TECHNICAL REPORT

APPLICATION OF GEOSTATSTICAL METHODS FOR ANALYZING SEDIMENTATION PATTERN IN RIVER BASINS OF KERALA STATE

NATIONAL INSTITUTE OF HYDROLOGY

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NATIONAL INSTITUTE OF HYDROLOGY

HARTD ROCK REGIONAL CENTRE

BELGAUM, KARNATAKA

2016

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APPLICATION OF GEOSTATSTICAL METHODS FOR ANALYZING SEDIMENTATION PATTERN IN RIVER BASINS OF KERALA STATE

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Study Group

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NATIONAL INSTITUTE OF HYDROLOGY
REGIONAL CENTRE
BELGAUM

2014

PREFACE

Analysis of spatial and temporal distribution of sediment deposition is an important area of study as far reservoirs are concerned. In geostatics, parameters concerned are analysed to reveal their spatial structure and inter-relationships. Processes like sedimentation have structural and random characteristics with variation in space and time. Thus, sedimentation is appropriately considered as a regionalized variable. Therefore, analysis of spatial correlation structure of sediment yield at various locations of different catchments may reveal the regional sedimentation characteristics. The estimates based on geostatistical analyses are considered to be better estimates of mass fluxes compared to those obtained through conventional methods. Analysis of sediment distribution pattern of west-flowing rivers of Kerala has been carried out by giving due consideration to regional as well as seasonal aspects. The sediment data has been partitioned into regional zones as well as seasonal (SW & NE monsoonal) basis to investigate variabilities. Spatial analysis of sediment yield data of the study area has been carried out using the software SGeMS available in public domain.

The analyses were based on regional variations, seasonal variations as well as monsoonal behavior in the northern and southern parts of the study area and carried out under various cases. In the first case data of the whole region is taken together and did the analysis. In the second and third cases, the study is divided into two zones of North and South regions separately to investigate any regional disparity. In the other cases seasonal variations of the monsoonal rainfall characterized by the southwest and northeast monsoon have been analyzed separately for the whole area as well as for the designated zones also.

Presented report of the study carried out by Dr. Mathew K Jose, Scientist D (Principal Investigator) along with Dr. T. Chandramohan of HRRC NIH contains technical brief on the subject matter, analyses and results using geostatistical methods. It is expected to provide useful information on the subject matter.

R D Singh
(DIRECTOR)

ABSTRACT

Analysis of spatial and temporal distribution of sediment deposition is an important area of study as far reservoirs are concerned. Processes like sedimentation have structural and random characteristics with variation in space and time. Thus, sedimentation is appropriately considered as a regionalized variable. Therefore, analysis of spatial correlation structure of sediment yield at various locations of different catchments may reveal the regional sedimentation characteristics. The estimates based on geostatistical analyses are considered to be better estimates of mass fluxes compared to those obtained through conventional methods. In geostatics, parameters concerned are analysed to reveal their spatial structure and inter-relationships.

Analysis of sediment distribution pattern of west-flowing rivers of Kerala has been carried out by giving due consideration to regional as well as seasonal aspects. The sediment data has been partitioned into regional zones as well as seasonal (SW & NE monsoonal) basis to investigate variabilities. Spatial analysis of sediment yield data of the study area has been carried out using the software SGeMS available in public domain. For spatial analyses, the long term averages of the sediment data were computed initially, and the long term mean value of each data sampling location were used. The study area consists of various river basins of Kerala state situated in the humid tropics and bound by $8^{0}18'$ N & $12^{0}48'$ N and $74^{0}52'$ & $77^{0}22'$E. In the study area there are 41 rivers flowing westward and 3 rivers flowing eastward originating in the Western Ghats. The state is characterized by distinct rainfall patterns consisting of SW monsoon during June to September and NE monsoon during October to December. The nature of rainfall, their intensities and spatial distribution vary between these two seasons.

The analyses revealed that north region has yielded comparatively good spatial correlation structure in both the monsoon seasons. During NE monsoon, Southern region yielded more sediment compared to northern region, possibly due to intense rainfall in the south during NE monsoon. However, sediment contribution from the northern region during SW monsoon is much higher compared to the southern region. For the south region, during SW monsoon, sediment yield has a variance just half of that of NE monsoon. Therefore, the sediment yields in the southern parts are highly variant during the NE monsoon period.

It has been identified that the sedimentation characteristics in river catchments in the study area (state of Kerala) exhibits considerable variation from northern parts of the state to southern side and also seasonally. The quantitative increment in sediment yield towards the southern parts of the state during NE monsoon may be due to the highly intense storms (thunderstorms) during the post-monsoon (ie. NE monsoon) period.

TABLE OF CONTENTS

PREFACE

TABLE OF CONTENT

ABSTRACT

INTRODUCTION

OBJECTIVES

DESCRIPTION OF STUDY AREA

REVIEW OF LITERATURE

METHODOLOGY

FIELD INVESTIGATIONS AND DATA COLLECTION

ANALYSIS AND DISCUSSION

CONCLUSION

REFERENCES

Introduction:

Sediment transport is an important aspect of river flows. It consists of the suspended particles and bed load material. The observation and analysis of sediment yield from various rivers are being carried out in the country by State agencies as well as Central agencies like Central Water Commission. The analysis of sediment yield data over long periods is helpful in investigating and understanding the distributional characteristics and pattern of sedimentation in river basins. Presented is a brief report of the works carried in this direction using the long term data record of sediment for the rivers of Kerala State.

Sediment is a naturally occurring material which is broken down by processes of weathering and erosion, and is subsequently transported by the action of wind, water, or glacier, and/or by the force of gravity acting on the particles. Sediment particles size ranges from small rocks and coarse gravel to silt and clay particles as fine as talcum powder.

Sediment transport starts once the shear stress acting on the bed exceeds the critical shear stress of the bed material, then sediment particles start moving in the general direction of flow from the high region above sea level to low region. The high region is characterized by comparatively few streams with poor drainage as they have high gradients. When the region advances to relatively medium gradient region the drainage is better developed with the number of increasing well established streams. Finally when all main streams have very flat slope, their velocities are low and transporting power of sediment is very limited.

Sediments transported depend on the flow conditions, ratio of densities of sediment and fluid and the size of the particle. The modes of transport can be classified into the following categories:

Contact load:

The sediment particles that roll or slide along the bed for some time, then come to rest and again start rolling or sliding constitute the contact load.

Saltation load:

The sediment particles hopping or bouncing along the bed thereby losing contact with the bed for sometime constitute Saltation load.

Bed-load:

Since Saltation load, especially in streams, is difficult to measure, it is clubbed with contact load and sediment moved on or near the bed is called bed-load.

Suspended load:

Suspended load is the material moving in suspension in the fluid, being kept in suspension by the turbulent fluctuations.

Sediment transport is not constant because it is constantly subject to changes. In addition to the changes in sediment load due to geology, geomorphology and organic e lements, sediment transport can be altered by other external factors. The alteration to sediment transport can come from changes in water flow, water level, weather events and human influence.

The methods and equipment used for sampling suspended sediment are different from those used for deposited sediments due to different discharges. Discharge measurement is generally carried out by current meters; also sampling methods and measurements of the quantity of sediment in transport are different. The reason for these differences reflects the fact that sediment sampling methods depend on the particle distributed in depth which is carried out by integrated samplers, instantaneous grab samplers, pump samplers, and sedimentation traps, whereas sediment quantity focuses on the sediment particle fraction (clay, silt, gravel, fine etc...) by sieve analysis which is not depth-dependent.

