Jurnal Teknologi

Full paper

Statistical Characterisation of Grain-Size Distribution in Fluvial Sediment of Kelantan Rivers

Wan Hanna Melini Wan Mohtar*, Siti Aminah Bassa Nawang, Mojtaba Porhemmat

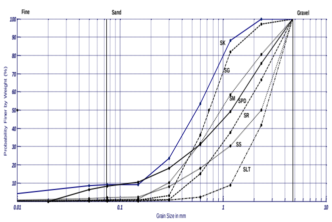
Department of Civil & Structural Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, Malaysia

*Corresponding author: hanna@eng.ukm.my

Article history

Received 23 February 2015
Received in revised form
11 March 2015
Accepted 8 April 2015

Graphical abstract



Abstract

The characteristic of sediment, in particular the particle size distribution is important to be correctly determined for an accurate representation in sediment transport. This article reports the grain size distributions of soil samples taken from seven tropical rivers i.e. the Sungai (Rivers) of Sam, Galas, Lata Tunggil, Mei, Rek, Peng Datu and the major Sungai Kelantan catchment area which spanned about 11, 900 km^2. The Sungai Galas is a direct tributary, whilst the Sungai Sam, Sungai Rek, Sungai Mei and Sungai Lata Tunggil are the tributaries into Sungai Lebir which subsequently feeds the Sungai Kelantan. Each obtained sample was sieved and the soil type distribution was determined. Statistical analysis of the samples was conducted; including the median grain sized_{50}, mean grain size, standard deviation (sorting), skewness and kurtosis. Most of the samples have insignificant fractions of finer grains, where coarse sand and gravel were the dominant. All sediment samples are negatively skewed towards coarse sand, have very platykurtic kurtosis suggesting that the sediment has single provenance.

Keywords: Statistical characterisation; fluvial sediments; particle size distribution; Kelantan rivers

Abstrak

Ciri-ciri sediment terutamanya taburan saiz partikel adalah penting untuk ditentukan dengan tepat untuk memastikan perwakilan jelas di dalam pengangkutan sedimen. Artikel ini melaporkan taburan saiz sedimen bagi sampel tanah yang diambil dari dasar tujuh sungai tropikal iaitu Sungai Sam, Galas, Lata Tunggil, Rek, Mei, Peng Datu dan kawasan tadahan utama Sungai Kelantan yang mempunyai keluasan 11,900 km^2. Sungai Galas adalah cawang langsung, manakalah Sungai Sam, Sungai Rek, Sungai Mei dan Sungai Lata Tunggil adalah cawang sungai kepada Sungai Lebir, di mana alirannya masuk ke dalam Sungai Kelantan. Setiap sampel di ayak dan taburan jenis tanah ditentukan. Analisa statistik untuk sampel yang diambil dijalankan termasuk mengenalpasti saiz butir median d_{50}, saiz butir purata, sisihan piawai (pengisihan), kepencongan dan kurtosis. Kebanyakan sampel mempunyai pecahan butiran kecil yang tidak signifikan, di mana pasir kasar dan kelikir adalah lebih dominan. Kesemua sampel mempunyai kepencongan negatif ke arah pasir kasar, jenis sangat platikurtosis di mana data mencadangkan bahawa sedimen terambil mempunyai provenan atau asal tunggal.

Kata kunci: Perincian statistic; sedimen fluvius; taburan saiz partikel; sungai-sungai di Kelantan

1.0 INTRODUCTION

Hydraulic transport of sediment not only sorted but also redistributed particles and changes the distribution of grain sizes in fluvial sedimentary systems. Differential in entrainment, transport and deposition of particles is promoted based on their size and shape (Russell, 1939). The transport rate depends on the homogeneity of the sediment mixture, where the sediment is commonly being transport in individual size fractions (Einstein and Chein, 1953). In non-homogeneous sediment mixture, hiding effect or shielding of small particles from the flow by larger particles resulted in varying fractions of transported sediment than their relative proportions in bed materials (Parker, 1982; Gomez, 2001).

