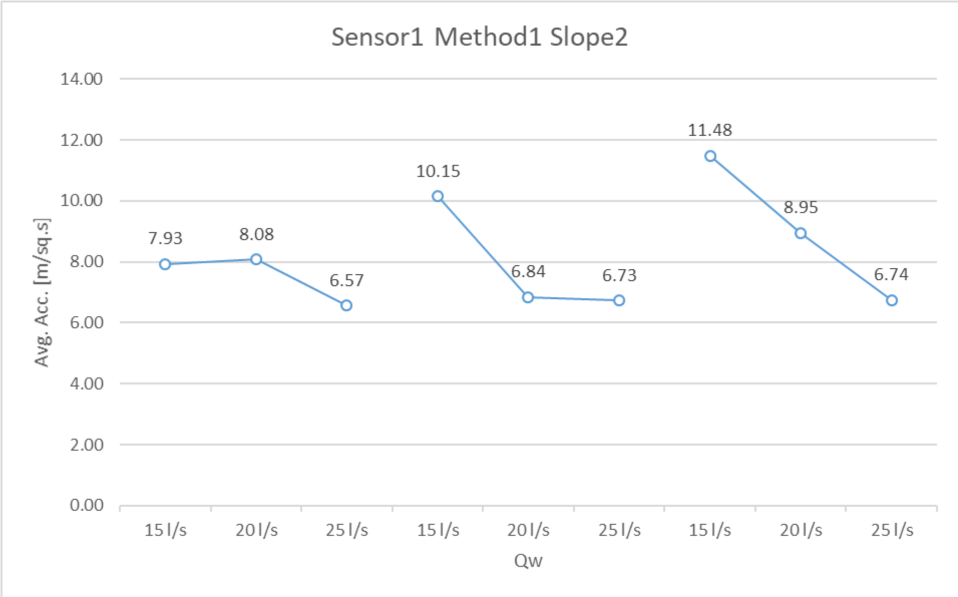

Figure 5.31: Plotting result of sensor1 method1 and slope2, with three variables of water discharge

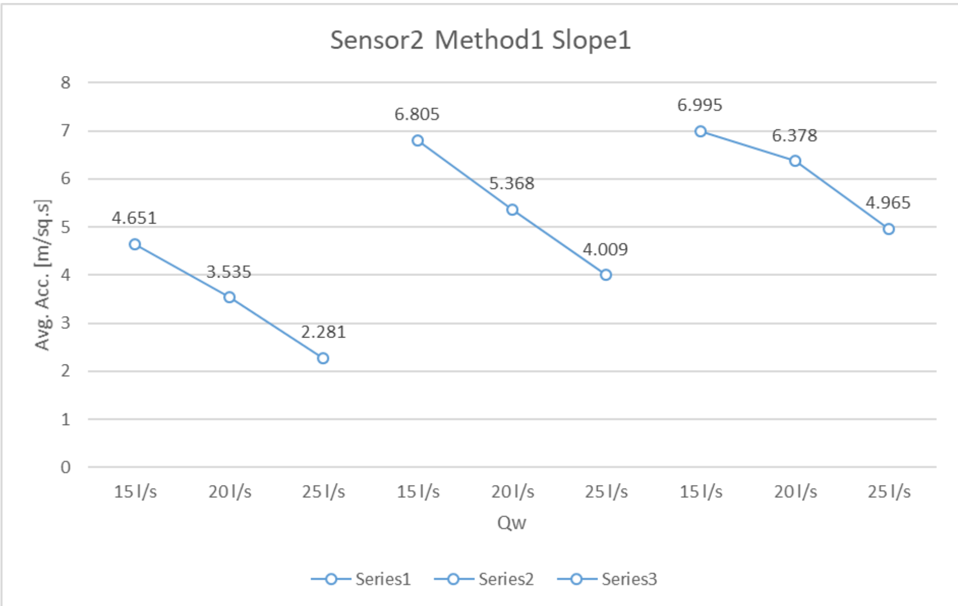

Figure 5.32: Plotting result of sensor2 method1 and slope1, with three variables of water discharge

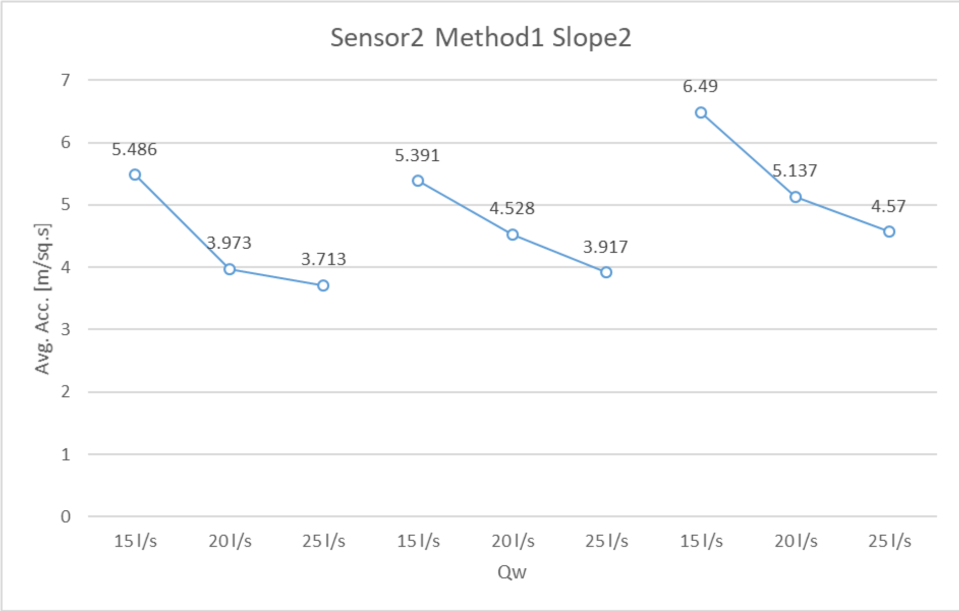

Figure 5.33: Plotting result of sensor2 method1 and slope2, with three variables of water discharge

- **Method 2**

For this method, the outcomes from sensor 1 are totally random and unstable. Therefore, results from sensor 2 are displayed only, shown in Figures 5.34 and 5.35. It is assumed, that the particles totally missed the sensor due to aggressive movement of sediment in the flow.

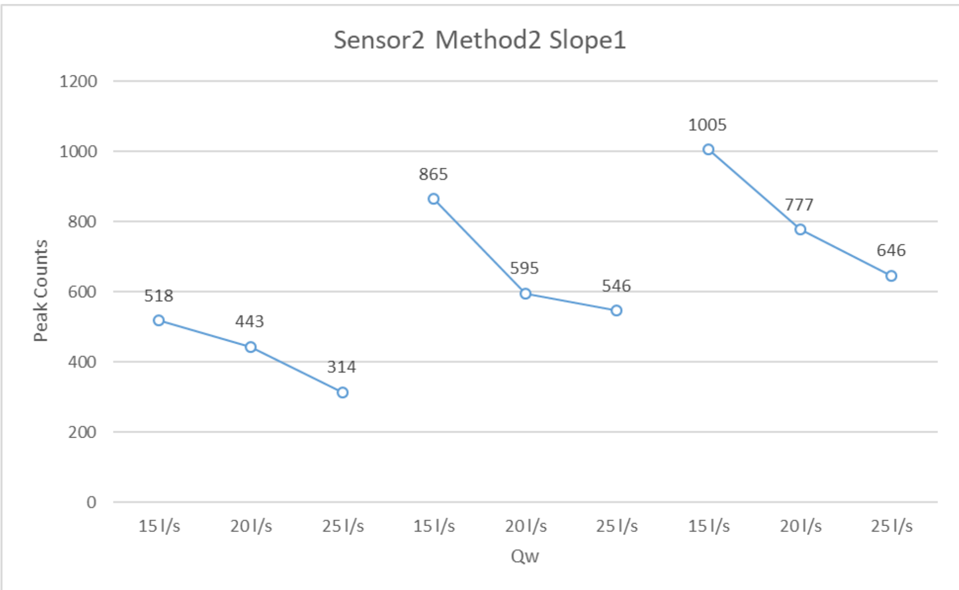

Figure 5.34: Plotting result of sensor2 method2 and slope1, with three variables of water discharge

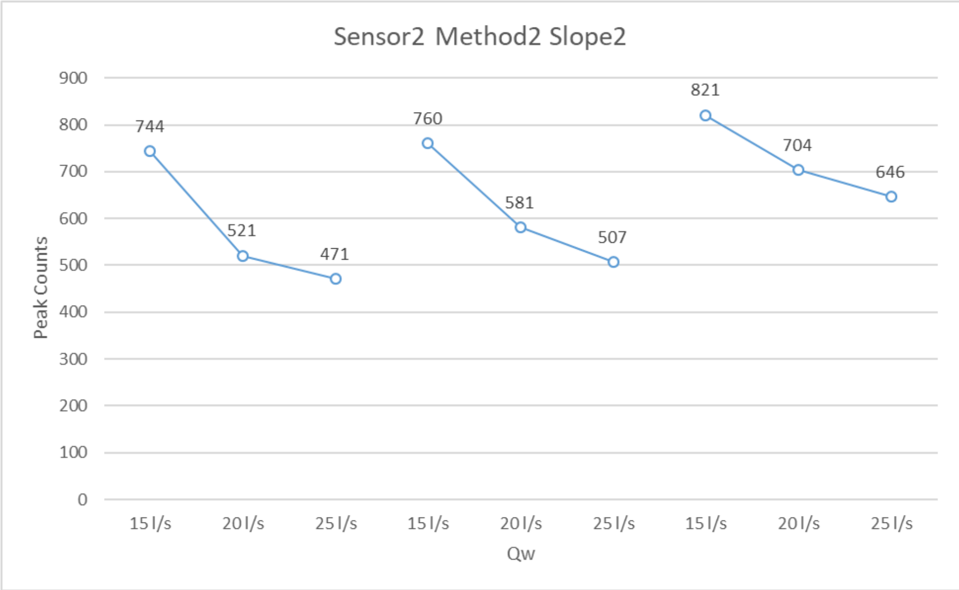

Figure 5.35: Plotting result of sensor2 method2 and slope2, with three variables of water discharge

5.4.2 Analysis of Sediment Size Dm

Particle size has a great impact in method 1, this is because it increases the amplitude with larger particle. The following figures and tables will elaborate this phenomenon;

5.4.2.1 As Session

Table 5.10 shows the placement of Qw as session. With the help of Table 5.11-5.14, the average Dm values are shown for both the methods of the two sensors. The highlighted rows follow a trend and is repeated most of the time. It is observed that the values increase with the increase in particle size.

Table 5.10: Three sessions of sediment size Dm in a system of slope

System	Session	Period	Variable
Slope 14°	**Dm1**	Qw1	Qs1
Slope 14°	**Dm1**	Qw1	Qs2
Slope 14°	**Dm1**	Qw1	Qs3
Slope 14°	**Dm1**	Qw2	Qs1
Slope 14°	**Dm1**	Qw2	Qs2
Slope 14°	**Dm1**	Qw2	Qs3
Slope 14°	**Dm1**	Qw3	Qs1
Slope 14°	**Dm1**	Qw3	Qs2
Slope 14°	**Dm1**	Qw3	Qs3
Slope 14°	**Dm2**	Qw1	Qs1
Slope 14°	**Dm2**	Qw1	Qs2
Slope 14°	**Dm2**	Qw1	Qs3
Slope 14°	**Dm2**	Qw2	Qs1
Slope 14°	**Dm2**	Qw2	Qs2
Slope 14°	**Dm2**	Qw2	Qs3
Slope 14°	**Dm2**	Qw3	Qs1
Slope 14°	**Dm2**	Qw3	Qs2
Slope 14°	**Dm2**	Qw3	Qs3
Slope 14°	**Dm3**	Qw1	Qs1
Slope 14°	**Dm3**	Qw1	Qs2
Slope 14°	**Dm3**	Qw1	Qs3
Slope 14°	**Dm3**	Qw2	Qs1
Slope 14°	**Dm3**	Qw2	Qs2
Slope 14°	**Dm3**	Qw2	Qs3
Slope 14°	**Dm3**	Qw3	Qs1
Slope 14°	**Dm3**	Qw3	Qs2
Slope 14°	**Dm3**	Qw3	Qs3

Table 5.11: Session of sediment size Dm of sensor 1 for method 1

	Sensor 1 Method 1		
	Avg. at Dm1	**Avg. at Dm2**	**Avg. at Dm3**
Slope 1 = 14°	6.460	8.160	8.340
Slope 2 = 10°	5.330	7.470	8.360
Slope 3 = 6°	4.290	5.460	7.580

Table 5.12: Session of sediment size Dm of sensor 2 for method 1

	Sensor 2 Method 1		
	Avg. at Dm1	Avg. at Dm2	Avg. at Dm3
Slope 1 = 14°	4.800	5.970	6.840
Slope 2 = 10°	4.210	5.000	6.310
Slope 3 = 6°	2.800	3.370	4.900

Table 5.13: Session of sediment size Dm of sensor 1 for method 2

	Sensor 1 Method 2		
	Avg. at Dm1	Avg. at Dm2	Avg. at Dm3
Slope 1 = 14°	748.000	906.560	651.440
Slope 2 = 10°	546.000	781.000	572.000
Slope 3 = 6°	470.000	659.000	513.000

Table 5.14: Session of sediment size Dm of sensor 2 for method 2

	Sensor 2 Method 2		
	Avg. at Dm1	Avg. at Dm2	Avg. at Dm3
Slope 1 = 14°	775.000	785.440	585.000
Slope 2 = 10°	511.670	634.330	507.330
Slope 3 = 6°	321.670	458.670	454.330

From the above tables, it is visible that the trend of increasing values along the row are only dominant in method 1 of both the sensors. However, method 2 values for both sensors are totally different. The assumptions for this are:

i. Method 2 is based on the total number of impact count. Therefore, the number of particles in the same amount of sediment are different for different sizes.

ii. As shown in Table 5.13 and 5.14, the first two values along the row are increasing. It drops certainly as the size reaches to a larger size (Dm3). This curve can be further diagnosed with a detailed study on particle size ranges.

5.4.2.2 As Period

System	Session	Period	Variable
Slope	Qw	**Dm**	Qs

After the evaluation of particle size in the session, it is placed in period now. The analysis is done by combining the variables in a line as a single period. The figures are shown for both the methods, each with three lines. Each line represents three particle sizes. The arrangement between the lines are done from smaller to larger size.

