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Particle tracking along Kinta River, Perak by using LABSWE™

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ABSTRACT

Kinta River is one of the major rivers spanning 17.1km from Tanjung Rambutan to Ipoh, Perak. Kinta River is important as both water source for local population as well as various economic activities. It is unavoidable that human activities cause siltation and sedimentation in the river. Suspended sediment is one of the main contributors to the turbidity problem in the river and it brings huge impact to the environment. This study aims to predict the transportation of sediment through displacement by application of LABSWE™. The model developed provides information about the sediment location and mitigation solutions could be proposed to tackle the turbidity issue of the river. In this study, the LABSWE™-Lagrangian Model is used to predict the particles transportation in water. It is shown the settling velocity generated by gravitational force could not be neglected. When the particle density increase, the corresponding sediment transportation increases. However, the density factors do not have significant effect to the particles as the particles are relatively small in grain size.

Key words : turbidity; density; particle diameter; settling velocity; particle motion

1. INTRODUCTION

Kinta River is a river located in Perak, West Malaysia. The total length of the river is approximated 17.1 km starting from Tanjung Rambutan till the capital of Perak, Ipoh. Kinta River is the primary water source for the inhabitants in Perak and it is also well known for its wide variety of fishery supplies. Other human activities including residential, mining, industrial, rubber and oil palm plantations and logging were carried on along the catchment area of the river. Such human activities in large scale causes siltation in the river resulting in the river to become extremely turbid. Siltation and high turbidity of Kinta River prone huge impact on the ecosystem in the river and lead to several environmental issues. Prior to propose a solution to this issue, the sediment transport in the river needs to be studied first.

The Lattice Boltzmann Method for Shallow Water with Turbulence Modelling, LABSWE™ is a computational method that could be used for simulation of shallow water flow. Over the last two decades, Lattice-Boltzmann Method (LBM) has been applied in various fields of research related to hydraulic. LBM has proved itself as another promising tool for modelling complex fluid flow [24]. Due to the efficiency and effectiveness of LBM, it would be applied to study the characteristic of the Kinta River flow and hence solving the problem encountered. Today, the Kinta River are seen in completely different color when compared to rivers in other countries such as Japan and South Korea. The river is silted and polluted seriously. The turbidity and pollution problems could not be evaded anymore and thus a proper solution need to propose to solve the issue, but first the root of the problems need to be identified [5]. Hence, this paper studies the solid particle size distribution along Kinta River, Perak by developing a flow model of the river comprising different solid particle sizes using LABSWE™ and analyzing the particles flow based on the simulation.

2. CRITICAL ANALYSIS

2.1. The effect of sediment size on the transportation capacity

The sediment transportation rate is represented by transportation capacity. The sediment transportation capacity is affected by sediment properties such as sediment size, density, shape and roughness and the shear stress are normally used to calculate the sediment transport capacity [21]. For the sediment to start transporting, the boundary shear stress coming from the fluid must first exceed the critical shear stress for the initiation of motion of the sediment resting on the bed. The shear stress is greatly affected by the diameter as well as the density of the sediment. At the same time, the density is also affected by the volume of the sediment.

2.2. The study on sediment and sedimentation rate

Suspended particles in the river include materials such as clay, silt and other soil particles. These particles will undergo the sediment transportation and move along the channel of the river. Eventually, the particle will settle down due to its settling velocity which is contributed by the gravity. The settling velocity is highly affected by the particle size. As the size of particles increases, its fall velocity increases [9]. The importance of the study of sedimentation rate is to prevent flood as when sedimentation occurred, the depth of the river will decrease and hence the catchment area has higher possibility to flood.

2.3. Particle size distribution transport by shallow flow

With the increment of particle size, the flow rate increases. It is believed that larger size particle will be moved easily as they will subject to greater vertical forces [7]. In Kinta River, it is expected the sediment will come in various sizes. It is important to identify the type of sediment that vary with changing in grains size as all the transport rate of sediment are different. However, other factor such as rainfall, bed roughness and discharge rate of the river should also be considered to improve the accuracy of the simulation.