Statistics:

Statistics is concerned with scientific methods for collecting, organizing, summarizing, presenting and analyzing data as well as deriving valid conclusions and making reasonable decisions on the basis of this analysis. Statistics is concerned with the systematic collection of numerical data and its interpretation. There are two major types of statistics:

1) Descriptive statistics consist of methods for organizing and summarizing information.
2) Inferential statistics consist of methods for drawing and measuring the reliability of conclusions about population based information obtained from a sample of the population. (Weiss, 1999)

Compared to the classic statistics which examine the statistical distribution of a set of sampled data, geostatistics incorporates both the statistical distribution of the sample data and the spatial correlation among the sample data. Because of this difference, many earth science problems are more effectively addressed using geostatistical methods.

In its broadest sense, geostatistics can be defined as the branch of statistical sciences that studies spatial/temporal phenomena and capitalizes on spatial relationships to model possible values of variable(s) at unobserved, unsampled locations" (Caers, 2005)

Objective:

Spatial analysis of sediment yield data from major rivers of Kerala state, in order to investigate regional as well as seasonal variations of mean annual sediment yield of rivers in the state of Kerala.

Study Area:

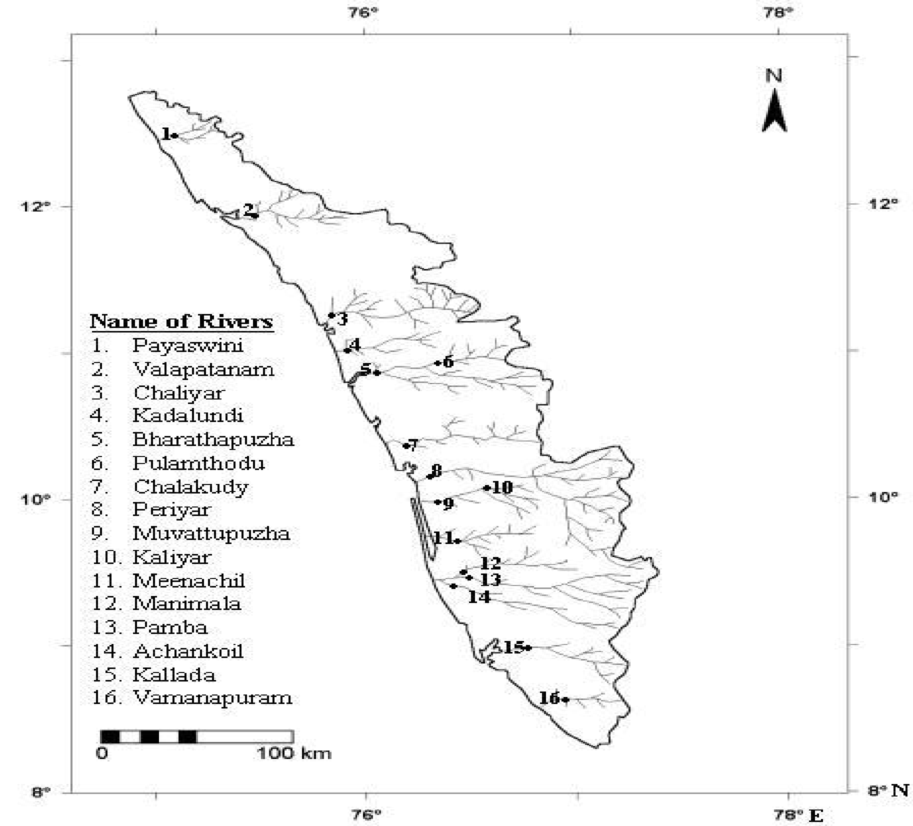
The study area is Kerala state, situated in the humid tropics and lies between $8^{0}18^{1}$ and $12^{0}48^{1}$ N and $74^{0}52^{1}$ and $77^{0}22^{1}$E. There are 41 rivers flowing westward and 3 rivers flowing eastward originating mostly from the western guards. The area under consideration has undulating features over varying altitudes. Based on topography, the state can be categorized into three natural land form namely low land (altitude less than 7.5m), mid land (altitude less than 75m) and high ranges (altitude greater than 75m).

Since the study area is having steep slopes consisting of mountains and valleys the production and transport of sediments is an important aspect of river discharge. The state is characterized by distinct rainfall pattern consisting of SW monsoon (season 1) and NE monsoon (season 2). The rainfall intensities and its spatial distribution vary during these two seasons.

Geological formations in the study area are crystalline rocks, sedimentary rocks and laterities. In the low lying areas and river valleys recent and sub-recent sediment formations also exist. The land use patterns observed in the study area are arable land, forest land, agricultural plantation, grass land and waste land.

The mean annual rainfall in the study area is more than 3000mm and the rainfall varies from about 900mm in the southern parts to 3500mm in the northern parts. Also there is spatial variation in the rainfall pattern from the coastal area to the high ranges ranging from about 1400mm to 600mm. The rainfall distribution during SW monsoon is approximately 70% and NE monsoon is 25%. The contribution of NE monsoon in the southern parts of the state is much higher than that of the north Kerala.

The present study contains sediment and flow data of 16 important river data from the state spanning over N to S are used. The data record varies between 19-20 years over a period of 1989-2007. The data used for the study is collected by CWC (Central Water Commission). Sediment data is obtained by sampling methods at the discharge measurement locations. The samples obtained daily are subjected to laboratory analysis and the concentration levels for fine, medium and coarse particles for the suspended load.



Literature review:

Geostatistics is the application of probabilistic methods to regionalized variables as defined by G. Matheron. Regionalized variables are variables that have an attribute value and a location in a two or three dimensional space. Geostatistics are also described sometimes as a set of techniques/tools used to analyze and predict values of a variable distributed in space or in time. With geostatistics we can explore our sample data by constructing variogram models and producing interpolated surfaces.

Variogram:

The variogram (or semivariogram) (Cressie 1991) is a function that describes spatial auto correlation of a regional (georeferenced) variable. Autocorrelation is the correlation between elements of a series and others from the same series separated from them by a given interval. Variogram contains the property of 'intrinsic stationarity' which indicate the natural increase in variance between observations of a regional variable as distance increases from each observation. Construction of variogram includes two stages such as calculating empirical variogram and model fitting.

Empirical variogram:

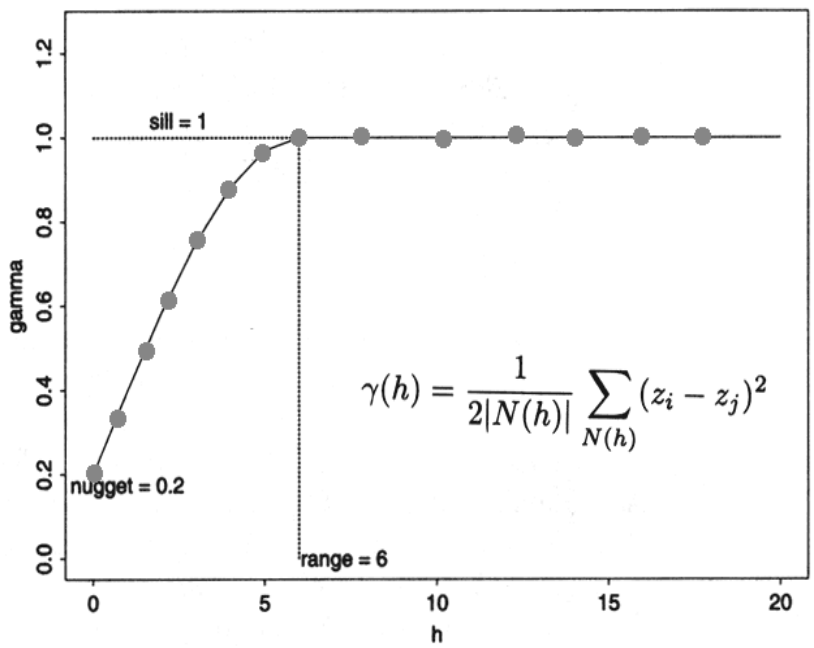
The empirical variogram provides a description of how the data is related (correlated) with distance. The semivariogram function, γ (h), was originally defined by Matheron (1963) as half the average squared difference between points separated by a distance h. The semivariogram is calculated as:

$$\gamma(\ ) = \frac{1}{2|N(\ )|} \sum_{N(h)} (z_i \quad z_j)^2$$

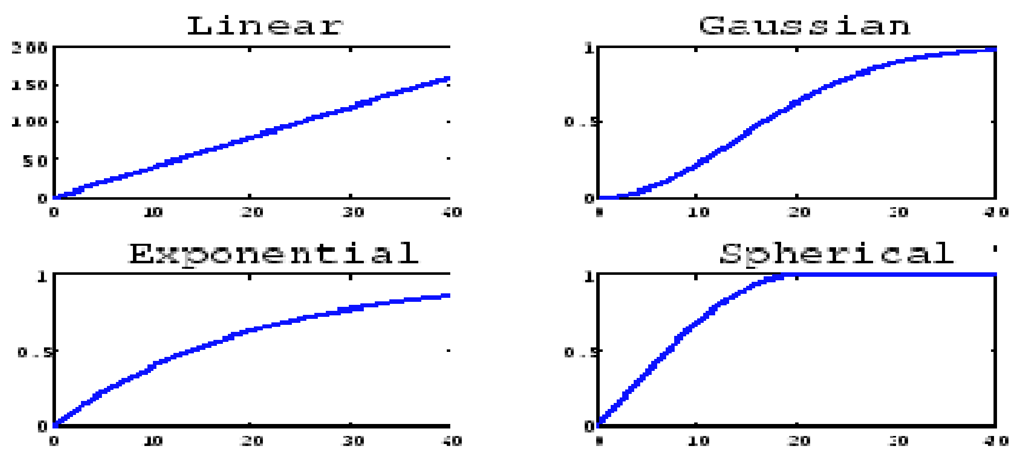
Where N (h) is the set of all pairwise Euclidean distance i-j=h, |N (h)| is the number of distinct pairs in N (h), and z_i and z_j are data values at spatial locations i and j, respectively. In this formulation, h represents a distance at spatial locations i and j, respectively. In this formulation, h represents a distance measure with magnitude only. Sometimes, it might be desirable to consider direction on in addition to distance. In such cases, h will be represented as the vector h, having both magnitude and direction.

Most variograms are defined through several parameters; namely, the nugget effect, sill, and range.

- Nugget Effect: Represents micro-scale variogram or measurement error. It is estimated from the empirical variogram as the value of γ (h) for h=0.
- Sill: The $\lim_{h\to\infty} \gamma(\ )$ representing the variance of the random field.
- Range: The distance at which data are no longer autocorrelated.



Types of variogram models:



Methodology:

The methodology adopted for present investigation is based on the theory of regionalized variables (geostatistical approach) by considering the sediment yield from different rivers and different locations as regionalized variables. The method of variogram analysis employed in the geostatistical techniques has been used for sediment yield data for distinct zones as well as different seasons. A brief description of the methodology is presented in the following sections.

Time series:

Time series arise as recordings of processes which vary over time. A recording can either be a continuous trace or a set of discrete observations. We will concentrate on the case where observations are made at discrete equally spaced times. Time series data analysis used to predict the data to future irrespective to the spatial variation.

SGeMS:

The Stanford Geostatistical Modeling Software (SGeMS) is an open-source computer package for solving problems involving spatially related variables. It provides geostatistics practitioners with a user-friendly interface, an interactive 3-D visualization, and a wide selection of algorithms. SGeMS is the first software to provide algorithms for multiple-point statistics. SGeMS software tools are QQ plot, PP plot, scatter plot, variogram modeling, simulation techniques (Simple Kriging (SK), Ordinary Kriging (OK), Kriging with Trend (KT) and Simple Kriging with Locally Varying Mean (LVM)) etc….

1) QQ-Plot:

This is a graphical procedure that plots the observed values on the X-axis and the expected values (assuming a normal distribution) on the Y-axis. Note that if the sample distribution is distributed exactly like a normal distribution, the points should fall on a straight line.

2) PP-Plot:

These are similar to Q-Q plots, but instead of plotting observed values, these plot cumulative probabilities (values range from 0 to 1), with observed probabilities (cumulative proportion of cases) on the X-axis and expected probabilities given the normal curve on the Y-axis. Again, if the sample were exactly normally distributed, the points would lie on a straight line.

3) Scatter plot:

Scatter plots are similar to line graphs in that they use horizontal and vertical axes to plot data points. Scatter plots show how much one variable is affected by another. The relationship between two variables is called their **correlation.** The closer the data points come when plotted to making a straight line, the higher the correlation between the two variables, or the stronger the relationship. If the data points make a straight line going from the origin out to high x- and y-values, then the variables are said to have a **positive correlation.** If the line goes from a high-value on the y-axis down to a high-value on the x-axis, the variables have a **negative correlation.**

4) Variogram:

The variogram for a 3D model is commonly expected to include as a minimum, three directions:

1) A vertical directional component to account for variability with respect to vertical axis
2) An Omni-directional component to account for global variability throughout the field, to See the overall picture, and
3) At least one horizontal directional component covering the major directions in the field.

Components in the SGeMS software define the location of the empirical variogram:

1) **Number of lags**: Number of variogram lags to compute
2) **Lag separation**: Distance between two lags. The experimental variogram will be Computed from h = 0 to h = Number of lags times the lag separation.
3) **Lag tolerance**: Tolerance around the lag separation. All pairs of data separated by Lag separation ± lag tolerance would be reported to the same lag.

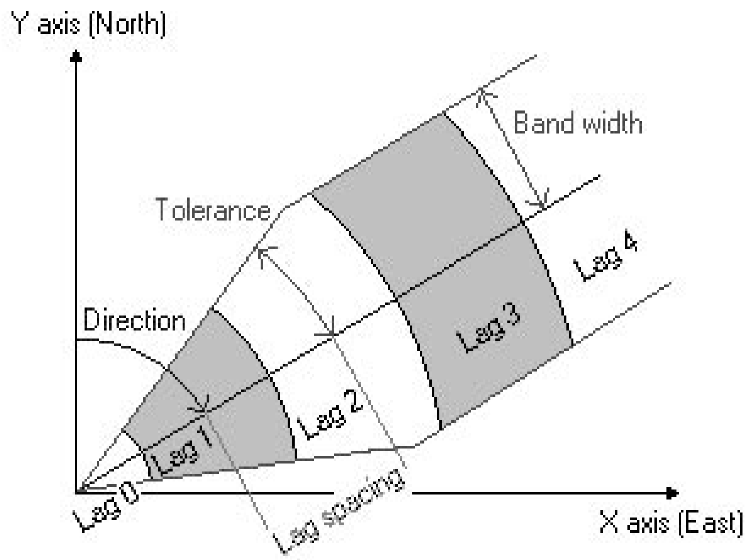
Components in the SGeMS software define the directionality of the empirical variogram:

1) **Azimuth**: corresponds to the direction on a planar surface measured in degrees from 0°-360°,

2) **Dip**: corresponds to the angle of descent relative to the azimuth measured in degrees from 0°-90°,

3) **Tolerance**: corresponds to the angle of tolerance of the directional variogram measured in degrees from 0°-90°,and

4) **Bandwidth**: corresponds to the maximum width of the area resulting from the directional variogram (Remy, Boucher and Wu 2009).



Tools to fit empirical variogram model in SGeMS:

1) **Nugget Effect**:

Initial abrupt jump to the first value at the beginning of the entire variogram model. Non-continuity only at the origin is due to either measurement error or variation at a scale smaller than the sampling distance.