- **Method 1**

In this method, the influence of Dm in sediment transport is same as that of the session for method 1. The average values are increasing from left to right of the figures. This shows, the integral curve method value is rising with increase in particle size. In other words, the influence of particle size on co-relation between sediment impact and impact counts is directly proportional. This logic is followed by all the results from both the sensors and all the slope condition. The following Figure 5.36 – 5.41 show a better understanding of the discovery;

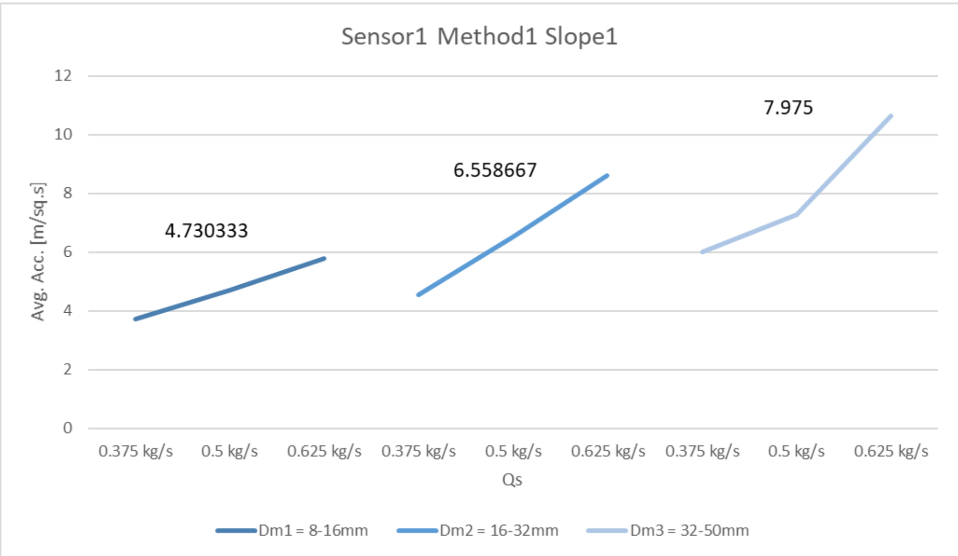

Figure 5.36: Plotting result of sensor1 method1 and slope1, with three periods of particle size

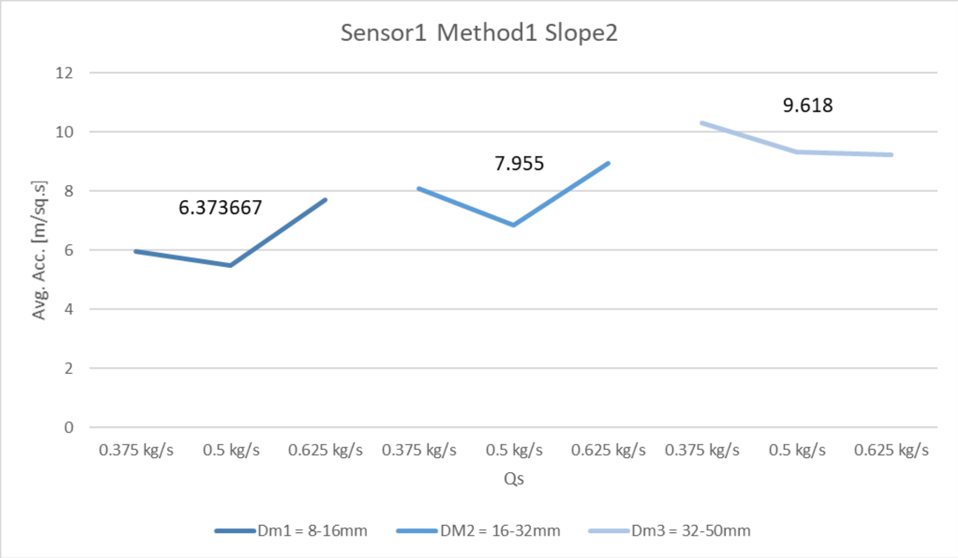

Figure 5.37: Plotting result of sensor1 method1 and slope2, with three periods of particle size

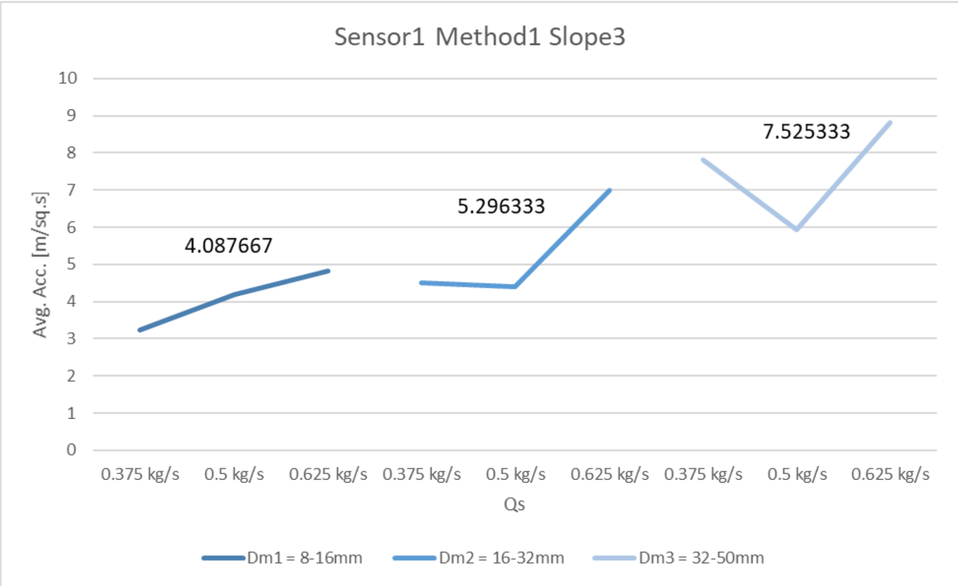

Figure 5.38: Plotting result of sensor1 method1 and slope3, with three periods of particle size

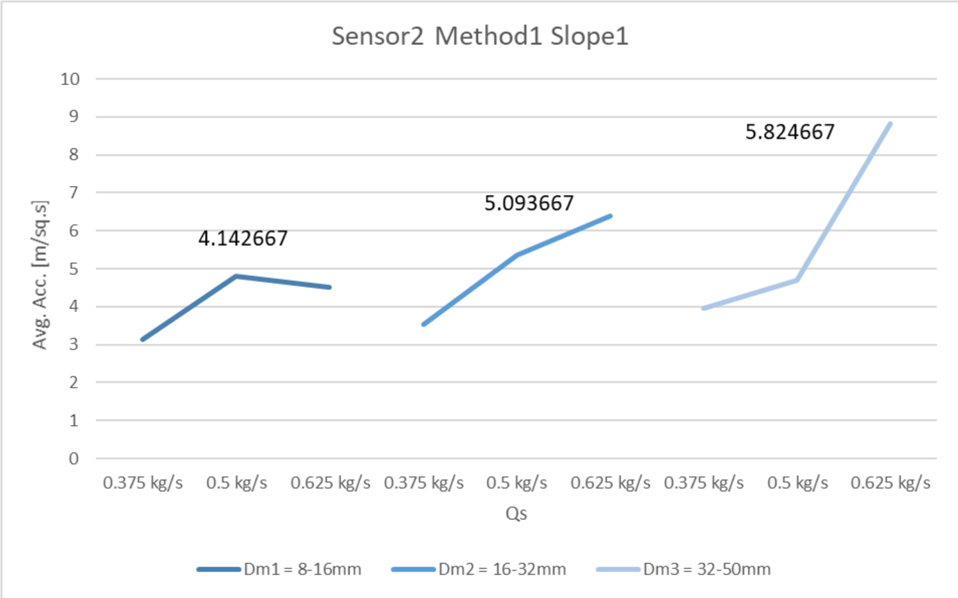

Figure 5.39: Plotting result of sensor2 method1 and slope1, with three periods of particle size

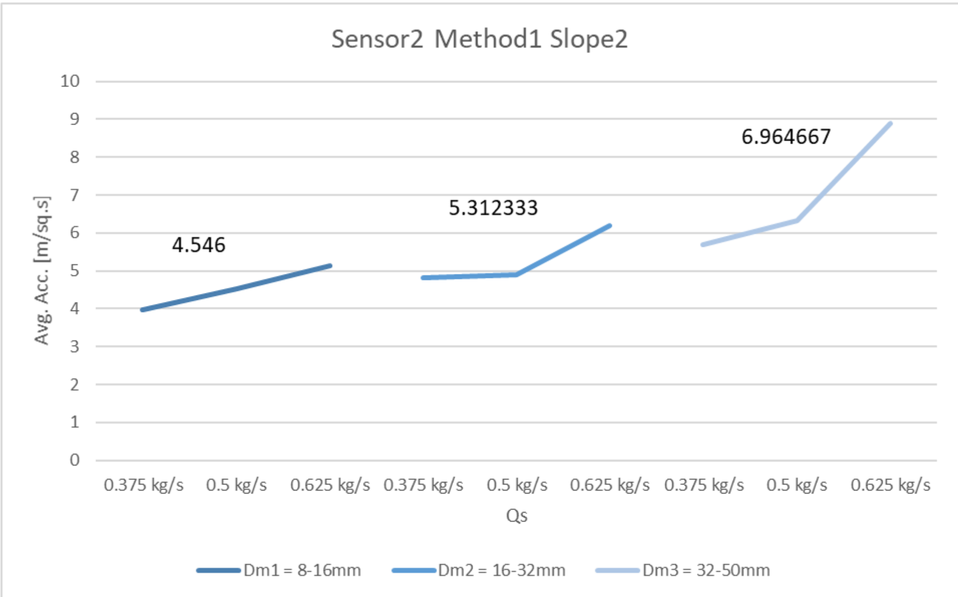

Figure 5.40: Plotting result of sensor2 method1 and slope2, with three periods of particle size

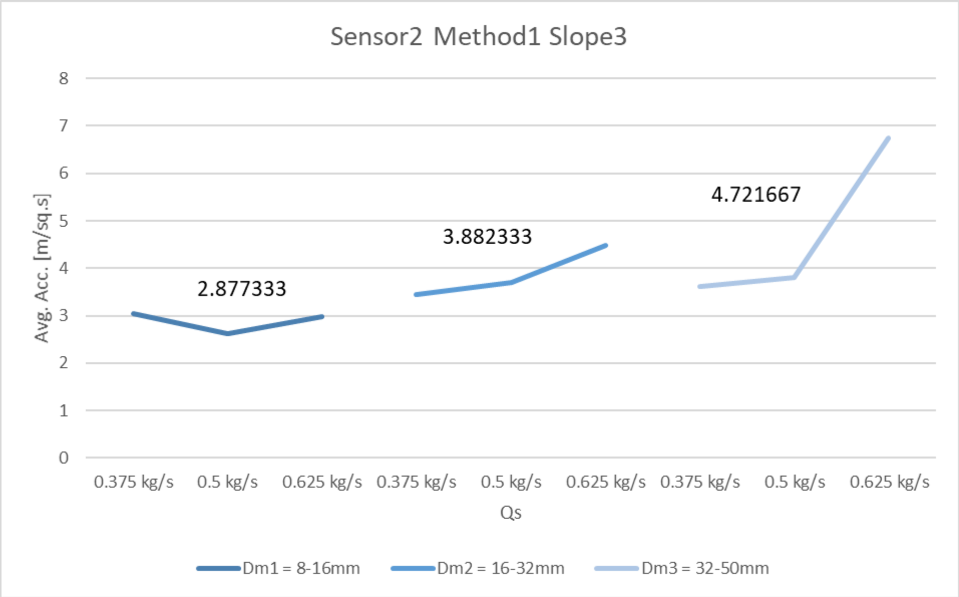

Figure 5.41: Plotting result of sensor2 method1 and slope3, with three periods of particle size

- **Method 2**

If on the one hand, where particle size shows the fix regime for method 1, on the other hand it behaves totally different for method 2. Similar to session, larger particle size (Dm3) shows sudden fall in peak counts. This can occur due to lesser number of particles in same amount of weights. Therefore, the third line segment of Figure 5.42 – 5.44 is lower than the remaining two.

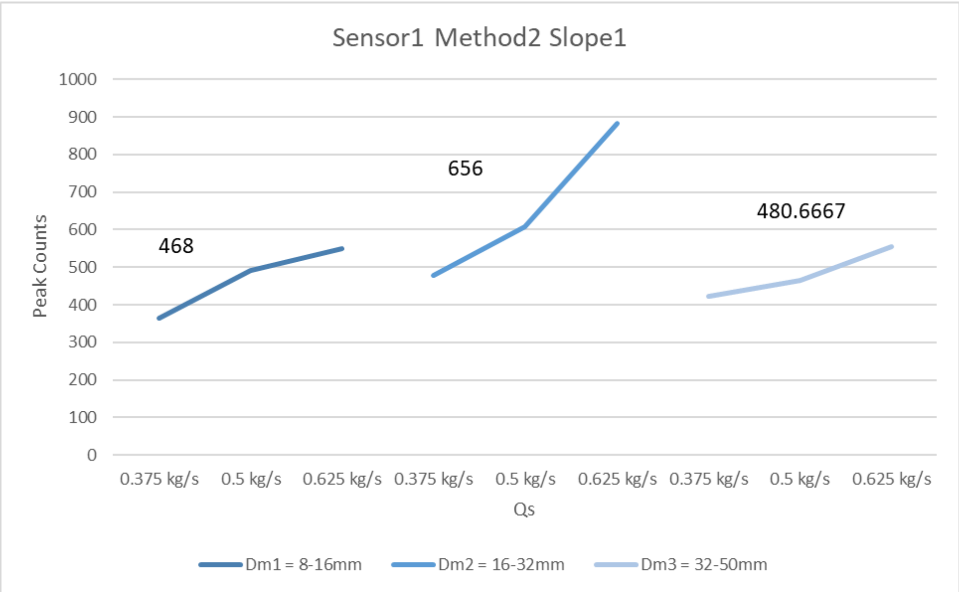

Figure 5.42: Plotting result of sensor1 method2 and slope1, with three periods of particle size

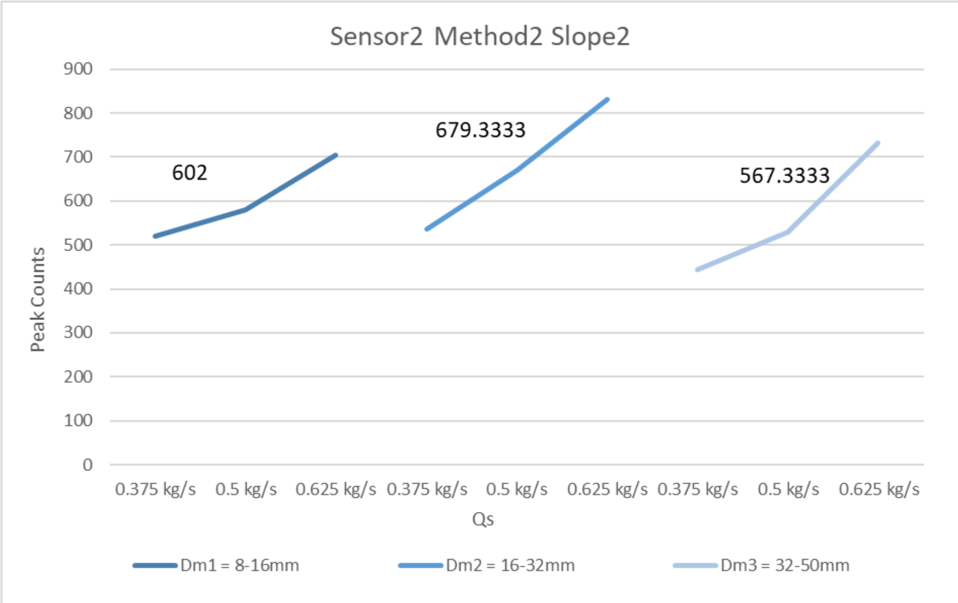

Figure 5.43: Plotting result of sensor2 method2 and slope2, with three periods of particle size

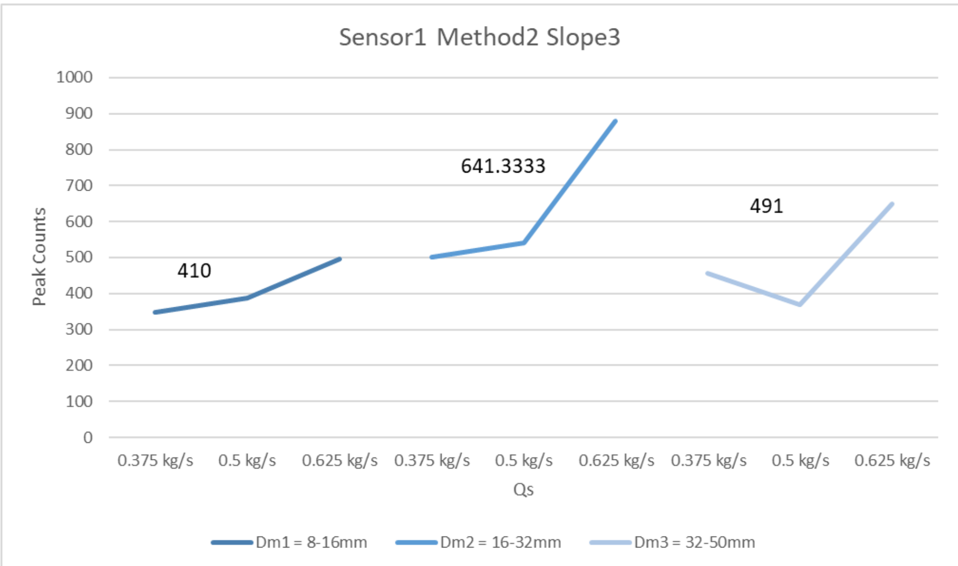

Figure 5.44: Plotting result of sensor1 method2 and slope3, with three periods of particle size

5.4.2.3 As Variable

System	Session	Period	Variable
Slope	Qs	Qw	**Dm**

Fortunately, the observations for particle size, when analysed as an individual variable also followed the same footsteps as before in session and period. Both method 1 and 2 have same graphical representation for particle size outcome of sediment transport.