The investigation of fluvial bed materials permits an identification of dominant sediment type in a particular river. Sand or gravel dominated fluvial sediments usually have varying range of grain size distributions. In gravel dominated particularly, the marginal difference in available sizes may vary from fine to coarse sediment up to 5 mm in size. Gravel-bed rivers have specific stream powers from 30 to 100 Wm^{-2} and sufficient to promote vigorous lateral bed activity (Knighton, 2014). They appear to develop at locations where sediment deposition is favoured, referred to as ‘sedimentation zones’ (Church, 1983).

Grain size distribution is one of the important characteristics in developing the sediment transport models including the incipient sediment motion and total sediment load capacity. In those models, commonly used parameter obtained is the median grain diameter d_{50}. The determination is often estimated by linearly interpolating between the percentages of 50th percentile to the empirical data distributions. Full particle size distributions also indicate the homogeneity of the sediment mixture through the standard gradation parameter $\sigma = \sqrt{d_{84}/d_{16}}$, where d_{84} and d_{16} are the 84th and 16th percentile grain diameters, respectively. Statistical analysis of grain size distribution also provides the transport history, sediment origin and the condition for deposition (e.g. Folk and Ward 1957) (Blott, 2001).

The determination of grain size distributions for fluvial sediment is a laborious process. Accurate representation of the physical parameters in fluvial sediment mixture assists in the determination of local bed and suspension loads to a high degree of certainty. Furthermore, the identification of soil properties may assists in the determination of the bed roughness parameter, i.e. the Manning's *n* value which is usually being assumed.

This article describes the sediment distribution of fluvial sediment in seven tropical rivers of Kelantan, Malaysia. Methodology of sampling, sieving process and statistical analysis are discussed in detail in the following subsections.

■2.0 METHODOLOGY

2.1 Study Area

Sediment samples from seven rivers (i.e. Sungai Sam, Sungai Lata Tunggil, Sungai Mei, Sungai Rek, Sungai Peng Datu, Sungai Galas and Sungai Kelantan) in the state of Kelantan, north east of Malaysia, were collected. Table 1 lists the specification of each river including length, distance from coastline, catchment area and river pattern. Sungai Galas and Sungai Lebir are the tributaries to the Sungai Kelantan, the major river in Kelantan with 248 km long which flows through the main towns of Kuala Krai, Tanah Merah and Pasir Mas and capital Kota Bharu and directly goes to the coastal waters. The catchment area of Sungai Kelantan spanned about 12,000 km^2 includes several activities of plantation and developed urban areas (Ahmad *et al*. 2009).

Figure 1 Map of sampling site

Rivers of Sam and Lata Tunggil, Mei and Rek are the tributaries to the wider Sungai Lebir, which subsequently contributed to the Sungai Kelantan, as shown in Figure 1. All tributaries to Sungai Lebir discussed here are small rivers, where the water is clear with minimal presence of suspended solids. Minimum human activities were seen and the river banks are immediately adjacent to a thick forest area.

Sungai Galas on the other hand, is a big river spanning about 180 km and catchment area of approximately 11,300 km^2. The river banks offer shelter to remote small villages with no accessible road. Both Sungai Galas and Sungai Kelantan were observed to have high turbidity. Research conducted by Ambak and Zakaria (2010) found ~~out~~ that the increasing turbidity due to high suspended solids and siltation is due to upstream sand mining activities.

All rivers were found to be meandering except Sungai Rek and Sungai Lata Tunggil who falls under the category of braided.