2) **Number of Structures**:

Number of (nested) variogram structures composing the variogram model. An accurate fit to a variogram model may be best constructed using a combination of multiple model functions (called nested structures), especially to model variability at different scales.

3) **Sill Contribution**:

Effect of the sill, or the maximum variance of the variogram. Sill is the limit (represented graphically as where the function flattens out) of the variogram model after a specific distance called the range.

4) **Type**:

There are different types of variogram models. SGeMS includes only models for variograms that have a sill: Spherical, Exponential and Gaussian. The model type depends on the function used to approximate the variogram (determines the overall shape of the model).

5) **Ranges (Max, Med, Min)**:

Ranges along each of the three directions of the anisotropy ellipsoid in the variogram structure (maximum, medium and minimum) used to approximate the model. Depending on the direction(s) specified these ranges help refine the shape/extent of the function.

6) **Angles**:

Measurement in degrees for each of the three angles (directions) of the 3D anisotropy ellipsoid in the variogram structure: azimuth, dip and rake. Rotation of the angles along the orthogonal planes of a Cartesian coordinate system positions the 3D ellipsoid in space

Kriging:

Kriging is an alternative to many other point interpolation techniques. Unlike straightforward deterministic methods, such as Nearest Point, Trend Surface, Moving Average or Moving Surface, it is a statistical method based on the theory of regionalized variables. Before you can use kriging, we must make a semivariogram model, which will determine the interpolation function.

Parameters description:

1. Hard Data [Hard Data]: The grid and the name of the property containing the hard data

2. Kriging Type [Kriging Type]: Possible types of kriging include: Simple Kriging (SK), Ordinary Kriging (OK), Kriging with Trend (KT) and Simple Kriging with Locally Varying Mean (LVM).

3. Local Mean Property [Local Mean Property]: The property of the simulation grid containing the non-stationary mean. A mean value must be available at each location to be estimated.

4. Max Conditioning Data [Max Conditioning Data]: The maximum number of conditioning data to be used for kriging at any location

5. Search Ellipsoid [Search Ellipsoid]: The ranges and angles defining the search ellipsoid

6. Variogram [Variogram]: The variogram of the variable to be estimated by kriging.

RESULTS:

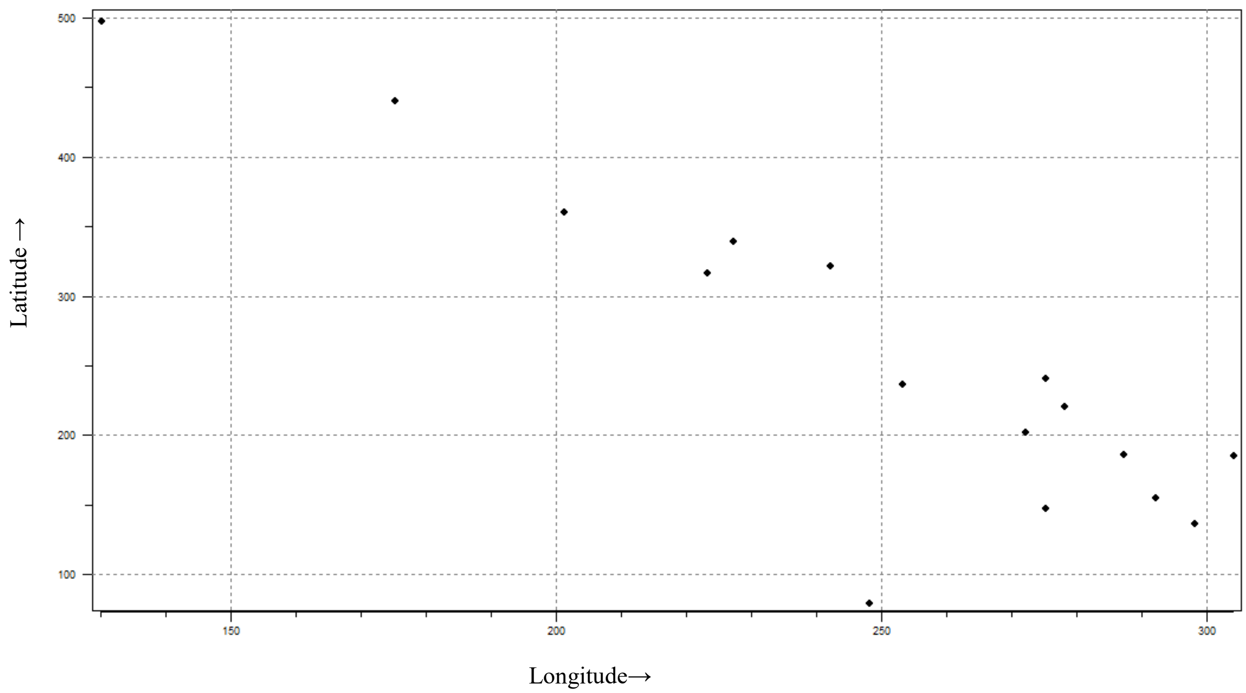


Fig.1 Location of sediment yield sampling points for North & South regions

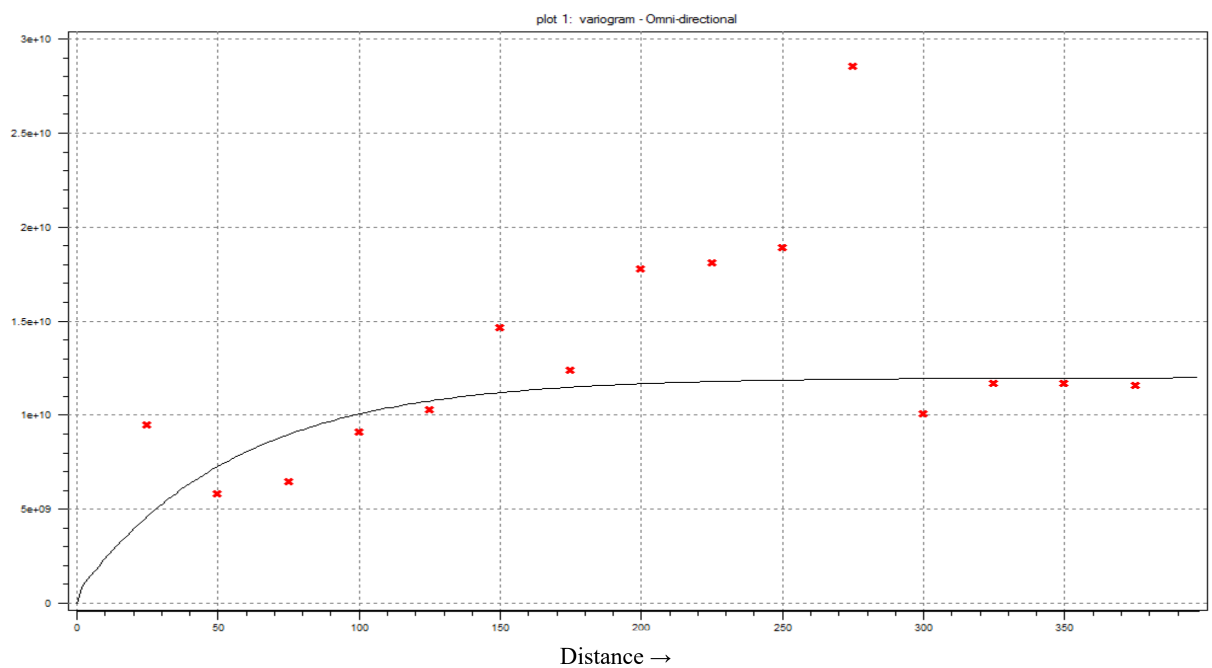


Fig.2 Variogram model (spherical function) for North & South regions

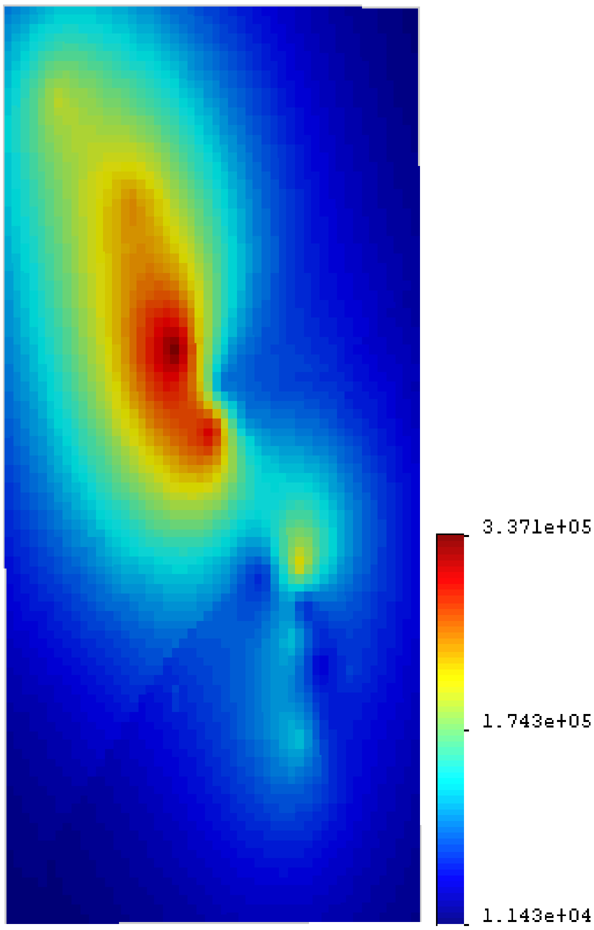


Fig.3 Kriged sediment values for North and south regions

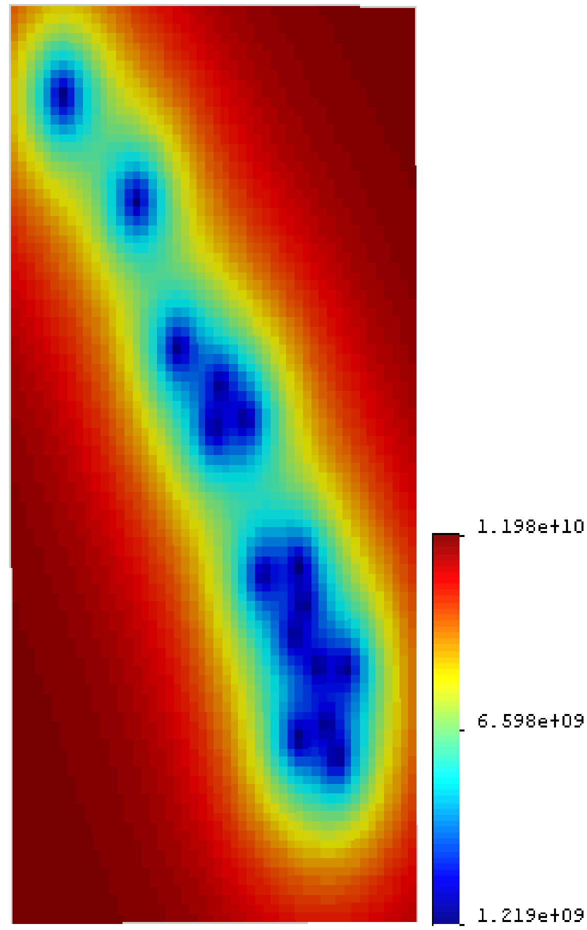
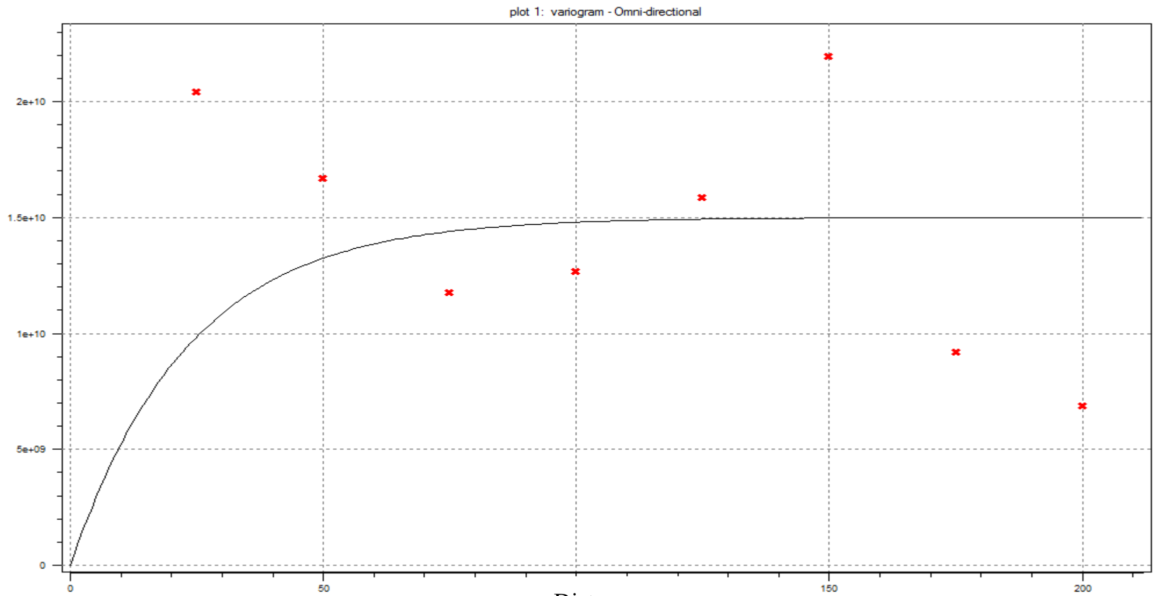
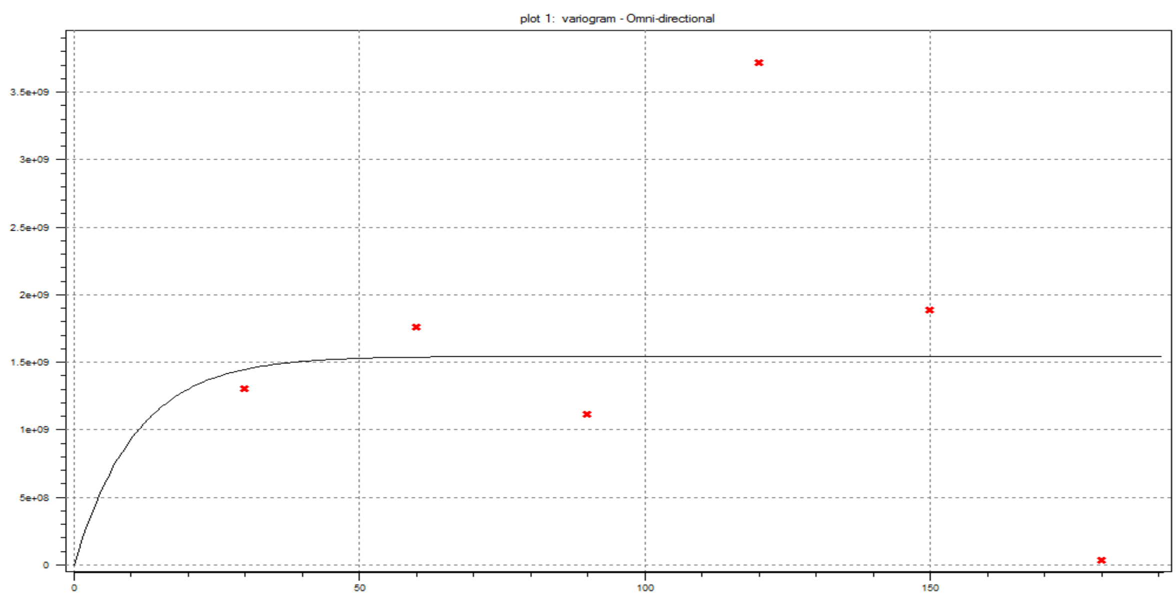