- **Method 1**

The three variable which construct a single period have same path. With increasing particle size there is a rise in the average integral curve value, as shown in Figure 5.45 - 5.47;

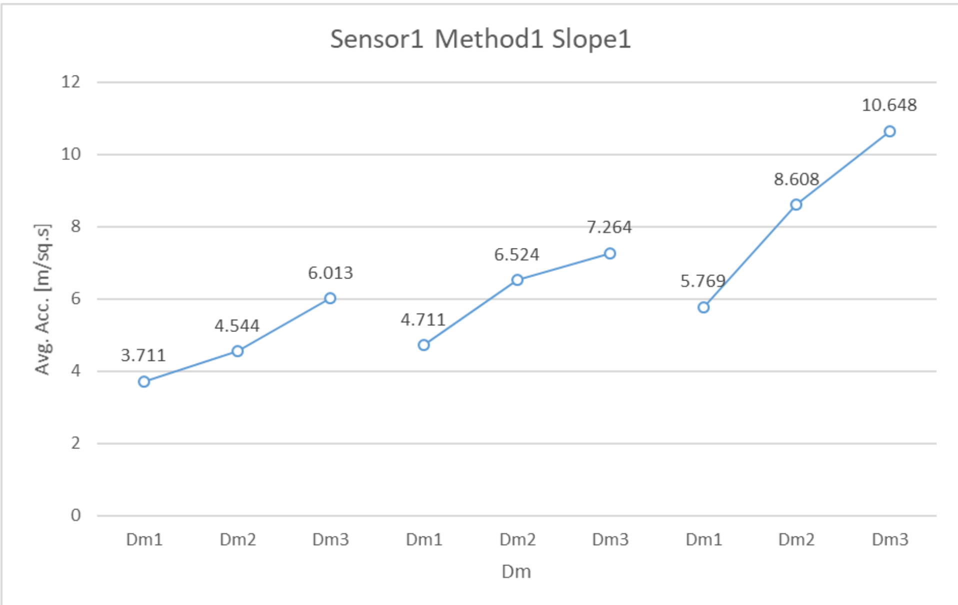

Figure 5.45: Plotting result of sensor1 method1 and slope1, with three variables of particle size

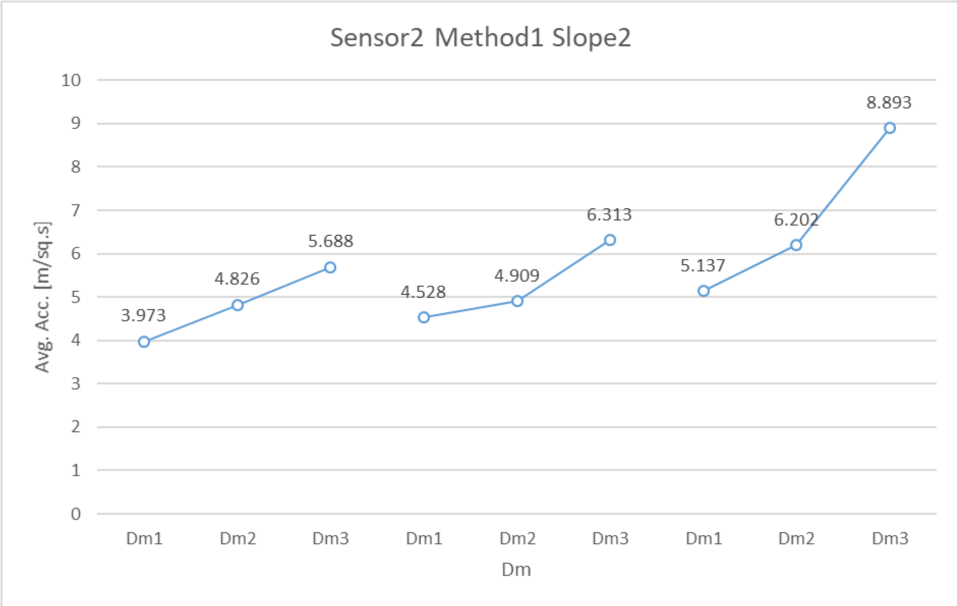

Figure 5.46: Plotting result of sensor2 method1 and slope2, with three variables of particle size

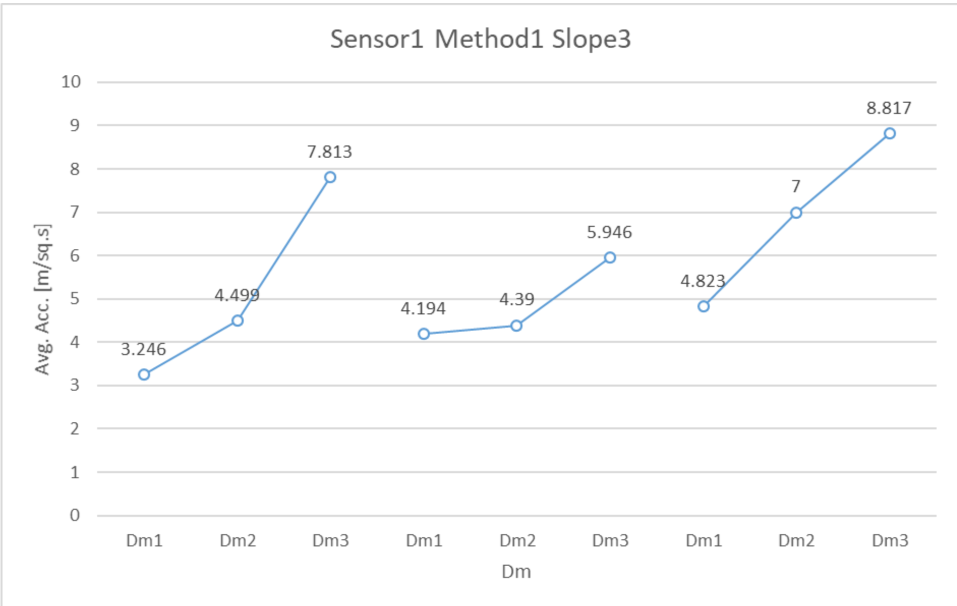

Figure 5.47: Plotting result of sensor1 method1 and slope3, with three variables of particle size

- **Method 2**

Alike session and period, particle size as a variable exhibits the same impression for method 2. Dm3 has the least peak counts of all sizes. This is visible in the following figure 5.48 – 5.50;

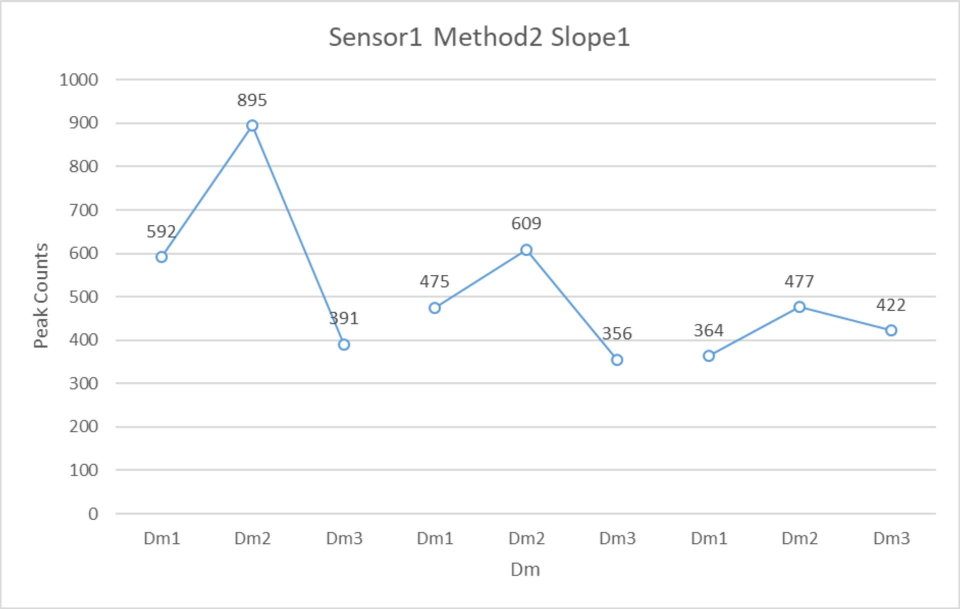

Figure 5.48: Plotting result of sensor1 method2 and slope1, with three variables of particle size

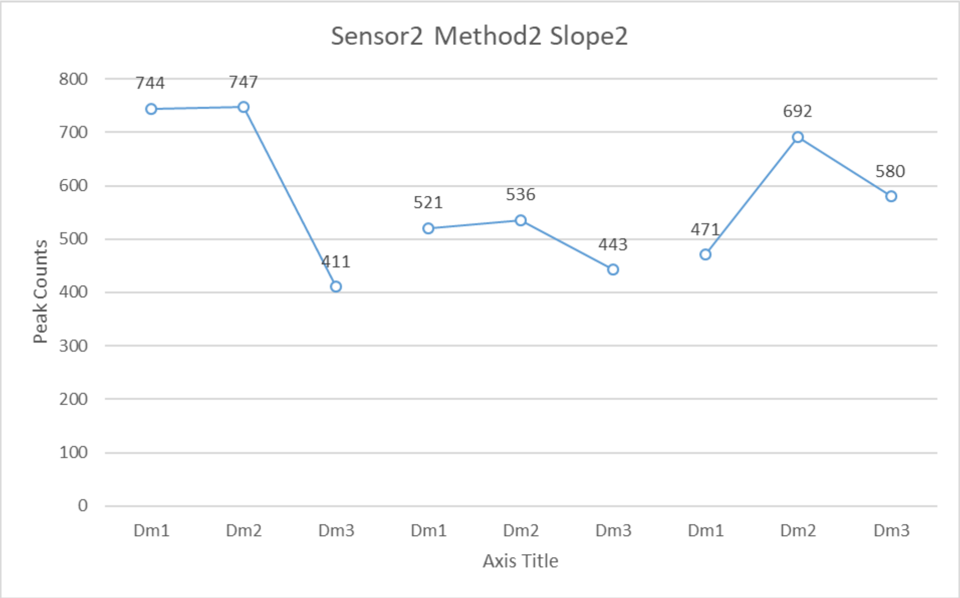

Figure 5.49: Plotting result of sensor2 method2 and slope2, with three variables of particle size

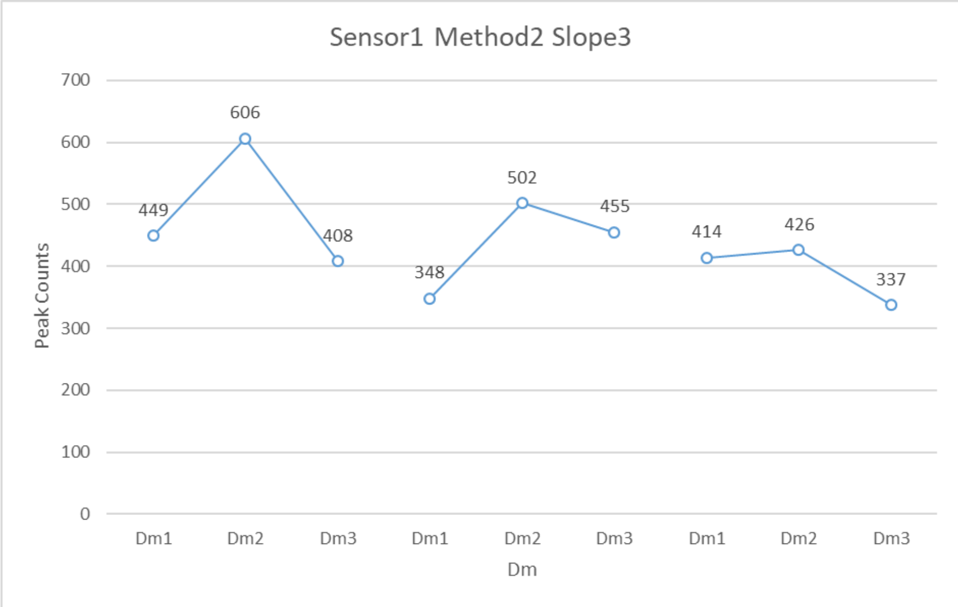

Figure 5.50: Plotting result of sensor1 method2 and slope3, with three variables of particle size

5.4.3 Analysis of Sediment Discharge Qs

Method 1 of the analysis is totally governed by this parameter. The change in the sediment discharge has direct control on sediment Impact Sensor. The evaluation of this parameter is conducted with two methods that are also previously done. The tables and figures given underneath, demonstrate the outcomes via this parameter.