Table 1 Specification of each river studied including length, distance from coastline, catchment area and river pattern

Name of the river	Length (km)	Distance from coastline (km)	Catchment area (km^2)	River Pattern
Sg. Kelantan (SK)	248	3.28	11,900	Meandering
Sg. Galas (SG)	179.5	103	11,300	Meandering
Sg. Sam (SS)	18.08	137.2	30	Meandering
Sg. Rek (SR)	23.7	139.6	100	Braided
Sg. Peng Datu (SPD)	39.4	4.21	50	Meandering
Sg. Mei (SM)	34.2	118	17	Meandering
Sg. Lata Tunggil (SLT)	18.8	128.5	150	Braided

2.2 Data Collection

Samples of sediment were taken at the center of each river using a grab sampler and were immediately sealed in an airtight container. Samples were dried in the oven at 105°C for 12 hours prior physical sieving. Sieve analysis is a procedure used commonly in engineering to assess the particle size distribution of a granular material includes of sand (Sonaye and Baxi, 2012). The sample was sieved using sieve series, including 4.75, 2.36, 1.18, 0.6, 0.3, 0.15 and 0.075 mm in sizes. The nest of sieves was put through on sieve shakers for ten minutes. The percentages of the sample retained and passed through the sieves were calculated using the following formulas:

$$\text{\% retained: } \frac{\text{Mass of soil}}{W_f} \times 100 \quad (1)$$

$$\text{Mass Loss (\%): } \frac{W_f}{W_t} \times 100 \quad (2)$$

(is accepted if less than 2%)

W_f = Weight after sieving
W_t = Weight before sieving

The particle size distribution of particle below than 75 µm was further determined using the Mastersizer 2000 (MU) where minimum detected size is 2 µm. The speed of the pump (2500 r.p.m.) was selected so as to obtain maximum homogenization of the suspension in a beaker while eliminating the air bubbles from the suspension. The statistical analysis of the size distribution for each sample was determined using the formulae from Folk and Ward (1957) obtained from the cumulative probability curves. Sediment type of clay, silt, fine sand and coarse sand is identified as sediment with sizes of < 0.002 mm, 0.002-0.5 mm and > 2 mm, respectively.

The statistical measurements includes measure of central tendency (median, mode and mean); a measure of degree of scatter or sorting, kurtosis, the degree of peakedness, and skewness. The logarithmic original formula for Folk and Ward (1957) as described in Table 2.

Table 2 Statistical formulate used in the calculation of grain size parameters using the logarithmic Folk and Ward (1957) graphical measures

Mean (M_z)	Standard deviation (σ_1)	Skewness (Sk_1)	Kurtosis (K_G)
$(M_z)=\frac{\varphi16+\varphi50+\varphi84}{3}$	$(\sigma_1)=\frac{\varphi84-\varphi16}{4}+\frac{\varphi95-\varphi5}{6.6}$	$(Sk_1)=\frac{\varphi16+\varphi84-2\varphi50}{2(\varphi84-\varphi16)}+\frac{\varphi5+\varphi95-2\varphi50}{2(\varphi95-\varphi5)}$	$(K_G)=\frac{\varphi95-\varphi5}{2.44(\varphi75-\varphi25)}$

Sorting (σ_1)		Skewness (Sk_1)		Kurtosis (K_G)	
Very well sorted	<0.35	Very fine skewed	$^+0.3$ to $^+1.0$	Very platykurtic	<0.67
Well sorted	0.35-0.5	Fine skewed	$^+0.1$ to $^+0.3$	Platykurtic	0.67-0.9
Moderately well sorted	0.7-1.00	Symmetrical	$^+0.1$ to $^-0.1$	Mesokurtic	0.9-1.11
Poorly sorted	1.00-2.00	Coarse skewed	$^-0.1$ to $^-0.3$	Leptokurtic	1.11-1.5
Very poorly sorted	2.00-4.00	Very coarse skewed	$^-0.3$ to $^-1.0$	Very leptokurtuic	1.5-3.00
Extremely poorly sorted	>4.00			Extremely leptokurtic	>3.0

The coefficient of uniformity C_u and coefficient of curvature C_c are obtained as

$$C_u = d_{60}/d_{10}, \quad \text{and} \qquad (3)$$

$$C_c = (d_{30}d_{30})/(d_{10}d_{60}), \qquad (4)$$

where the subscript numbers denote the percentages of passing in the cumulative curves.

3.0 RESULT AND DISCUSSION

The bed material size was analysed in terms of the median grain size d_{50}, d_{84}, gradation parameter σ_g.