Fig.3 (b) Distribution of variance of Kriged field in Fig 3(a)



Distance →

Fig.4 Variogram model for data of North region



Distance →

Fig.5 Variogram model for data of South region

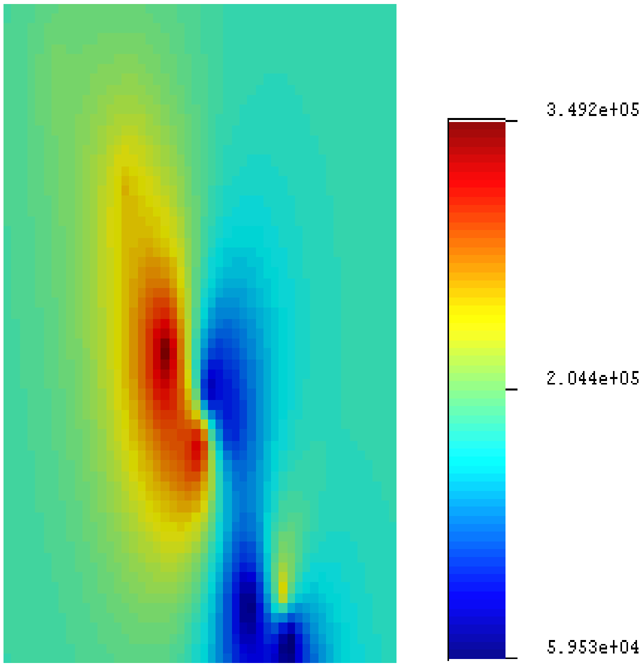


Fig.6 (a) Kriged sediment values for North regions

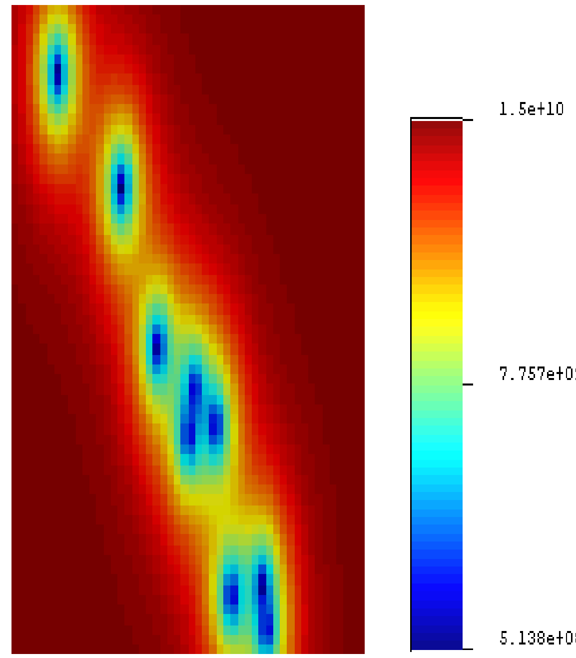


Fig.6 (b) Distribution of variance of Kriged field in Fig 8(a)

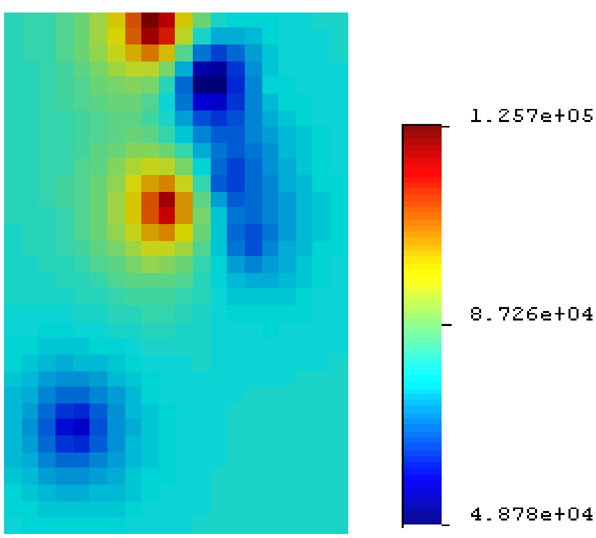


Fig.7 (a) Kriged sediment values for South regions

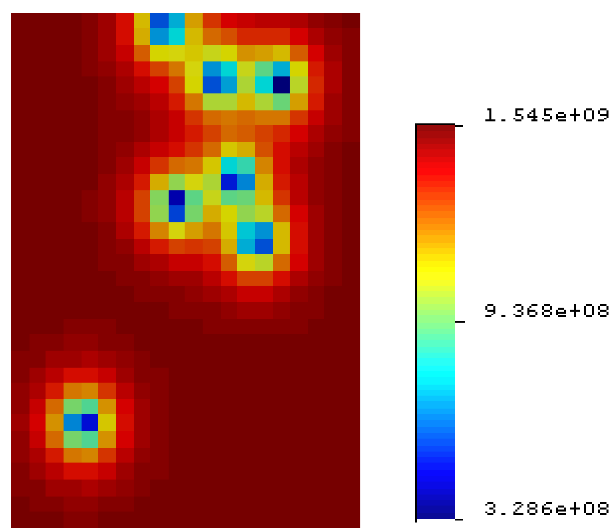
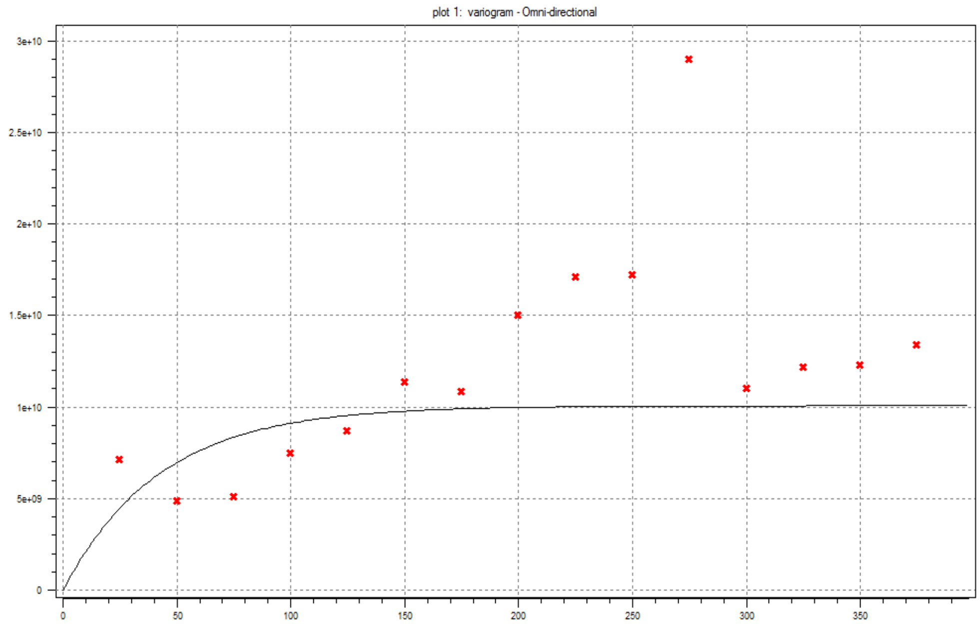
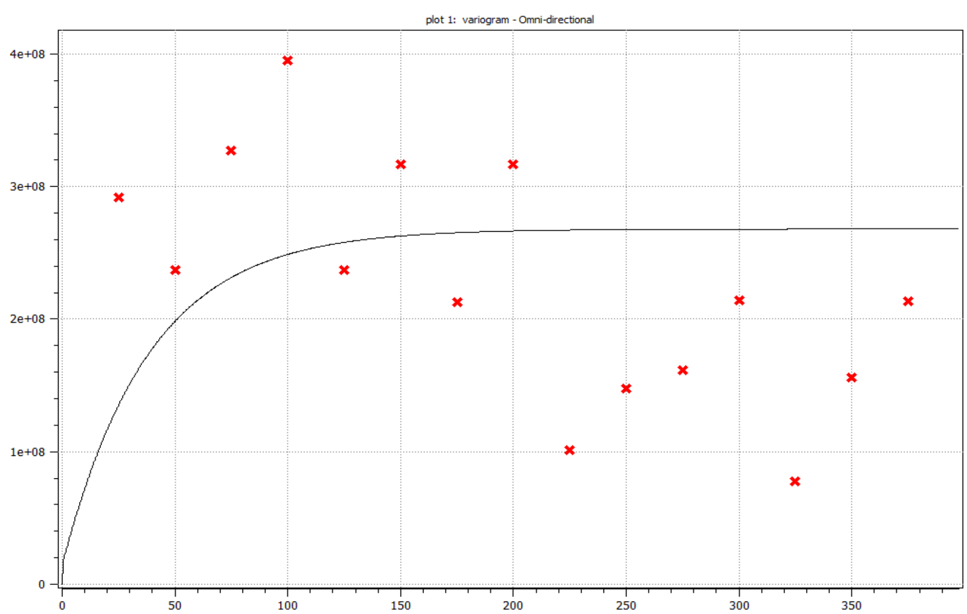