5.4.3.1 As Session

Particle size influence on sediment bedload transport is major and this is proved by the following promising results. Table 5.15 shows the results after placing Qs as session;

Table 5.15: Three sessions of sediment discharge Qs in a system of Slope

System	Session	Period	Variable
Slope 14°	**Qs1**	Qw1	Dm1
Slope 14°	**Qs1**	Qw1	Dm2
Slope 14°	**Qs1**	Qw1	Dm3
Slope 14°	**Qs1**	Qw2	Dm1
Slope 14°	**Qs1**	Qw2	Dm2
Slope 14°	**Qs1**	Qw2	Dm3
Slope 14°	**Qs1**	Qw3	Dm1
Slope 14°	**Qs1**	Qw3	Dm2
Slope 14°	**Qs1**	Qw3	Dm3
Slope 14°	**Qs2**	Qw1	Dm1
Slope 14°	**Qs2**	Qw1	Dm2
Slope 14°	**Qs2**	Qw1	Dm3
Slope 14°	**Qs2**	Qw2	Dm1
Slope 14°	**Qs2**	Qw2	Dm2
Slope 14°	**Qs2**	Qw2	Dm3
Slope 14°	**Qs2**	Qw3	Dm1
Slope 14°	**Qs2**	Qw3	Dm2
Slope 14°	**Qs2**	Qw3	Dm3
Slope 14°	**Qs3**	Qw1	Dm1
Slope 14°	**Qs3**	Qw1	Dm2
Slope 14°	**Qs3**	Qw1	Dm3
Slope 14°	**Qs3**	Qw2	Dm1
Slope 14°	**Qs3**	Qw2	Dm2
Slope 14°	**Qs3**	Qw2	Dm3
Slope 14°	**Qs3**	Qw3	Dm1
Slope 14°	**Qs3**	Qw3	Dm2
Slope 14°	**Qs3**	Qw3	Dm3

Table 5.16: Session of sediment discharge Qs of sensor 1 for method 1

	Sensor 1 Method 1		
	Avg. at Qs1	Avg. at Qs2	Avg. at Qs3
Slope 1 = 14°	6.643	7.676	9.256
Slope 2 = 10°	5.229	6.614	9.318
Slope 3 = 6°	4.647	6.011	6.670

Table 5.17: Session of sediment discharge Qs of sensor 1 for method 2

	Sensor 1 Method 2		
	Avg. at Qs1	Avg. at Qs2	Avg. at Qs3
Slope 1 = 14°	618.444	775.000	912.556
Slope 2 = 10°	509.000	604.778	785.778
Slope 3 = 6°	438.333	536.667	667.000

Table 5.18: Session of sediment discharge Qs of sensor2 for method 1

	Sensor 2 Method 1		
	Avg. at Qs1	Avg. at Qs2	Avg. at Qs3
Slope 1 = 14°	4.939	5.667	7.007
Slope 2 = 10°	3.996	5.006	6.513
Slope 3 = 6°	2.826	3.330	4.906

Table 5.19: Session of sediment discharge Qs of sensor 2 for method 2

	Sensor 2 Method 2		
	Avg. at Qs1	Avg. at Qs2	Avg. at Qs3
Slope 1 = 14°	571.667	651.000	787.222
Slope 2 = 10°	387.889	565.667	699.778
Slope 3 = 6°	296.667	375.556	519.000

From the Tables 5.16 to 5.19, it is noticed that the pathway throughout all the sensors and all the methods are identical. Along the rows, in every slope the average value of integral curve and peak counts are increasing with increase in particle discharge. With this evidence, particle discharge is the most dominant parameter to control the bed load transport.

5.4.3.2 As Period

System	Session	Period	Variable
Slope	Dm	**Qs**	Qw

To investigate this parameter in more detail, we will place it as a period. The three lines in the figures are representing the path that is generated due to sediment discharge.

- **Method 1**

In the following Figure 5.51 – 5.54, the line representing 1st period of sediment discharge is lower than the 2nd line. This means the average integral curve value of 0.375kg/s is less than the values of 0.5kg/s. Based on this result; it can be claimed that sediment discharge is directly proportional to bedload transport.

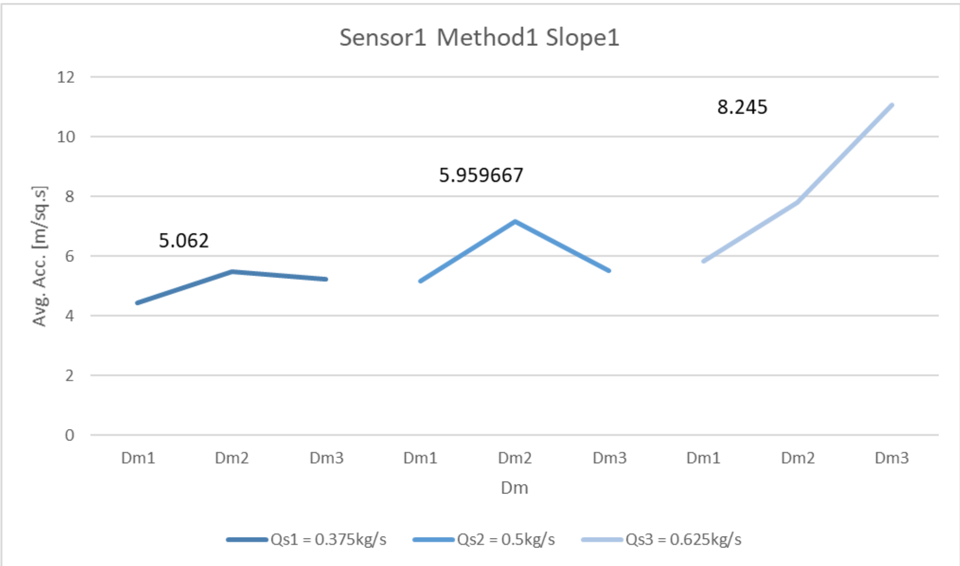

Figure 5.51: Plotting results for sensor1 method1 and slope1, with three periods of sediment discharge

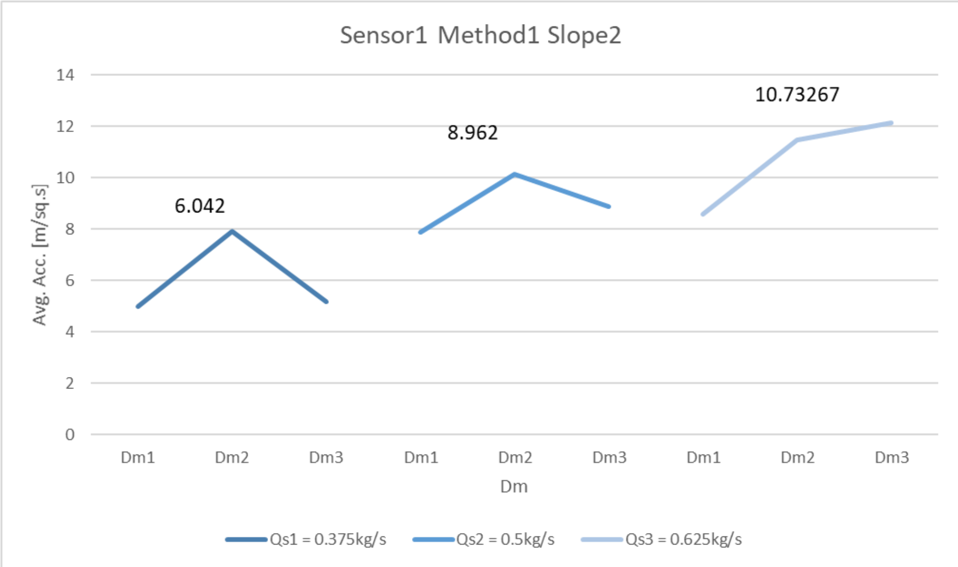

Figure 5.52: Plotting results for sensor1 method1 and slope2, with three periods of sediment discharge

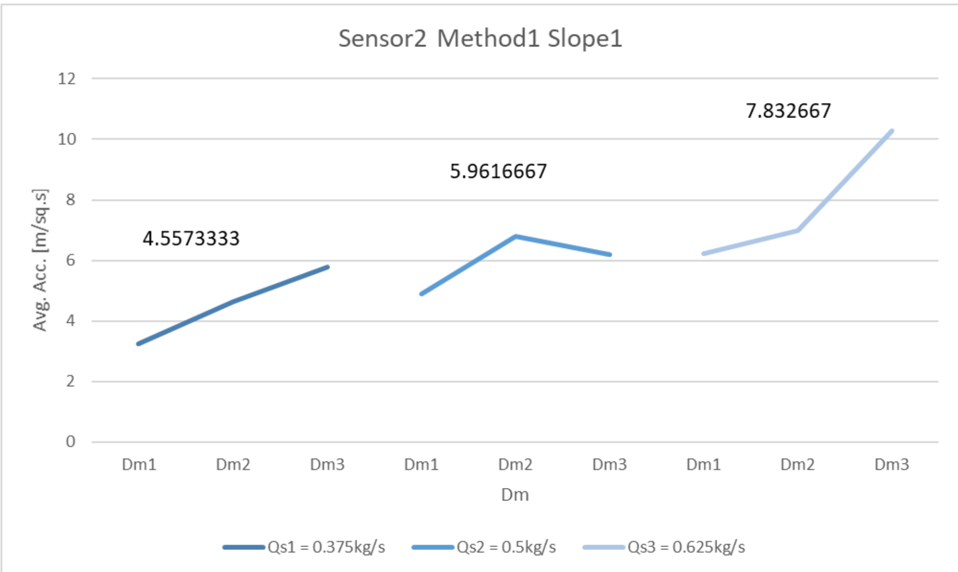

Figure 5.53: Plotting results for sensor2 method1 and slope1, with three periods of sediment discharge

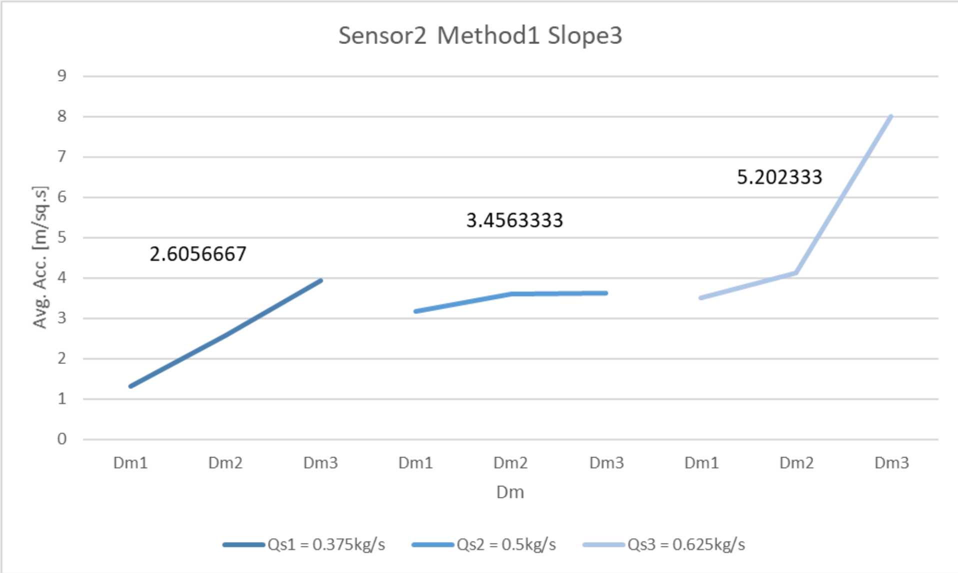

Figure 5.54: Plotting results for sensor1 method1 and slope1, with three periods of sediment discharge

- **Method 2**

Likewise, the results of method 1, which follow the same path, the number of peak counts is greater with the larger amount of sediment that passes through the sensor. Despite to the variable parameter, the period of sediment discharge is increases along the figure. Following are the Figures 5.55 – 5.59, which also reveal this same scenario;

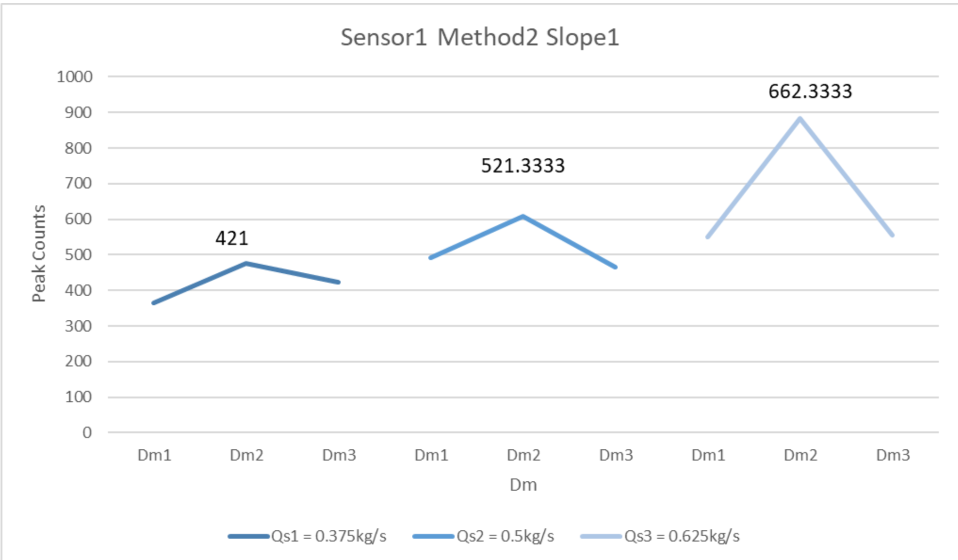

Figure 5.55: Plotting results for sensor1 method2 and slope1, with three periods of sediment discharge

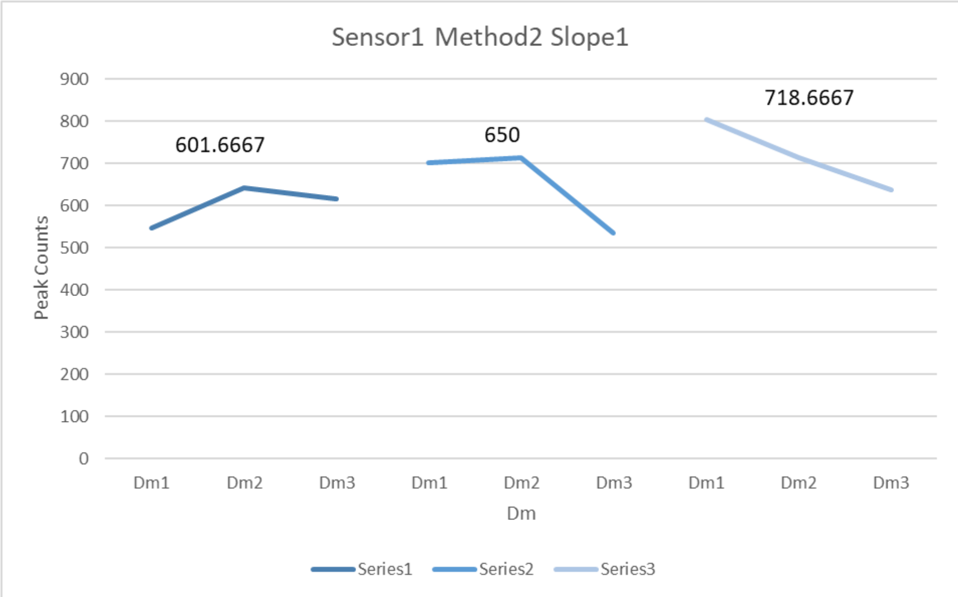

Figure 5.56: Plotting results for sensor1 method2 and slope1, with three periods of sediment discharge