2.4. The effect of gravitational settling velocity on the particle

Suspended particles in a flowing river are subjected to several forces and transport mechanisms. The effect of gravitational settling velocity cannot be ignored when the particle diameter is bigger than 1µm [25]. For a dilute mixture, the particle motion will depend only on the fluid but not vice-versa. Under the assumption of that the particle acquired full-drag motion in the water, the effect of lift force, unsteady forces and Brownian diffusion can be ignored as relative to drag and gravity [6]. Under all these assumptions, the particle velocity will be equal to the summation of fluid velocity with the settling velocity caused by the gravitational force.

3. METHODOLOGY

3.1. Data collection

The Kinta river topography and dimensions were provided by the Department of Irrigation and Drainage of Negeri Perak (DID). The cross-section detail is given per 500 meters all along the Kinta river starting from Chenderong Balai till Gunung Korbu, Perak.

Site measurement was taken at 4"36'49.0N 101"05'39.0E based on Google Map as shown below. The result from site measurement is used to compare with the data provided by DID for verification.

Figure 1: Location of site measurement in Google Earth

For site measurement, two cross-sections at 50 m intervals were measured. The width and height of the river were measured and recorded along the cross-section. Velocity of the river flow was measured as well at the cross-section by using current-meter. In each point, velocity at 0.2d, 0.6d, and 0.8d were recorded, where d = depth of the river.

3.2. Validation of model by using analytical method

The basic modelling codes for the shallow water flow was provided. With initialisation of the flow parameter of the channel such as initial velocity, discharge, channel length, initial height of water, boundary condition, etc., the resulting water flow parameter could be obtained after the simulation. The particle settling velocity was included in this study to observe the changes in diameter and density of particles would affect its transportation.

A simulation was performed over a simple rectangular channel for validation purpose. The simulation was carried on a rectangular channel with 4 m long and 2 m width. The channel was divided into 300x150 grids. The discharge, initial height of water, velocity of water was set as 0.248m^3/s, 0.185m, and 0.670m/s respectively. The initial location of particle (x,y) is set at (2 , 150). The settling velocity of particle was calculated by using equation (1).

$$\frac{\rho_p * d_p^2}{18\mu} \quad (1)$$

The location of the particle after each iteration was then calculate based on equation (2) which obtained from [6].

$$x_{pi}(t+\Delta t) = x_{pi}(t) + [u_i(x_p, t) + w_s\delta_{ij}]\Delta t \quad (2)$$

Where w_s = settling velocity of the particle in water, and δ_{ij} = Kronecker delta, where is equal to zero in this case since the lattice pattern used was square lattice whereby the width and length is the same. The result obtained from lattice Boltzmann method after simulation would be compared with manual calculation for validation purpose.

3.3. Model simulation

The data obtained from the site measurement are converted into LABSWE™ format in MATLAB. Then, several simulations were carried out by changing with the particle diameter and density. With the simulation performed, the particle motion in the river could be observed as the particle density and diameter were changing.

The simulations were performed by including the settling velocity as mentioned above. The particle release point was set as initial location. After the simulation, the particle motion in the river and final location were recorded.

In lattice Boltzmann method, the river channel was divided into grids of row and column. The water particle and sediment particle would move from one lattice cell into another lattice cell. In this study, the particle was assumed to flow together with the river velocity, and hence the particle velocity could be determined by using interpolation method between the lattice cell. The particle parameter (density, diameter) and computational data used for this project is shown as follows:

Table 1: Particle Parameter

No	Particle Density, kg/m^3	Particle Diameter, mm
1	2636	70
2	2636	510
3	2636	3860
4	3750	71

Table 2: Computational Parameter Used

Grid No	500 x 282
Lattice size, dx	0.1
Time Step	0.005
Total Time of simulation, s	30
Boundary Condition	Bounce-back scheme

A total of six trial simulations were performed with changing the particles density, particle diameter and the initial location of particles. From the site measurement, it was found out that the main sediment that present in the Kinta River was sand. Thus, the particle sample that was carried in the simulation was assumed to be sand particle with density of 2636kg/m^3 and diameter varying from 70µm to 2855µm. The sand particle diameter size and density used are standard values as per [20].