Fig.7 (b) Distribution of variance of Kriged field in Fig 9(a)



Distance →

Fig.8 Variogram model for SW monsoon season



Distance →

Fig.9 Variogram model for NE monsoon season

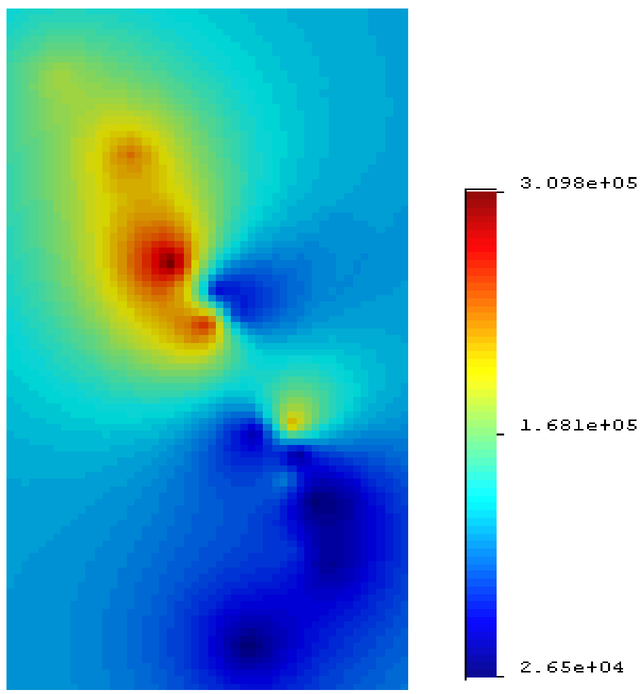


Fig.10 (a) Kriged sediment values for SW monsoon season

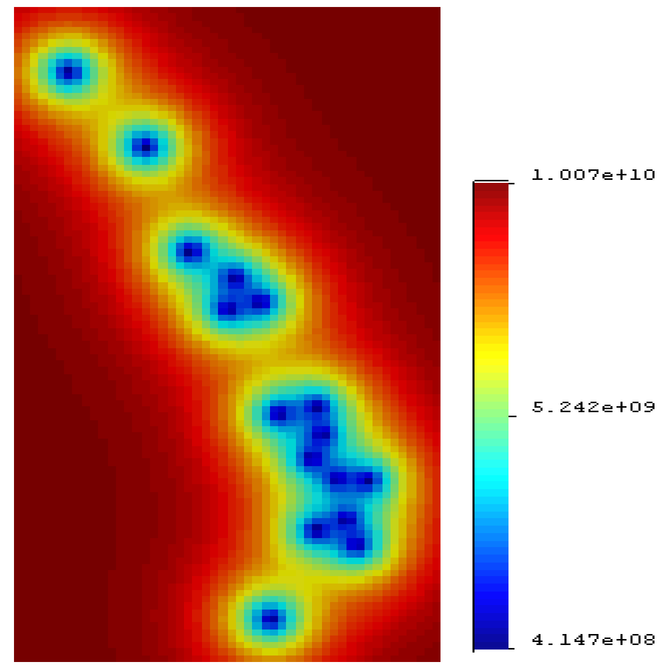


Fig.10 (b) Distribution of variance of Kriged field in Fig.10 (a)

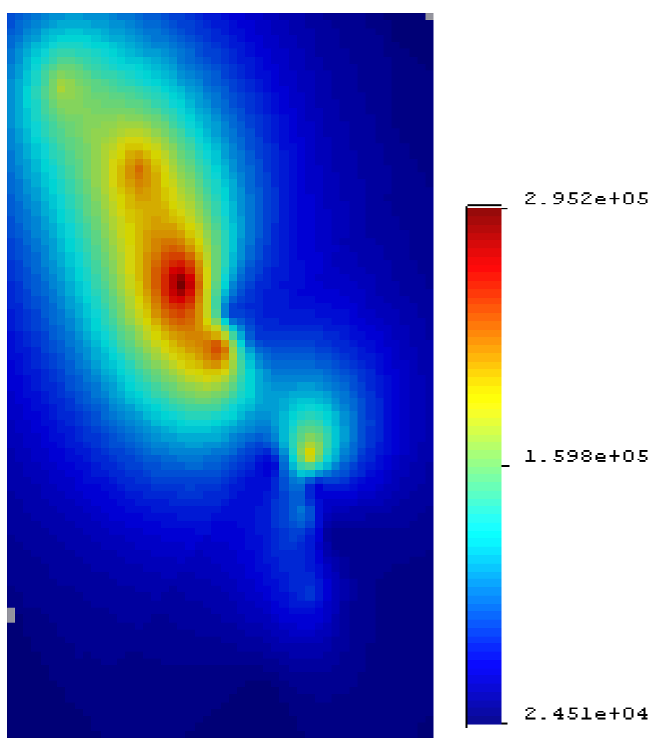


Fig.11(a) Kriged sediment values for NE monsoon season

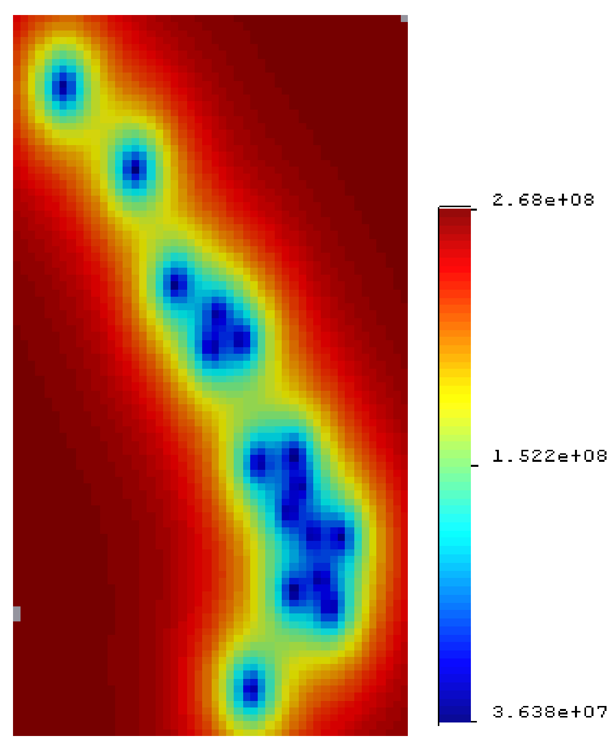


Fig.11 (b) Distribution of variance of Kriged field in Fig.11 (a)