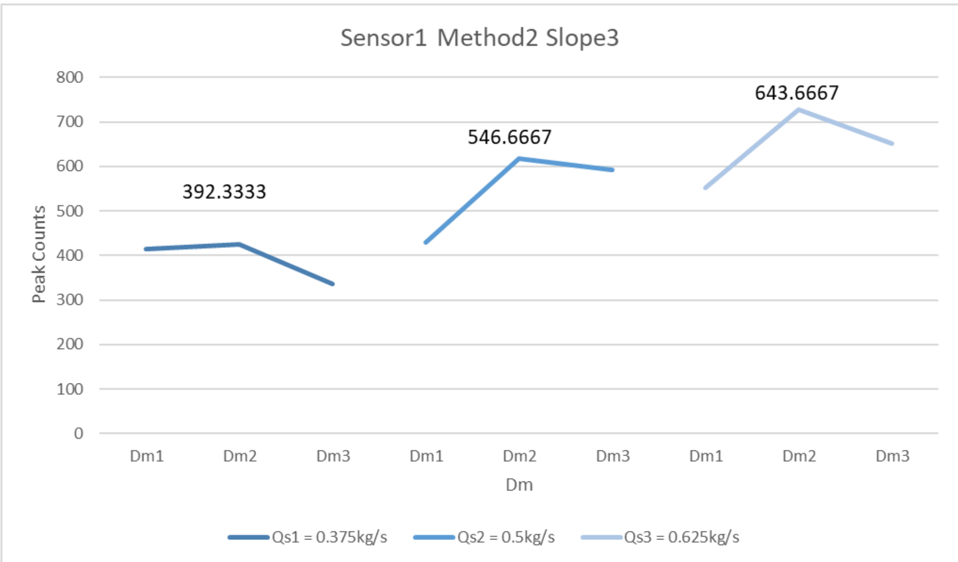

Figure 5.57: Plotting results for sensor1 method2 and slope3, with three periods of sediment discharge

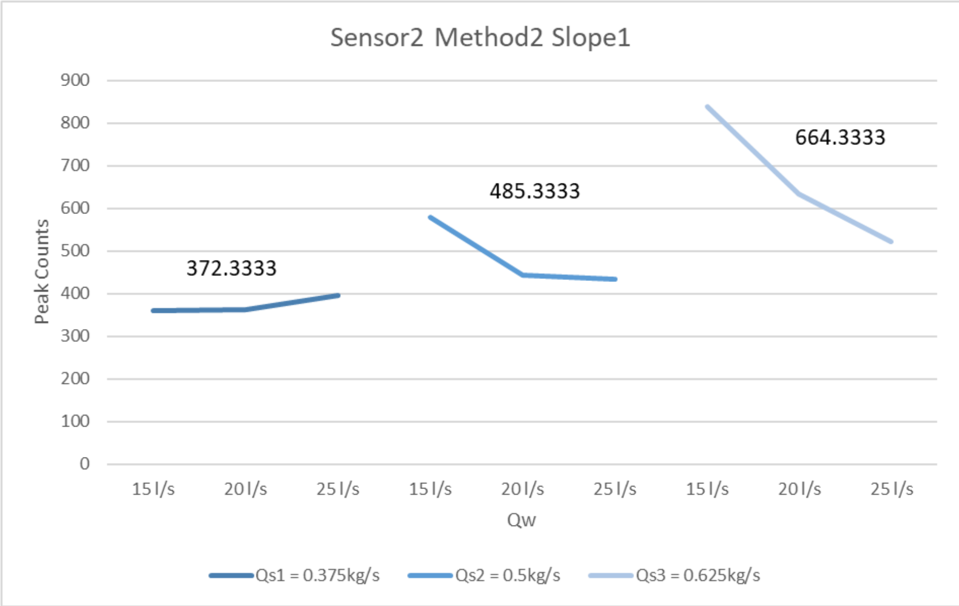

Figure 5.58: Plotting results for sensor1 method2 and slope1, with three periods of sediment discharge

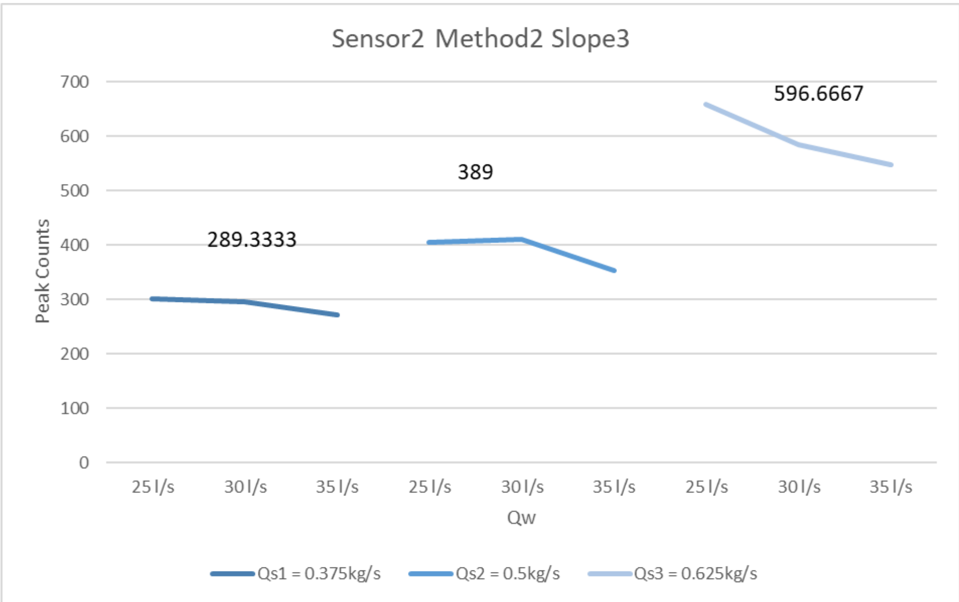

Figure 5.59: Plotting results for sensor2 method2 and slope3, with three periods of sediment discharge

5.4.3.3 As Variable

System	Session	Period	Variable
Slope	Qw	Dm	**Qs**

After cumulative analysis of sediment discharge, now we will now see if the track is still followed when it is evaluated individually.

- **Method 1**

In this method, the Figures 5.60 to 5.64 show that the parameter of Qs influences the sediment transport consistently. Regardless of any slope, water discharge and particle size, it obeys the pathway from one test to another. This also illustrates the complete meaning of integral under curve method. It is logical that the summation of all the number of hits and their amplitudes is dependent on the number of particles flowing in the river.

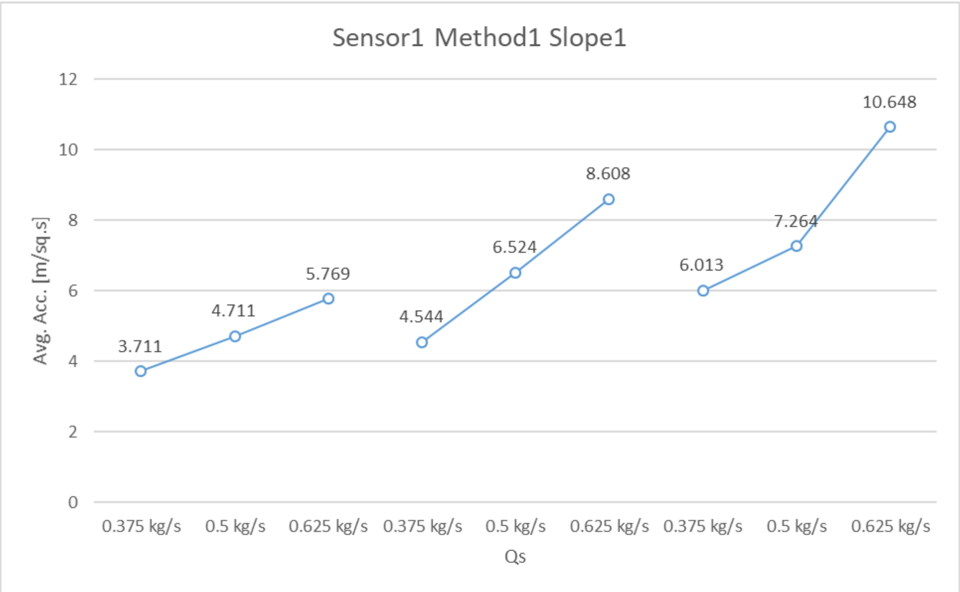

Figure 5.60: Plotting results for sensor1 method1 and slope1, with three variables of sediment discharge

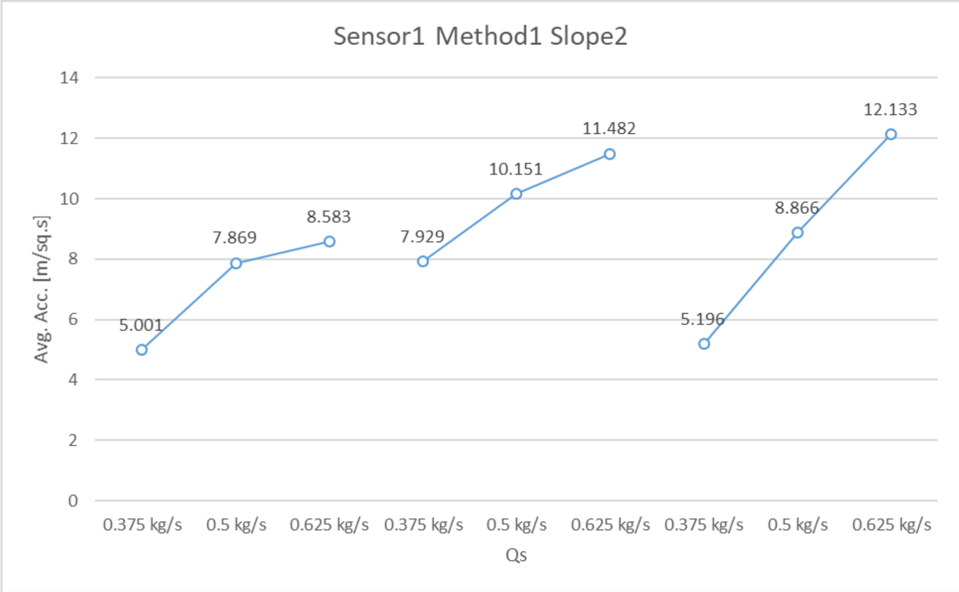

Figure 5.61: Plotting results for sensor1 method1 and slope2, with three variables of sediment discharge

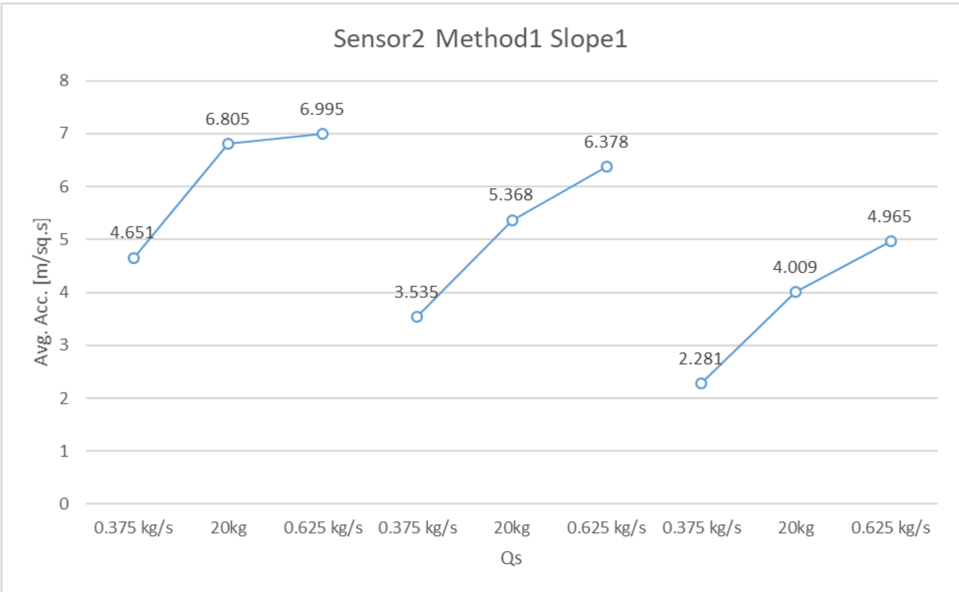

Figure 5.62: Plotting results for sensor2 method1 and slope1, with three variables of sediment discharge

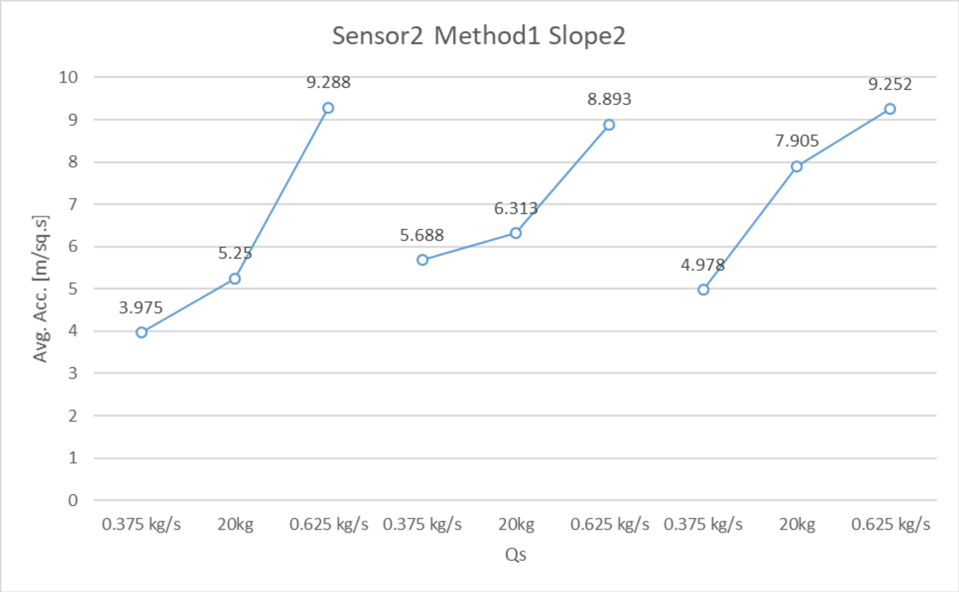

Figure 5.63: Plotting results for sensor2 method1 and slope2, with three variables of sediment discharge

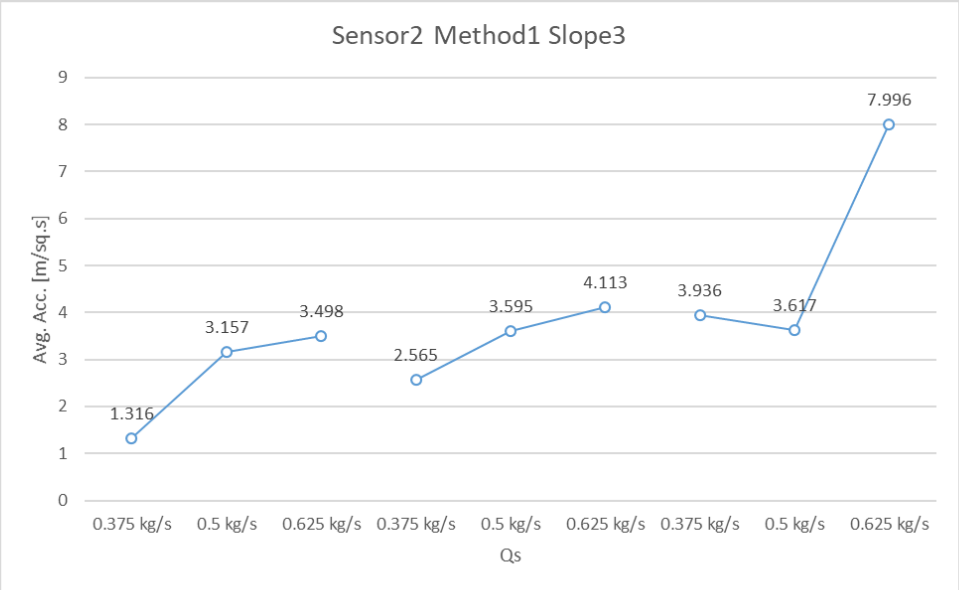

Figure 5.64: Plotting results for sensor1 method1 and slope1, with three variables of sediment discharge

- **Method 2**

The total number of peak counts are always increasing with an increase in sediment discharge Qs. This could be seen in the following Figures 5.65 to 5.69. It is obvious that the greater the mass of sediment contains the higher number of particles, the greater will the number of impacts on sensor be caused.