4. RESULT AND DISCUSSION

4.1 River topography and flow characteristics

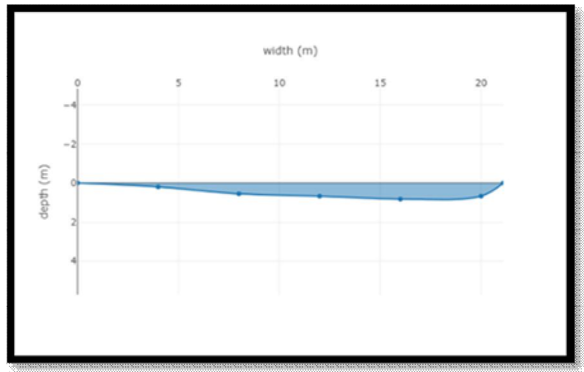

Figure 2: Inflow cross-section (Site measurement)

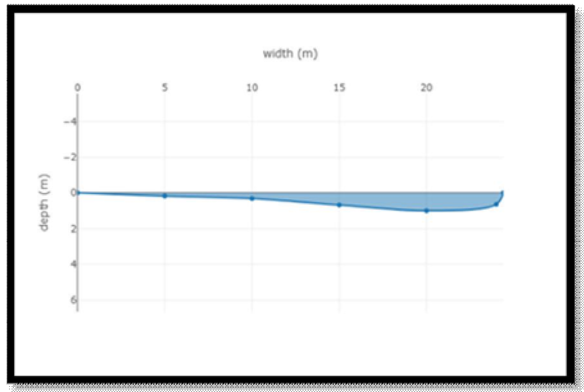

Figure 3: Outflow cross-section (Site measurement)

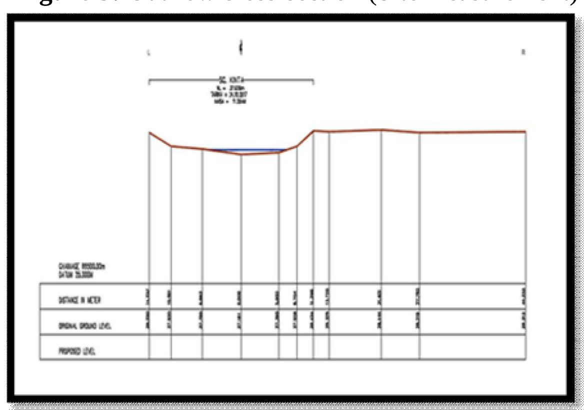

Figure 4: Cross-section of river at chainage provided by (DID)

The site measurement topography obtained is similar with the data provided by DID, thus the topography data from site measurement can be used for this project. However, the water depth provided by DID is shallower than the site measurement result. This is due to heavy rain at one day before the site measurement process. The heavy rain increases the discharge of the river and hence increase the depth of the river. Another cross-section is measured as outflow with 50 m interval from the inflow, but due to the data provided by DID is in 500 m interval, the outflow data from site measurement cannot be compared. The data from DID can help to provide information for the boundary condition.