Prior to the detailed discussion on the size characteristics, images shown in Figure 2 give a visual representation of the sediment type and distribution.

Figure 2 Visual presentation of samples collected from downstream of (a) Sungai Kelantan, (b) Sungai Galas, (c) Sungai Lata Tunggil (d) Sungai Sam (e) Sungai Mei, (f) Sungai Rek and (g) Sungai Peng Datu

Sediment taken from Sungai Galas, Sungai Lata Tunggil, Sungai Rek and Sungai Peng Datu was found to be uniformly near-spherical shape, whilst the samples from Sungai Kelantan, Sungai Sam and Sungai Mei are near-spherical sediment with fractions of sub-angular particles.

The particle size distribution obtained for each Sungai is presented in Table 3, including the median grain size d_{50}, standard gradation parameter σ, soil type distribution and the classification of soil, according to the Unified Soil Classification System (USCS) and Unified Soil Department of Agriculture (USDA) guidelines.

The sediment taken from the Sungai Sam will be first discussed. The median size found is about 2.37 mm and the sediment is non-uniformly distributed as shown by its gradation parameter value more than 1.4. As the Sungai Sam has no tributary river, the bigger sediment size or coarse sand was expected. Sediment was identified as sandy loam with the sediment is approximately equally distributed between coarse sand and gravel, 49.5 and 48.5%, respectively. A tiny fraction of 1.99% of silt and minimum presence of clay can be found. The sample was categorized as poorly graded sand and silt loam according to USCS and USDA, respectively.

Sungai Lata Tunggil has quite significant fraction of sand, negligible presence of cohesive sediment and most of the sediment found falls under the category of gravel. Lata Tunggil also has no tributary river and the river is less deep than the Sungai Sam. The sediment collected falls under the category of silt loam, quite uniformly distributed with median grain size d_{50} of 2.67 mm.

Both small rivers of Mei and Rek have comparable gradation parameter between 2.2 to 2.5, although their median grain sizes are different with the former river has 0.95 mm compared to slightly bigger 1.61 mm of size in Sungai Rek. Bed materials from both rivers have minimum percentage of clay and silt and mostly fall under the sand category. Even so, it should be highlighted that significant fractions of gravel were available up to 32%. The sediment obtained from Sungai Mei and Sungai Rek were classified as sand and sandy loam, respectively according to USDA.

The wider Sungai Galas has very fine sand with d_{50} is about 0.72 mm, (rather) uniformly distributed sediment and falls under the category sand loamy. Small percentage of ≈3% of gravel was found in the sample. This is to be expected as the point taken for sampling in this river is very much downstream and about 86.6 km from the converging point with Sungai Lebir to Sungai Kelantan.

The sediment sample of Sungai Kelantan was collected about 3.37 km from the coastal waters. Data shows that the median grain size d_{50} obtained was 0.56 mm and the sediment is non-uniformly distributed. Negligible percentage of clay and gravel was available and a small quantity of silt. The sediment in Sungai Kelantan was identified as sand with almost range of 91% sediment was found to be between the 0.05 to 2 mm sediment sizes.

Sungai Peng Datu has percentage sediment distribution of approximately 8/69/23 of silt/sand/gravel, respectively. The bed materials with median grain size of 1.21 mm and relatively high gradation parameter of 4 were categorized as sandy loam. Note that the sediment distribution of two rivers to the ocean (i.e Sungai Kelantan and Sungai Peng Datu) has different characteristics. All samples obtained from the seven rivers were negatively skewed towards coarse sand and has very small percentage of cohesive sediment, where only <1% fraction of clay and about <5% of silt, even for sediment at the near-shore location of Sungai Kelantan. It was perceived that towards the coastal area, the size distribution is expected to fall under the category of fine sand. However, data shows this was not the case.