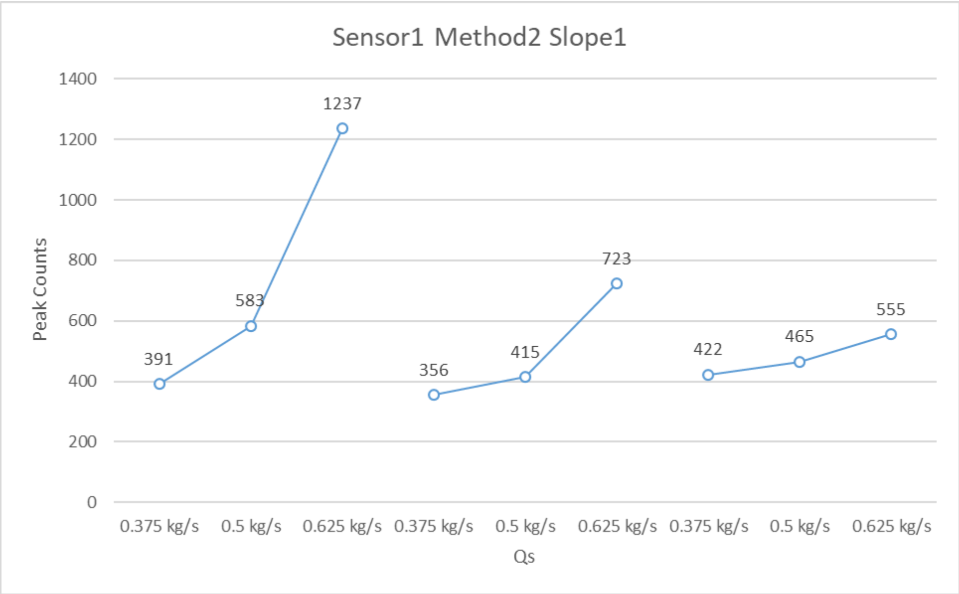

Figure 5.65: Plotting results for sensor1 method2 and slope1, with three variables of sediment discharge

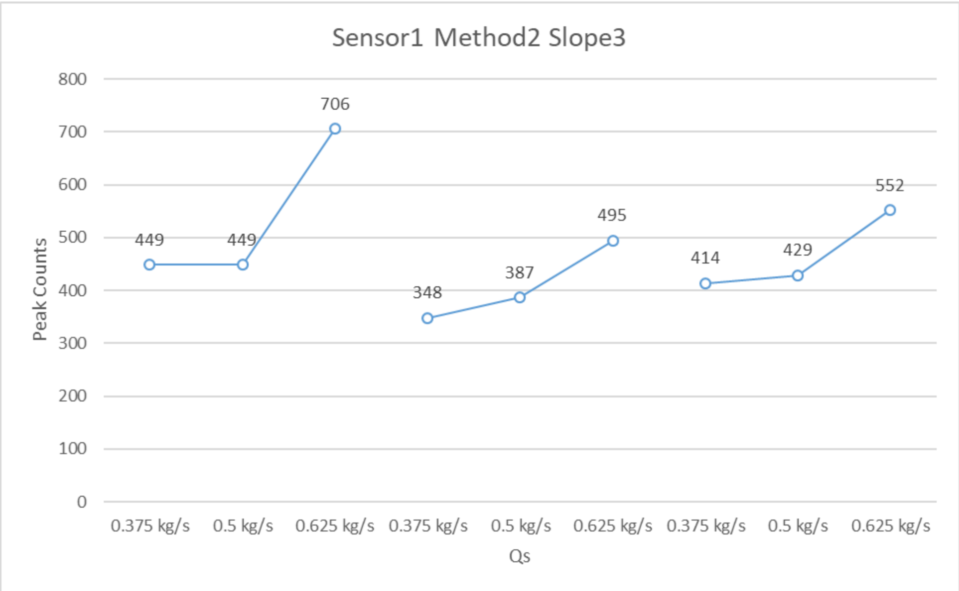

Figure 5.66: Plotting results for sensor1 method1 and slope3, with three variables of sediment discharge

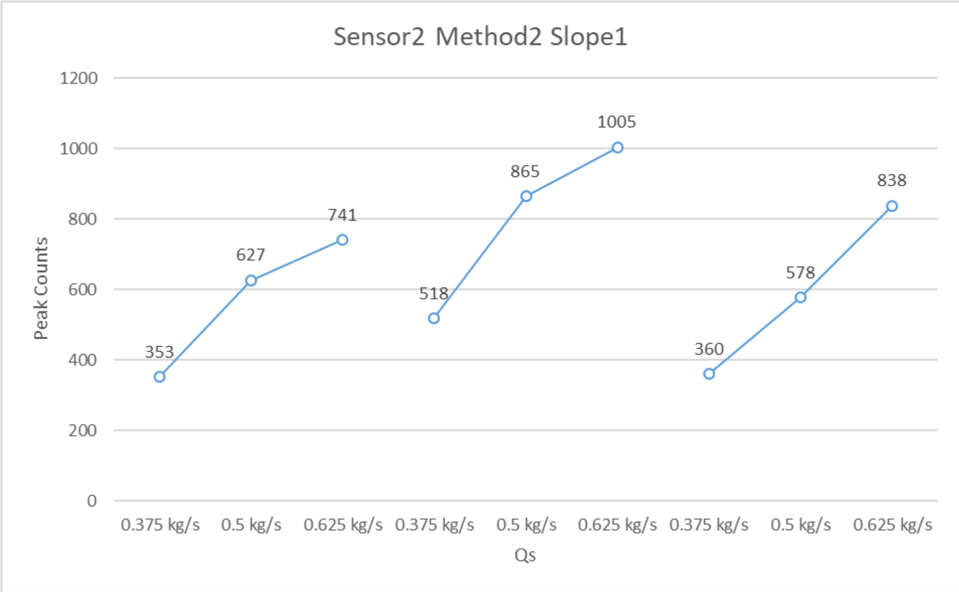

Figure 5.67: Plotting results for sensor2 method2 and slope1, with three variables of sediment discharge

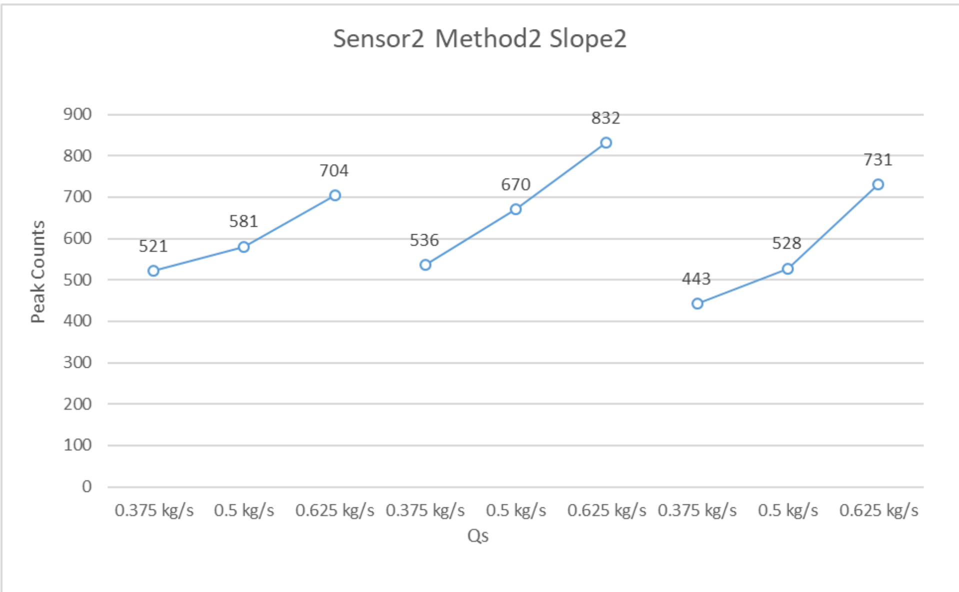

Figure 5.68: Plotting results for sensor2 method2 and slope2, with three variables of sediment discharge

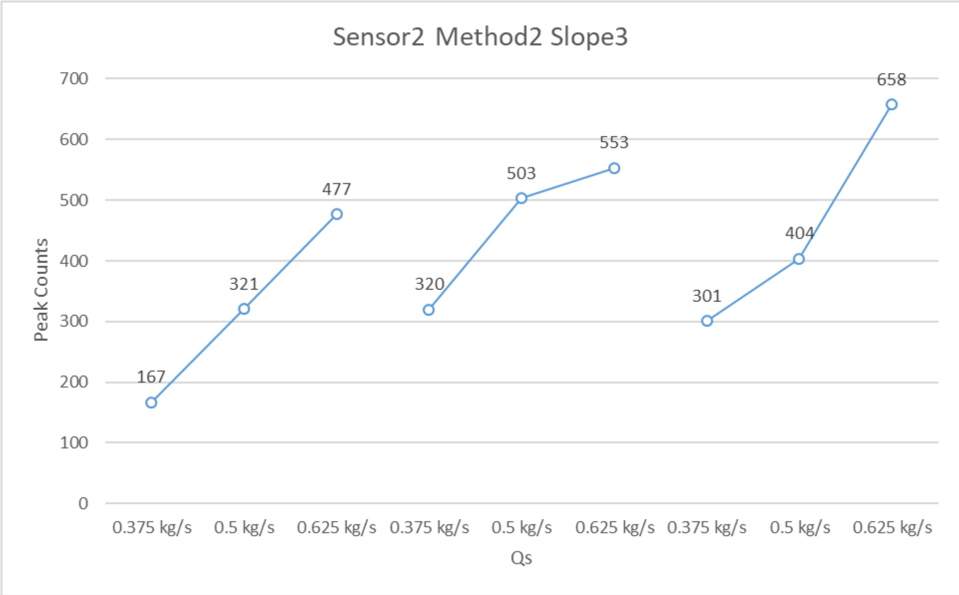

Figure 5.69: Plotting results for sensor2 method2 and slope3, with three variables of sediment discharge

5.4.4 Analysis of Slope Sl

At last, analysis of slope for sediment transport is executed. To discover the influence of this parameter, same protocol is followed. The evaluation will be carried out in three different positions and two methods are applied in each position. Figures and tables given below will exemplify the outcome of slope.

5.4.4.1 As Session

As mentioned earlier, the analysis of group session is evaluated by taking the average of each session of slope, as shown in Table 5.20. The average from each slope of all the three systems of water discharge Qw is organized in the following Tables 5.21 to 5.24;

Table 5.20: Three sessions of slope Sl in a system of water discharge Qw

System	Session	Period	Variable
Qw1	**Slope 14°**	Dm1	Qs1
Qw1	**Slope 14°**	Dm1	Qs2
Qw1	**Slope 14°**	Dm1	Qs3
Qw1	**Slope 14°**	Dm2	Qs1
Qw1	**Slope 14°**	Dm2	Qs2
Qw1	**Slope 14°**	Dm2	Qs3
Qw1	**Slope 14°**	Dm3	Qs1
Qw1	**Slope 14°**	Dm3	Qs2
Qw1	**Slope 14°**	Dm3	Qs3
Qw1	**Slope 10°**	Dm1	Qs1
Qw1	**Slope 10°**	Dm1	Qs2
Qw1	**Slope 10°**	Dm1	Qs3
Qw1	**Slope 10°**	Dm2	Qs1
Qw1	**Slope 10°**	Dm2	Qs2
Qw1	**Slope 10°**	Dm2	Qs3
Qw1	**Slope 10°**	Dm3	Qs1
Qw1	**Slope 10°**	Dm3	Qs2
Qw1	**Slope 10°**	Dm3	Qs3
Qw1	**Slope 6°**	Dm1	Qs1
Qw1	**Slope 6°**	Dm1	Qs2
Qw1	**Slope 6°**	Dm1	Qs3
Qw1	**Slope 6°**	Dm2	Qs1
Qw1	**Slope 6°**	Dm2	Qs2
Qw1	**Slope 6°**	Dm2	Qs3
Qw1	**Slope 6°**	Dm3	Qs1
Qw1	**Slope 6°**	Dm3	Qs2
Qw1	**Slope 6°**	Dm3	Qs3

Table 5.21: Sessions of slope Sl of sensor1 for method 1

	Sensor 1 Method 2		
	Avg. at Sl1	Avg. at Sl2	Avg. at Sl3
Qw1 = 15l/s & 25l/s	8.317	8.579	6.021
Qw2 = 20l/s & 30l/s	6.422	7.982	5.636
Qw3 = 25l/s & 35l/s	6.421	7.014	5.670

Table 5.22: Sessions of slope Sl of sensor1 for method 2

	Sensor 1 Method 2		
	Avg. at Sl1	Avg. at Sl2	Avg. at Sl3
Qw1 = 15l/s & 25l/s	778.333	906.556	600.333
Qw2 = 20l/s & 30l/s	586.333	742.667	514.111
Qw3 = 25l/s & 35l/s	534.889	656.778	527.556

Table 5.23: Sessions of slope Sl of sensor2 for method 1

	Sensor 1 Method 2		
	Avg. at Sl1	Avg. at Sl2	Avg. at Sl3
Qw1 = 15l/s & 25l/s	6.117	6.607	3.755
Qw2 = 20l/s & 30l/s	5.020	5.608	3.827
Qw3 = 25l/s & 35l/s	4.377	5.398	3.480

Table 5.24: Sessions of slope Sl of sensor2 for method 2

	Sensor 1 Method 2		
	Avg. at Sl1	Avg. at Sl2	Avg. at Sl3
Qw1 = 15l/s & 25l/s	653.889	778.667	411.556
Qw2 = 20l/s & 30l/s	543.778	616.222	425.778
Qw3 = 25l/s & 35l/s	455.667	615.000	353.889

While noticing these tables, it is perceived that there is no sequence in the results from both the methods. In the system of Qw1, there are three sessions of slopes i.e. 14°, 10° and 6°. When we see the average values, then there is no sequential behaviour among the results with decrease in slope. The 10° slope has the highest value, followed by 14° value and at last 6° value is the smallest in most of the cases. The analysis of slope in session is very complex at this cumulative stage.

5.4.4.2 As Period

Period is an advanced stage of analysis, in which a combination of three values (variable) is taken into consideration to build a line segment. Further, the trajectory of these line segments will later elaborate the pathway of the results influenced by this parameter.