Table 3: Velocity of River at Inflow Along the Cross-Section (Site Measurement)

Accumulative width (m)	Depth (m)	D at 0.2, 0.6 & 0.8	Rotation	Rotation per Second	Velocity
0	0	0.00	0	0.00	0.00123
		0.00	0	0.00	0.00123
		0.00	0	0.00	0.00123
4	0.22	0.40	54	1.80	0.45804
		0.12	58	1.93	0.49142
		0.16	71	2.33	0.59414
8	0.55	0.11	90	3.00	0.76620
		0.33	132	4.40	1.12572
		0.44	129	4.30	1.10004
12	0.67	0.13	118	3.93	1.00502
		0.40	151	5.03	1.28750
		0.54	149	4.97	1.27210
16	0.82	0.16	144	4.80	1.22844
		0.49	146	4.87	1.24642
		0.66	158	5.20	1.33116
20	0.67	0.13	37	1.23	0.31648
		0.40	33	1.10	0.28433
		0.54	34	1.13	0.29175
21.1	0	0.00	0	0.00	0.00123
		0.00	0	0.00	0.00123
		0.00	0	0.00	0.00123

Table 4: Velocity of River at Outflow Along the Cross-Section (Site Measurement)

Accumulative width (m)	Depth (m)	D at 0.2, 0.6 & 0.8	Rotation per 30 Secs	Rotation per Second	Velocity
0	0	0.00	0	0.00	0.01230
		0.00	0	0.00	0.01230
		0.00	0	0.00	0.01230
5	0.18	0.04	50	1.67	0.42529
		0.11	52	1.73	0.44013
		0.15	67	2.23	0.56846
10	0.32	0.06	61	2.03	0.51710
		0.19	126	4.20	1.07436
		0.26	85	2.83	0.72254
15	0.68	0.14	100	3.33	0.85094
		0.41	127	4.23	1.08206
		0.54	135	4.50	1.15140
20	1	0.20	107	3.57	0.91258
		0.40	121	4.03	1.03070
		0.60	155	5.17	1.32346
24	0.64	0.13	75	2.50	0.63780
		0.38	71	2.37	0.60442
		0.51	87	2.90	0.74052
24.4	0	0.00	0	0.00	0.00123
		0.00	0	0.00	0.00123
		0.00	0	0.00	0.00123

The velocity of the river at is measured along the cross-section with 4 m intervals and 5 m intervals for inflow and outflow respectively. The average velocity obtained will be used for the simulation in MATLAB which is equal to 0.609 m/s. The river topography data and boundary conditions are then converted into programming codes for simulation. The topography and boundary conditions along the 50 m channel generated from MATLAB is shown as follow:

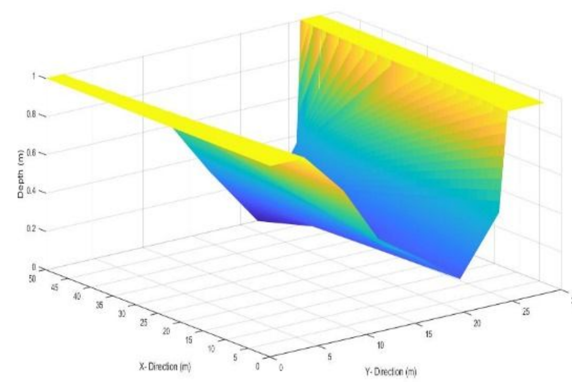

Figure 5: River topography along 50m channel

4.2 Validation of model by analytical method

Particle motion depends on the fluid motion. With the assumption of the particle is in full-drag motion, the particle acquires the fluid velocity [6]. In lattice Boltzmann method, the particle velocity in each lattice cell can be calculate by using interpolation formula. For particles larger than 1µm, the settling velocity caused by the gravitational forces could not be neglected [25]. Thus, the settling velocity equation, Eq 3 is written in MATLAB coding.

The simulation was carried out with the parameters mentioned in previously in section III. The time for simulation is 30 s and after the simulation, the particle moves from its original location (0.026, 2) to (0.294, 2). The particle is expected to travel in a straight-line motion as only velocity in x direction is introduced in the coding and there is no any obstacle or disturbance the flow of the particle. The particle travel for 0.264m with total time of 30 s flow. The result from the simulation is validated by manual calculation and is tabulated.