The discussion is continued with the statistical analysis conducted, where Figure 3 shows the collective cumulative probability curve for each sediment sample. The curves provide the graphical measures to calculate the mean, standard deviation, skewness and kurtosis for each sample. Data shows that all samples have similar grain-size spectra, where most of the sediments are in the regions of sand and gravel. The mono-segmental cumulative curves often characterise the sediment as aeolian deposits, but also can be found for fluvial deposits, in particular in meandering rivers (Mycielska-Dowgiallo, 2011). Sediment from Sungai Lata Tunggil is well-sorted, characterised by the steeply inclined section (i.e. range between $1 < d < 4$ mm) is within 75^{o}. Admixtures of finer grains and gravel are also evident from the cumulative curves of Lata Tunggil. Other samples show a rather poorly sorted sediment distribution, characterised by the inclination of the middle section is around the value of 30-40^{o}. The sediment is speculated to be deposited from high-energy currents, that is during settling, the gravel-sized particles are deposited first, then the finer grains are trapped between them (Garde, 1972). Both meandering and braided rivers (in this study) evidently show similar grain-size spectra.

Interestingly, the cumulative curves are the steepest for Sungai Lata Tunggil bed materials and consistently less steep towards Sungai Kelantan. This evidently shows that for upstream rivers, bed materials are consistently larger in size. As coming towards the coastal area, the distribution of bed materials are more varied in sizes as shown here in Figure 3.

3.1 Statistical Parameters of Fluvial Sediment in Kelantan Rivers

The common statistical parameters of the grain size were calculated using the formulae developed by Folk and Ward (1957) for each sample. The classifications of skewness $Sk$and kurtosis K, were done also based on the description defined by Folk and Ward (1957). Table 4 lists all the statistical parameters for each river including coefficient of uniformity and coefficient of curvature.

Data shows that all samples have unimodal type of sediment, negatively skewed and all samples were kurtosis classified as very platykurtic. This suggests that the sediment from these seven samples is well distributed, but heavily sorted at one tail of the grain size distribution, as showed in the analysis.

The extreme low values of kurtosis suggest that part of the sediment is sorted elsewhere in a high energy environment (Friedman, 1962). Dominant very platykurtic nature of sediment is likely due to continuous addition of finer/coarser materials in varying proportions (Prabhakara, 2001).

Values of coefficient of uniformity C_u for all samples were found within the range of 0.83-1.51, suggesting that the samples are considered as poorly or uniformly graded. This conforms to the measured coefficient of curvature C_c, where most of the samples were out of range between 1 to 3. Note that although samples from Rek and Galas lies within the well graded category, the both samples has $C_u < 4$. Data shows bed materials from Sungai Peng Datu has the largest ranges of particle sizes with the highest C_c 11.9.

Table 3 The sediment characteristics, percentage of soil type and classification of sediment samples according to the USCS and USDA. SP and SW denote poorly graded sand and well graded sand, respectively

Sample	d_{50} (mm)	σ	Soil (%) Clay (< 0.002)	Silt (0.002 - 0.05) (mm)	Sand (0.05–2)	Gravel (>2)	USCS	USDA
Sungai Kelantan	0.56	3.02	0.77	8.12	91.04	0.08	SP	Sand
Sungai Galas	0.72	1.73	0.02	0.53	96.56	2.88	SP	Sand
Sungai Mei	0.95	2.59	0.03	0.91	79.78	19.28	SP	Loamy sand
Sungai Sam	2.37	2.72	0.12	1.87	49.48	48.53	SW	Silt loam
Sungai Rek	1.61	2.22	0.48	0.62	66.95	32.4	SP	Sandy loam
Sungai Lata Tunggil	2.67	1.67	0.01	0.12	41.97	57.9	SP	Silt loam
Sungai Peng Datu	1.21	4.00	0.39	7.8	69.21	22.6	SW	Sandy loam