System	Session	Period	Variable
Qw	Dm	**Slope**	Qs

- **Method 1**

In this method, slope's impact on co-relation of particle size Dm and sediment discharge Qs could be seen. The order of outcomes can specify the trend of change in slopes. Focusing Figure 5.66 to 5.68, we explore that the path of integral curve values is the same as in session. The 1st line of 14° is followed by rising period line of 10°, but suddenly the 3rd period of 6° has drastically fallen down. To acquire the knowledge of this method, the following Figures 5.70 – 5.72, are taken into consideration;

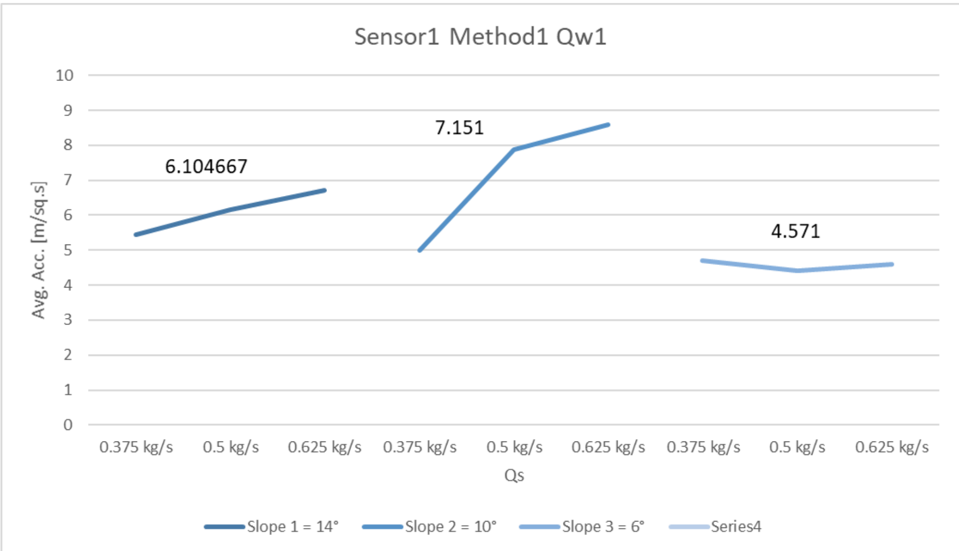

Figure 5.70: Plotting results for sensor1 method1 and Qw1, with three periods of slope

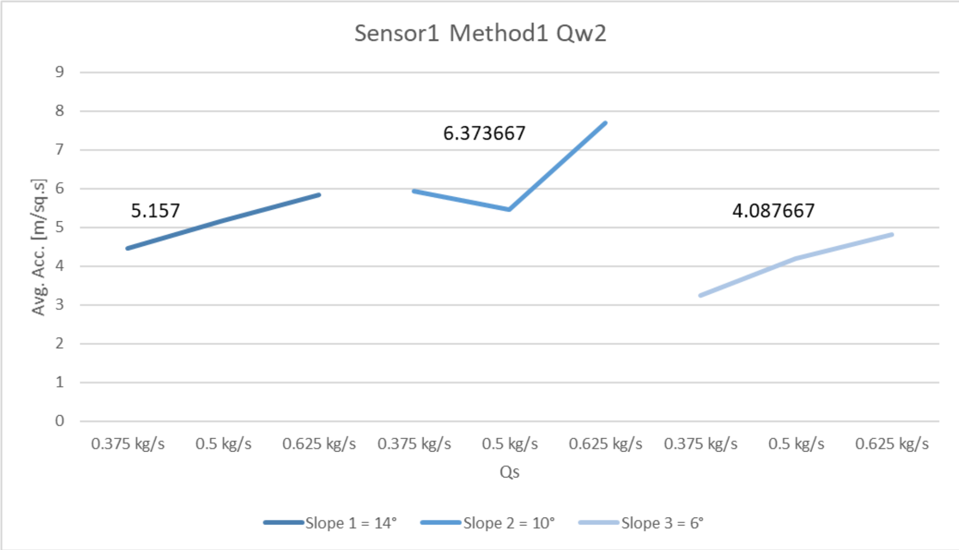

Figure 5.71: Plotting results for sensor1 method1 and Qw2, with three periods of slope

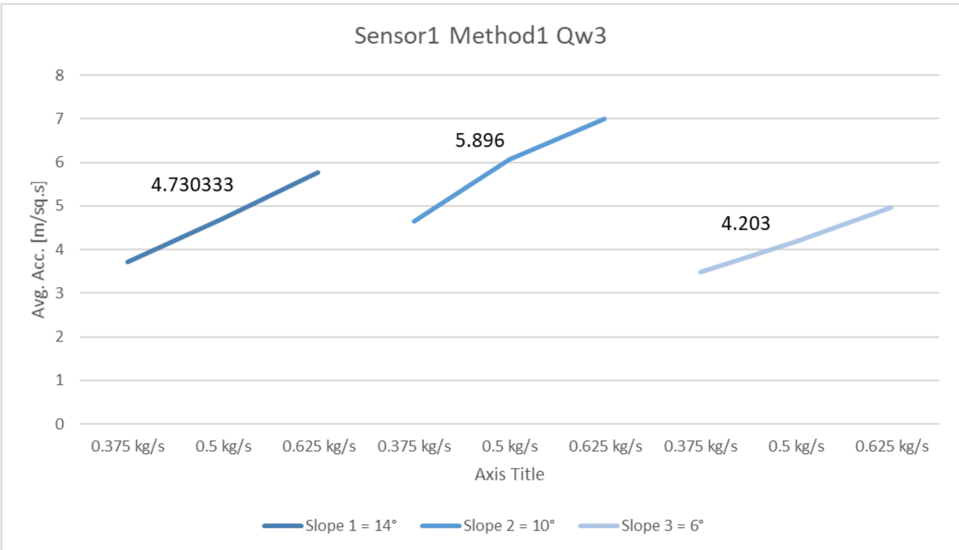

Figure 5.72: Plotting results for sensor1 method1 and Qw3, with three periods of slope

The figures of sensor 2 have the same pathway as sensor 1. This counter checks the proposition.

- **Method 2**

After method 1, method 2 is applied to the sensor readings. So as to check the effect of slope on impact count on sensor. The vertical gravitational force on sediments, which is responsible for the magnitude of impact on sensor is manipulated due to slope variations. When the slope is gradual, this force is smaller. Since this force is smaller, it is difficult to see it on sensor signals after filtering. This is could be the reason for an uneven path on figures. The peak counts for different slopes are shown in Figures 5.73 to 5.75.

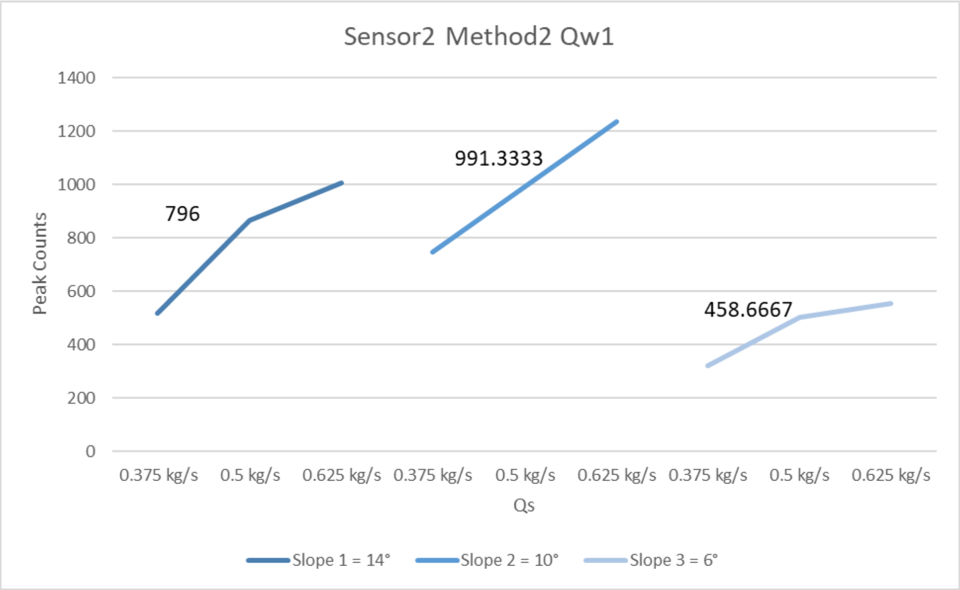

Figure 5.73: Plotting results for sensor2 method2 and Qw1, with three periods of slope

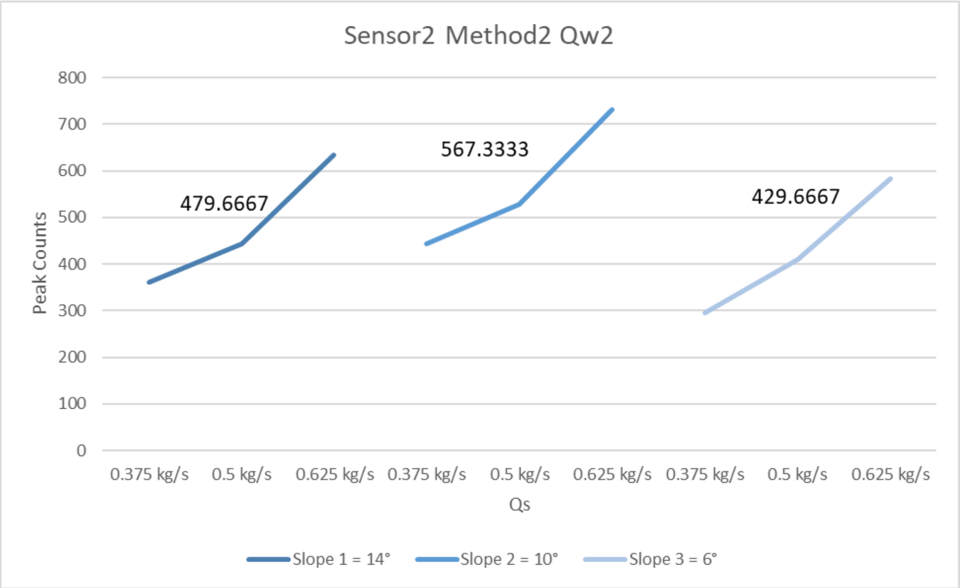

Figure 5.74: Plotting results for sensor2 method2 and Qw2, with three periods of slope

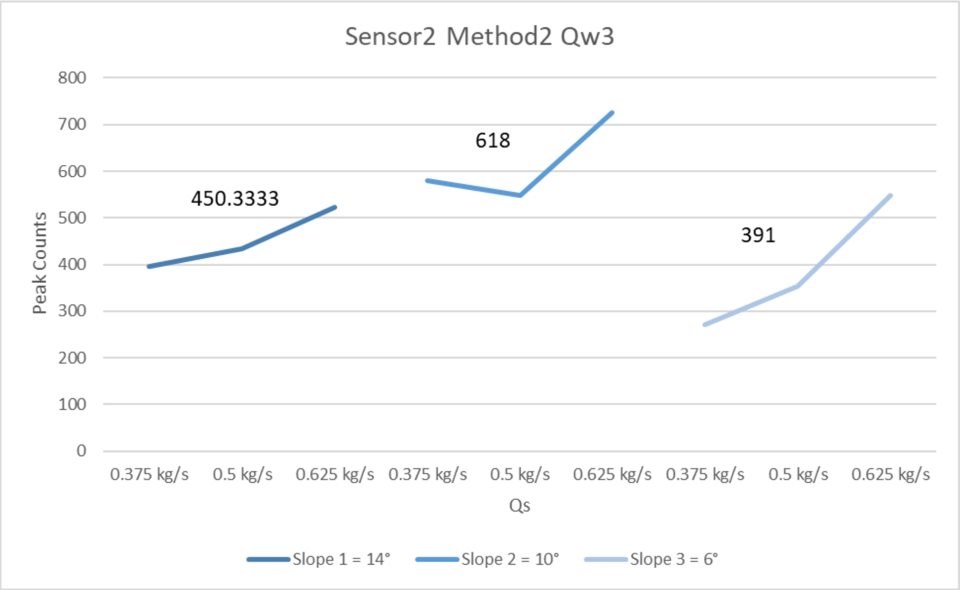

Figure 5.75: Plotting results for sensor2 method2 and Qw3, with three periods of slope

Since the figures for sensor 1 are also same and they follow the same track, they are therefore not displayed.

5.4.4.3 As Variable

To erase all kinds of remaining aims regarding slope, the analysis on the position variable is carried out. This analysis is very basic and individual evaluation. This leads to make a final decision for the order of result values.

System	Session	Period	Variable
Qw	Dm	Qs	**Slope**

- **Method 1**

Figures given below, are showing the same phenomena as before. 10° slope generates the biggest value, 2nd biggest value is given by 14° and finally 6° slope has the smallest value. This arrow shaped figure could be further enhanced with additional slopes to form a parabolic curve that can communicate the order of slope effect on sediment impact sensor. Figure 5.76 – 5.78 are examples for this method.