Table 5: Comparison of Result for Validation

LABSWE™		Manual Calculation	
Initial Location	Final Location	Initial Location	Final Location
(0.027,2)	(0.294,2)	(0.027,2)	(0.295,2)

In manual calculation, the parameters of the flow and particle initial location is set same as in MATLAB. With 15000 iterations of calculation, the particle travel for 0.264m in x-direction. The result generated from lattice Boltzmann method using MATLAB is similar from the result calculated from manual calculation, hence the LABSWE™-Lagrangian Particle Tracking model is valid for particle tracking prediction in river.

4.3 Model simulation

Multiple simulations were carried on by changing the particle diameter and density. The river flow conditions were kept constant for all the simulations. The river flow direction and river height along the channel are illustrated as follows:

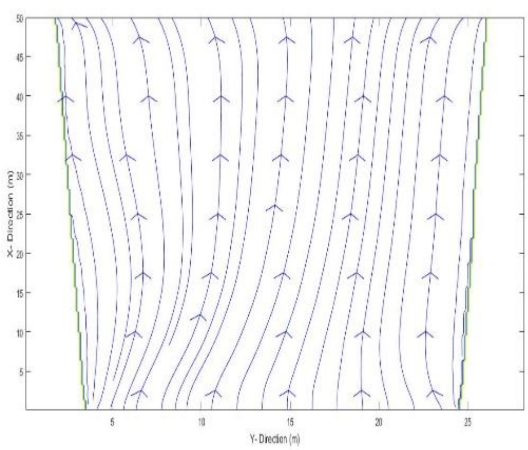

Figure 6: River flow direction along the channel

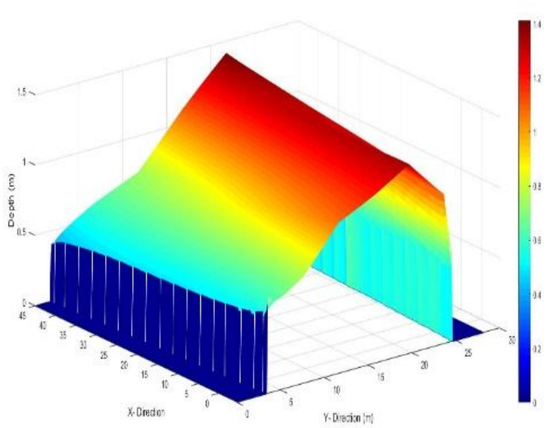

Figure 7: Water height along the channel

A suspended particle traveling in flowing water is exposed to several type of forces which include forces such as drag force, gravitational force and lift force where all these types of forces will affect its transportation in water. In order to neglect the effect of lift forces and drag force acting on the particle, assumption is made such that the particle decay occurs fast enough to obtain full-drag hence particle will carry the same velocity as the water plus the settling velocity [6]. In this scenario, the velocity of particle depends fully on the flow velocity. In Lattice Boltzmann Method, the channel is divided into grid cell of row and columns and the velocity and height of water of each cell is known, thus when the particle is in a grid, the velocity of it could be calculated by using interpolation method. The new location of the particle could be track down by using the equation (2). The results of simulation of particle motion generated LABSWE™-Lagrangian Particle Tracking model by using MATLAB are tabulated as follows:

Table 6: Simulation Results

No	Particle Diameter, μm	Particle Density, kg/m^3	Initial Location	Final Location
1	70	2636	(1,14)	(3.8006,14.3295)
2	515	2636	(1,14)	(3.8006,14.3296)
3	2855	2636	(1,14)	(3.8011,14.3301)
4	71	3750	(1,14)	(3.8006,14.3295)
5	70	2636	(2.5,5)	(8.4223,5.8769)
6	70	2636	(25,14)	(28.6735,14.4881)

The first three simulations were carried on as the initial location of particle is at grid (1,14) with increasing particle diameter from 70 μm, to 515 μm and 2855 μm. The fourth simulation is performed to observed how does the increase of particle density affect the transportation, while the fifth and sixth simulations were carried on by changing the initial location of particle which were (2.5, 5) and (25, 14) respectively. Each of the particle motion are demonstrated in the graphs as follows:

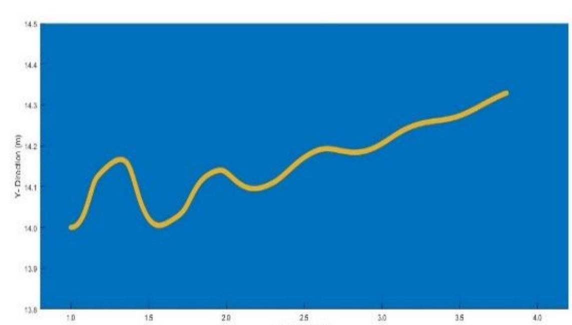

Figure 8: Particle motion with (p=2636kg/m3, diameter= 70μm) at initial location (1,14)

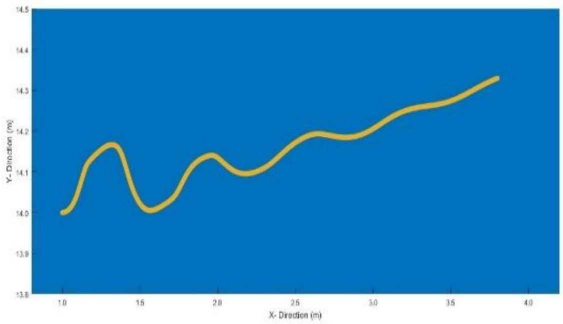

Figure 9: Particle motion with (p=2636kg/m3, diameter= 515µm) at initial location (1,14)

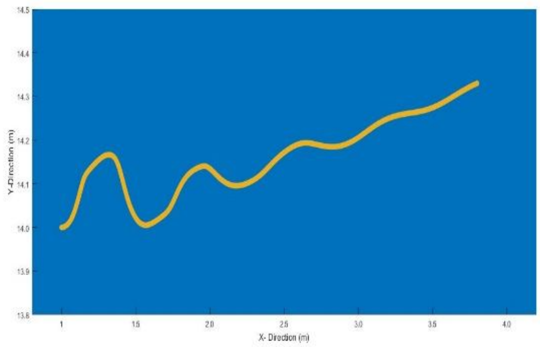

Figure 10: Particle motion with (p=2636kg/m3, diameter= 2855µm) at initial location (1,14)

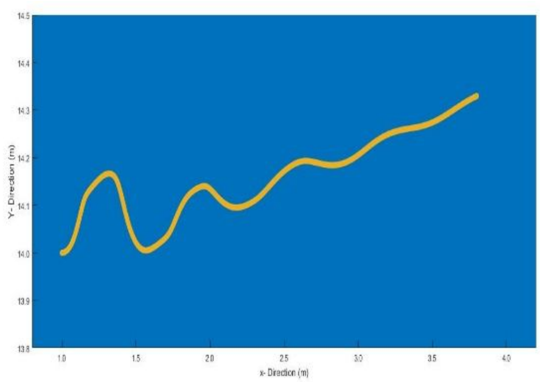

Figure 11: Particle motion with (p=3750kg/m3, diameter= 71µm) at initial location (1,14)

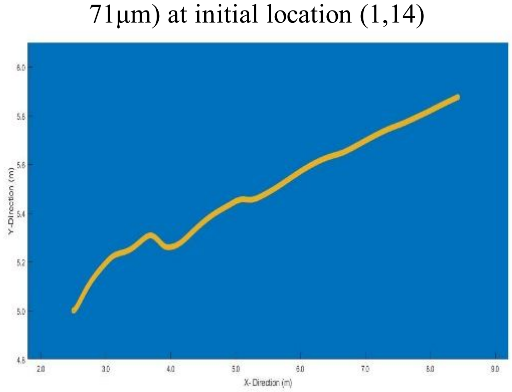

Figure 12: Particle motion with (p=2636kg/m3, diameter= 70µm) at initial location (2.5,5)