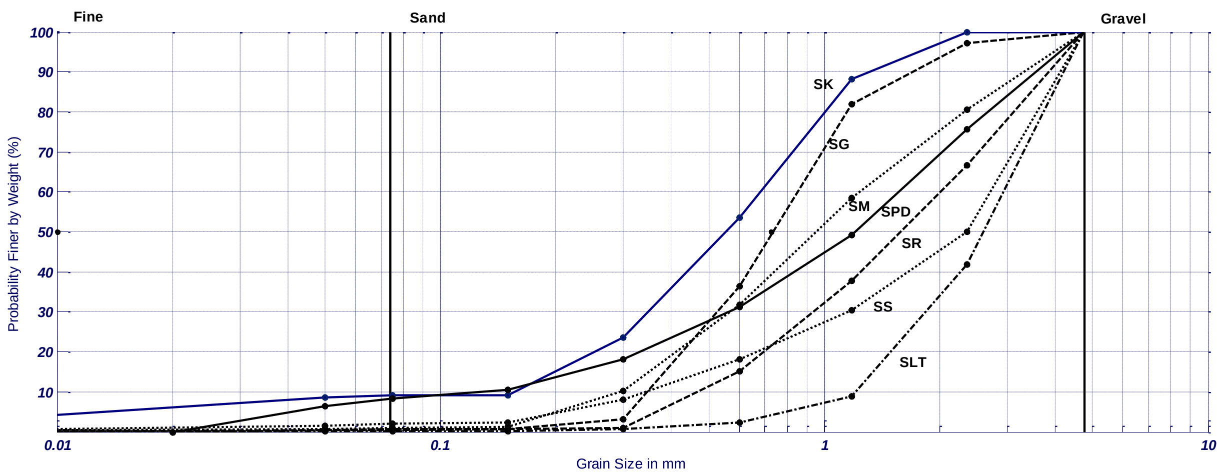


Figure 3 Cumulative Probability Curve of (a) Sungai Kelantan, SK (d_{50}=1.06), (b) Sungai Galas, SG (d_{50}=0.14), (c) Sungai Lata Tunggil , SLT (d_{50}=2.07), (d) Sungai Sam, SS (d_{50}=1.64)

Table 4 Statistical analysis of the grain size parameters for each sediment sample obtained

	Sungai Kelantan	Sungai Galas	Sungai Sam	Sungai Mei	Sungai Rek	Sungai Lata Tunggil	Sungai Peng Datu
Mean Grain Size $\bar{d}$ (mm)	0.54	0.75	1.72	0.99	1.51	2.55	0.98
Skewness Sk	1.26	1.73	1.43	0.97	1.08	1.19	0.52
Kurtosis K	0.28	0.47	0.55	0.56	0.59	0.52	0.45
Coefficient of uniformity (C_c)	1.14	0.89	1.32	0.89	0.84	1.03	1.51
Coefficient of curvature (C_u)	3.93	2.00	8.15	4.16	3.79	2.45	11.88
Skewness classification	Very fine skewed	Very fine skewed	Very fine skewed	Very fine skewed	Very fine skewed	Very fine skewed	Very fine skewed
Kurtosis classification	Very platykurtic	Very platykurtic	Very platykurtic	Very platykurtic	Very platykurtic	Very platykurtic	Very platykurtic

■4.0 CONCLUSION

The sediment samples collected at the (selected) rivers in Kelantan shows that the fluvial bed materials have homogenous sedimentary environment. Most of the samples have significant fractions of sand and gravel whereas finer grains of silt and clay have minimal percentage, even for sediment collected at near coastal line. Upstream river, as shown by Sungai Lata Tunggil has well sorted sediment distribution. Even so, the other tributaries shows no similar grain size distribution with Lata Tunggil and the sediment fall under the category of poorly sorted.

The unimodal frequency distribution suggests a single provenance for the sediments.

Acknowledgement

This research was given the financial support by grants from the Ministry of Education (ERGS/1/2013/TK03/UKM/02/7) and the Ministry of Science, Technology and Innovation (06-01-02-SF-1077). We thank Mohd Faizan and Ahmad Amirul for their help during the field work.

References

[1] Ahmad, A. K., Mushrifah, I., and Mohamad, S. O. 2009. Water Quality and Heavy Metal Concentrations in Sediment of Sungai Kelantan, Kelantan, Malaysia: A Baseline Study. *Sains Malaysiana*. 38(4): 435–442.