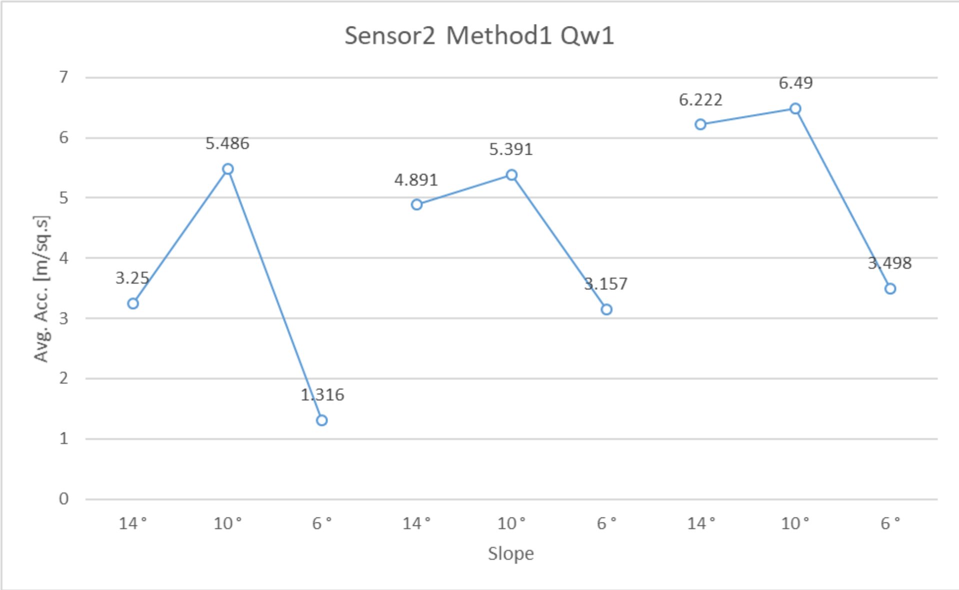

Figure 5.76: Plotting results for sensor2 method1 and Qw1, with three variables of slope

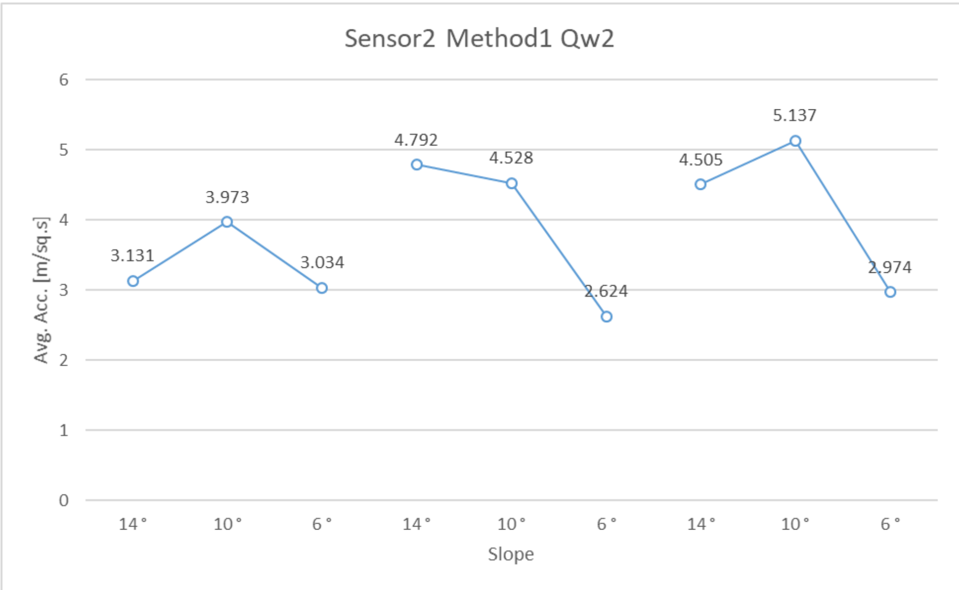

Figure 5.78: Plotting results for sensor2 method1 and Qw2, with three variables of slope

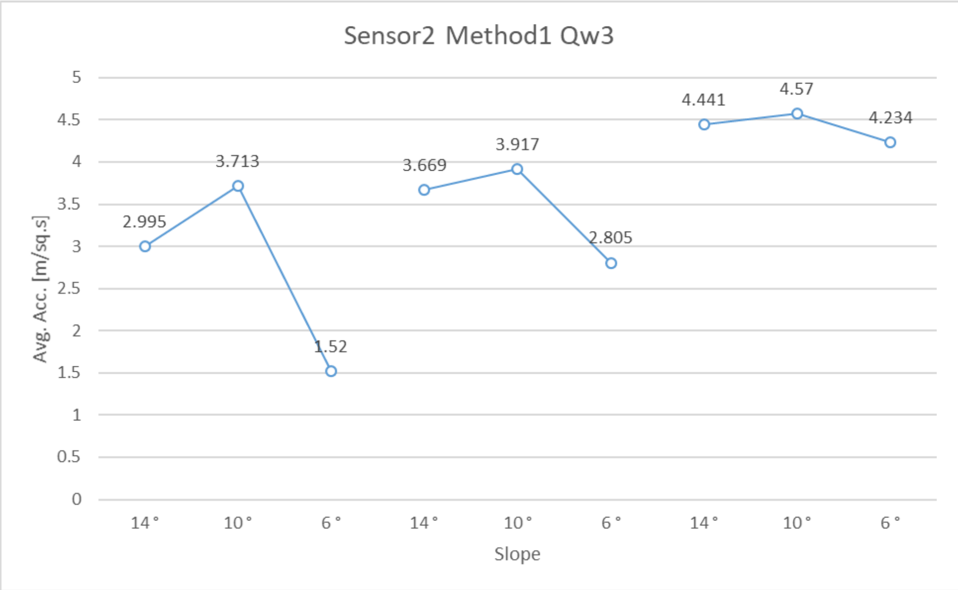

Figure 5.78: Plotting results for sensor2 method1 and Qw3, with three variables of slope

- **Method 2**

Unfortunately, the traces of method 2 for variable are identical to earlier evaluations, as shown in Figure 5.79 – 5.81;

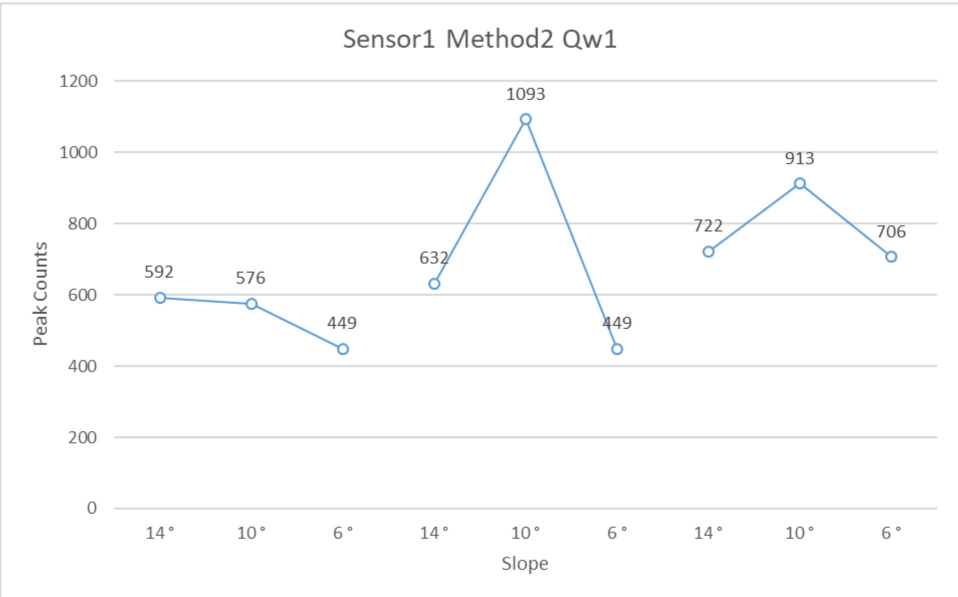

Figure 5.79: Plotting results for sensor1 method2 and Qw1, with three variables of slope

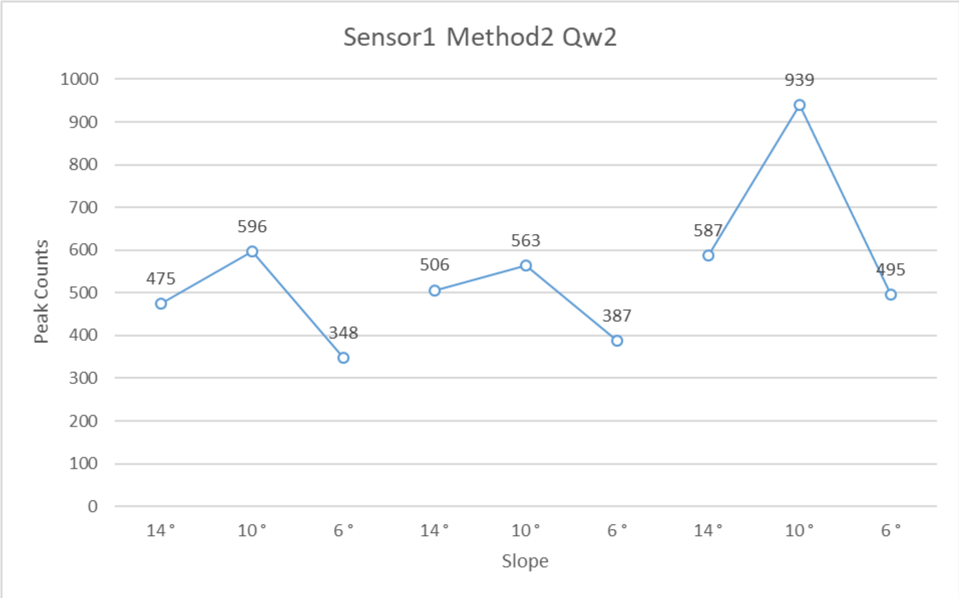

Figure 5.80: Plotting results for sensor1 method2 and Qw2, with three variables of slope

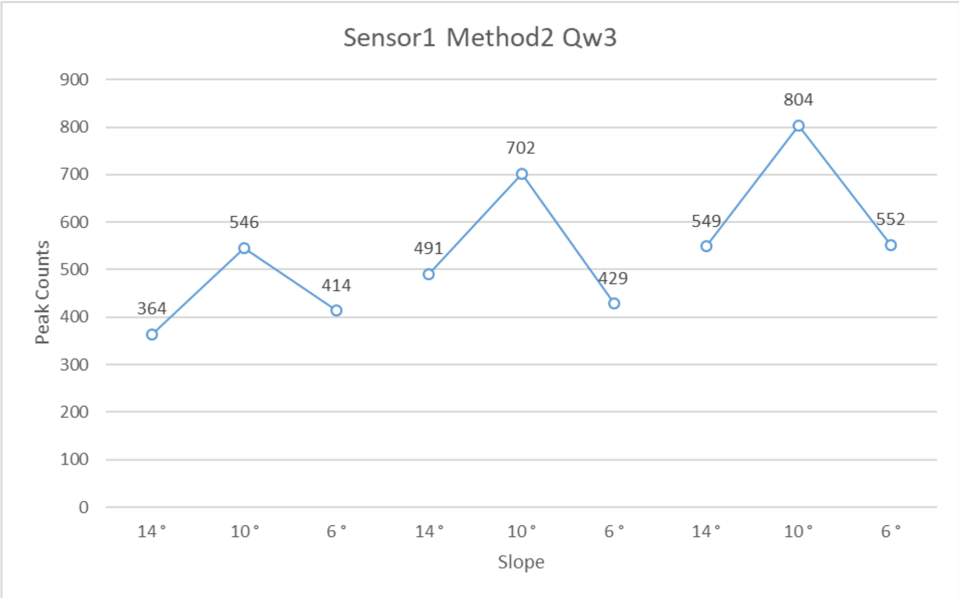

Figure 5.81: Plotting results for sensor1 method2 and Qw3, with three variables of slope

This demonstration of figures shows that the slope is the most complex parameter with no significant order of results. It could be said that the selected values of slopes are boundary values. Tests with detailed measures should be conducted with intermediate slope points to see the parabolic effect.

6. Conclusion and Recommendation

6.1 Conclusions

The influence of sediment transport parameters on the acceleration signals of sensors is seen through out in the result chapter. After detecting the effect of every parameter, from every possible angle, following observations are given:

i. After observing the parameter water discharge Qw, it is concluded that this parameter is inversely proportional to the results of sediment transport. This is proven by evaluating the results on individual (variable) and cumulative (session and period) basis.

ii. Sediment size Dm is interesting parameter because it showed two different behaviour by changing the method approach. In method 1, sediment size is directly proportional to integral area under curve values. This means, the combined result of number and strength of impact increase with larger particles size. Moreover, in method 2, different sediment size has different number of particles in same amount of weight. Therefore, the sudden fall in peak counts for Dm3 is occurred.

iii. The conclusion for the parameter, sediment discharge Qs is very direct. On the basis of all figures and mathematical values, it is concluded that sediment discharge is directly proportional to sediment transport. It has direct impact on sensor signals.

iv. Where every parameter showed different level of significance, parameter slope Sl is very random. The zigzag line on figure shows no pathway, when the slope is changed from steeper to gradual.

v. The methods adopted during this project; many unknown facts are discovered. This methodology gave a concept to focus on influence of different parameters governing the sediment transport.

6.2 Recommendations

During the implementation of this project, many major and minor questions arise that leads to future study of this phenomenon. To acknowledge these suggestions and recommendations, following improvements are listed below:

i. In this project, the sensors are placed one after the other. Due to which, many sediment particles passed without being detected by sensors. It is suggested that a model with wider section and sensors installed along the width may give more accurate results.

ii. Although the methods gave good results, but they are very limited compared to the field of study. Adopting more approaches in future may give different perspective of the sediment transport.

iii. However, the project focused on only four parameters responsible for sediment transport, still the study is very general. Focusing on less parameters and studying their individual impact on transportation may show better results. For example: detailed study on individual particle size and their sensor signals can help in future to interpret the sensor results.

iv. It is recommended that in future, same tests with more variety of slopes should be performed to observe the parabolic track in the result graphs.

Reference

Bernecker, C. T. (2018): Development of a Micro Electromechanical System Accelerometer for Measurements of Sediment Transport in Mountain Torrents. Graz University of Technology. Available online at https://diglib.tugraz.at/development-of-a-micro-electromechanical-system-accelerometer-for-measurements-of-sediment-transport-in-mountain-torrents-2018.

Eroğlu, H.; Çakır, G.; Sivrikaya, F.; Akay, A. E. (2010): Using high resolution images and elevation data in classifying erosion risks of bare soil areas in the Hatila Valley Natural Protected Area, Turkey. In *Stoch Environ Res Risk Assess* 24 (5), pp. 699–704. DOI: 10.1007/s00477-009-0356-5.

Ezugwu, C. N. (2013): Sediment Deposition in Nigeria Reservoirs: Impacts and Control Measures. In *ISDE* 4 (15). DOI: 10.7176/ISDE.

Gabe (2016): Finding only the “prominent” local maxima of a 1d array. Stack Overflow. Available online at https://stackoverflow.com/questions/40538028/finding-only-the-prominent-local-maxima-of-a-1d-array.

Joe (2018): Why is the area under a curve the integral? Mathematics, Stack Exchange. Available online at https://math.stackexchange.com/questions/15294/why-is-the-area-under-a-curve-the-integral.

Lee, G.; Gommers, R.; Waselewski, F.; Wohlfahrt, K.; O'Leary, A. (2019): PyWavelets: A Python package for wavelet analysis. In *JOSS* 4 (36), p. 1237. DOI: 10.21105/joss.01237.

Partheniades, E. (2009): Cohesive sediments in open channels. Properties, transport, and applications / Emmanuel Partheniades. Place of publication not identified: Butterworth-Heinemann.

Rickenmann, D.; Turowski, J. M.; Fritschi, B.; Wyss, C.; Laronne, J.; Barzilai, R. et al. (2014): Bedload transport measurements with impact plate geophones: comparison of sensor calibration in different gravel-bed streams. In *Earth Surf. Process. Landforms* 39 (7), pp. 928–942. DOI: 10.1002/esp.3499.

Šafarek, G. (2018): SEDIMENT TRANSPORT – GRAVEL AND SEND “FLOWS” TOO. WORLD RIVERS. Available online at http://worldrivers.net/2020/03/31/sediment-transport/.

Simons, D. B.; Şentürk, F. (1992): Sediment transport technology. Water and sediment dynamics : solutions manual. Littleton, Colo.: Water Resources Publications.

Sumi, T.; Hirose, T. (2009): Water storage, transport and distribution. Accumulation of Sediments in Reservoirs. Oxford: Eolss Publishers Co Ltd.

van Rijn, L. C. (2007): Unified View of Sediment Transport by Currents and Waves. I: Initiation of Motion, Bed Roughness, and Bed-Load Transport 133. Available online at 10.1533/9780857098801.1.42.

Walling, D. E.; Fang, D. (2003): Recent trends in the suspended sediment loads of the world's rivers. In *Global and Planetary Change* 39 (1-2), pp. 111–126. DOI: 10.1016/S0921-8181(03)00020-1.

Wang, D.; Fan, L.-S. (2013): Particle characterization and behavior relevant to fluidized bed combustion and gasification systems. In : Fluidized Bed Technologies for Near-Zero Emission Combustion and Gasification: Elsevier, pp. 42–76.