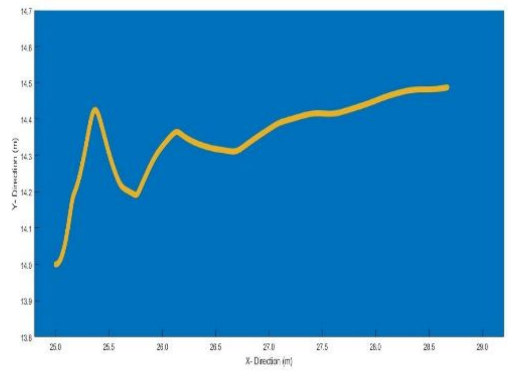

Figure 13: Particle motion with (p=2636kg/m3, diameter= 70µm) at initial location (25,14)

From the results obtained, it is shown that with increment of particle diameter, the particle transportation in term of displacement will increase. Because as the particle size becomes bigger, the particles are subjected to higher vertical forces, and hence the particle will tend to travel more easily than those particles which is smaller in size [7]. Figure 14 shows the final location of particles with same density of 2636kg/m^3 but different diameter of 70 µm and 2855 µm respectively.

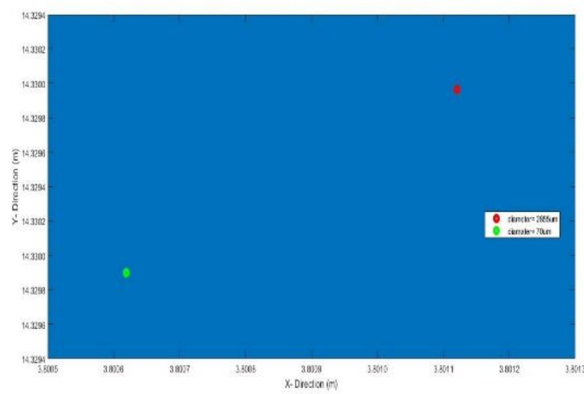

Figure 14: Comparison of final location of particles with diameter 2855 µm (red) and 70 µm (green)

Another simulation was carried out to observe the effect of particle density to its transportation. Theoretically, particle motion with higher density is less as compared to those that have smaller density as particle that is heavier tends to settle faster due to the gravitational force acted on it. However, in this case, the density does not cause significant effect on the particle motion. This is due to the size of particles are too small in the unit of micro-meter and increase of density of the particle does not make significant increase in the weight of the particle.

In summary, with the inclusion of settling velocity into the LABSWE^{TM}-Lagrangian Particle Tracking model, the effect of particle density and diameter onto the particle motion can be observed. Increase on the particle diameter will also increase the sediment transportation distance.

5. CONCLUSION AND RECOMMENDATION

In summary, the settling velocity will affect the transportation of the sediment in the river. The LABSWE^{TM} model is validated and proven by analytical method that it can be apply applied to real life cases. The simulations are based on a few assumptions such as the sediment flow velocity is equal to the flow velocity of water, and the settling velocity is directly affected to the flow velocity of sediment without consideration of any other factor. The model is hoped to be improved by adding more factors in the future such as rainfall density, turbulence flow, and wind driven force whereby all this factor is present in real world scenario. As conclusion, the Kinta River has faced the serious pollution problem due to the siltation and causing the river to be extreme turbid. The siltation in river will change the river flow patterns and can lead to the potential of flooding to the inhabitant area and it will harm the aquatic ecosystem and causing declination of the fishery resources. By performing this research, researchers can understand and identify the sediment transport pattern which is one of the factors that caused the turbidity in the river. With all the information obtained, the researcher can carry on with designing the best engineering solution to cure the existing problems in the river. Finally, understanding more about the flow pattern of river will benefit the future generation of Malaysia as engineers can design a more sustainable living environment.

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