[2] Blott, S. J. and Pye K. 2001. Gradistat: A Grain Size Distribution and Statistics Package for the Analysis of Unconsolidated Sediments. *Earth Surface Processes and Landforms*. 26: 1237–1248.

[3] Bieganowski, A., Witkowska-Walczak, B., Glinski, J., Sokolowska, Z., Slawinski, C., Brzezinska, M. and Wlodarczyk, T. 2013. Database of Polish Arable Mineral Soils: A Review. *Int. Agrophys*. 27: 335–350.

[4] Church, M. 1983. Pattern of Instability in a Wandering Gravel Channel Bed. Special Publs. *Int. Ass. Sediment.* 6: 169–180.

[5] Einstein, H. A., and N. Chien. 1953. Transport of Sedimen Mixtures with a Larger Ange of Grains Sizes. M., R. D. Ser.2 , U.S. Army Corps of Eng. Mo. River Div. Omaha.

[6] Folk, R. L., Ward, W. C. 1957. Brazos Sungai Bar: A Study in the Significance of Grain Size Parameters. *Journal of Sedimentary Petrology*. 27(1): 3–26.

[7] Friedman, G. M. 1967. Dynamic Processes and Statistical Parameters Compared for Size Frequency Distribution of Beach and River Sands. *Journal of Sediment Petrology*. 37: 327–354.

[8] Garde, R. J. 1972. Bed Material Characteristics of Alluvial Streams. *Journal of Sedimentary Petrology.* 7: 127–135.

[9] Gomez, B., Rosser, B. J., Peacock, D. H., Hicks, D. M. and Palmer, J. A. 2001. Downstream Fining in a Rapidly Aggrading Gravel Bed River. *Water Resources Research*. 37(6): 1813–1823.

[10] Knighton, D. 2014. *Fluvial Forms and Processes: A New Perspective.* Routledge, New York.

[11] McLaren, P. and Bowles, D. 1985. The Effects of Sediment Transport on Grain-size Distribution. *Journal of Sedimentary Research*. 55(4): 457–470.

[12] Miliman J. D., Ren M. 1995. Climate Change: Impact On Coastal Habitation, Chapter 4: River Flux To The Sea: Impact Of Human Intervention On River Systems And Adjacent Coastal Area. United States. CRC Press.

[13] Mycielska-Dowgiallo, E. & Ludwikowska-Kedzia, M. 2011. Alternative Interpretations of Grain-size Data from Quarternary Deposits. *Geologos*. 17(4): 189–203.

[14] Sochan, A., Bieganowski, A., Ryzak, M., Dobrowolski, R. and Bartminski, P. 2012. Comparison of Soil Texture Determined by Two Dispersion Units of Mastersizer 2000. *International Agrophysics*. 26: 99–102.

[15] Sonaye, S. Y. & Baxi, R. N. 2012. Particle Size Measurement and Analysis of Flour. *International Journal of Engineering Research and Applications (IJERA)*. 2(3):1839–1842

[16] Tasdemir, A., Huseyin, O. and Guven, O. 2011. Image Analysis of Narrow Size Fractions Obtained by Sieve Analysis-An Evaluation by Log-normal Distribution and Shape Factors. *Journal of Physiochemical Problems of Mineral Processing*. 46: 95–106.

[17] Prabhakara, Rao., A., Anilkumar, V., Yugandhar Rao, A., Ravi G. S. and Krishnan, S. Grain Size Parameters in the Interpretation of Depositional Environments of Coastal Sediments Between Bendi Creek and Vamsadhara River, East Coast, India. *Journal of Indian Association Sedimentologist*. 20(1): 106–116.

[18] Russell, R . D. 1939. Effects of Transportation on Sedimentary Articles. In Recent Marine Sediments edited by P. D. Trask. Am. Assoc. of Pet. Geol. Tulsa, Okla. 33–47.

[19] Parker, G., P. C. Klingerman, and D. G. McLean. 1982. Bedload and Size Distribution in Pavedg Ravel-bed Streams. *J. Hydraul. Div. Am. Soc.Civ. Eng.* 108: 544–571.