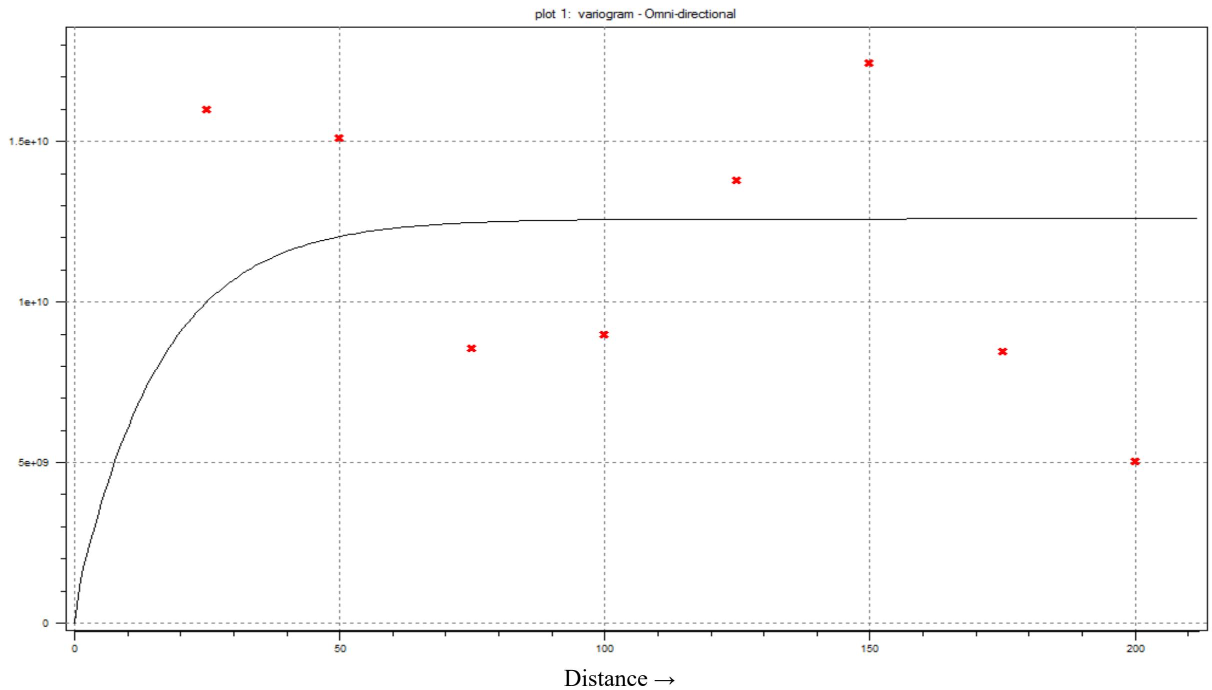


Fig.12 Variogram model North region for SW monsoon

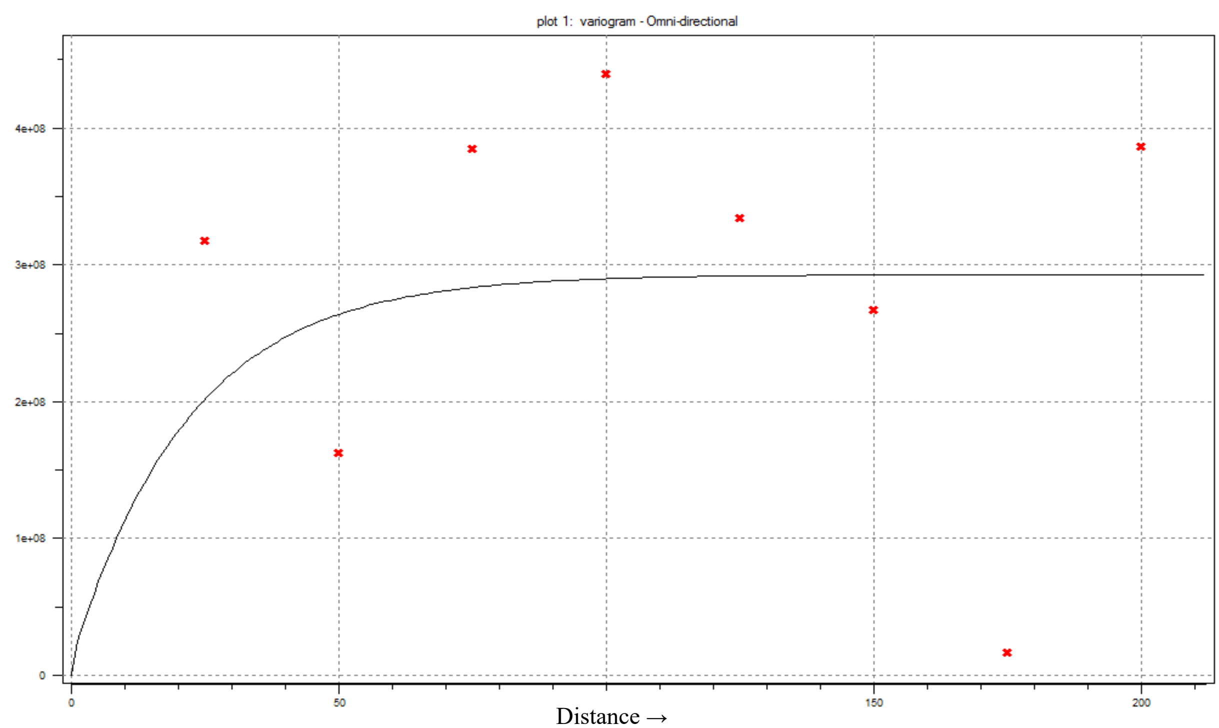


Fig.13 Variogram model North region for NE monsoon

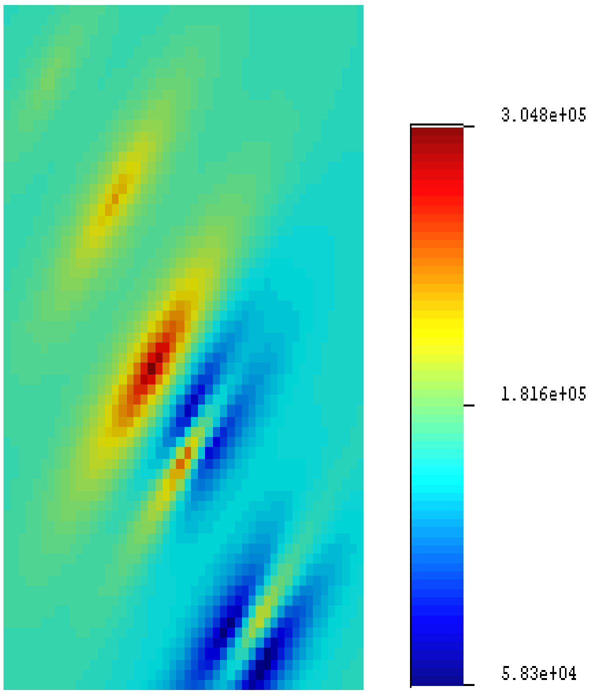


Fig.14 (a) Kriged sediment values for North Region SW monsoon season

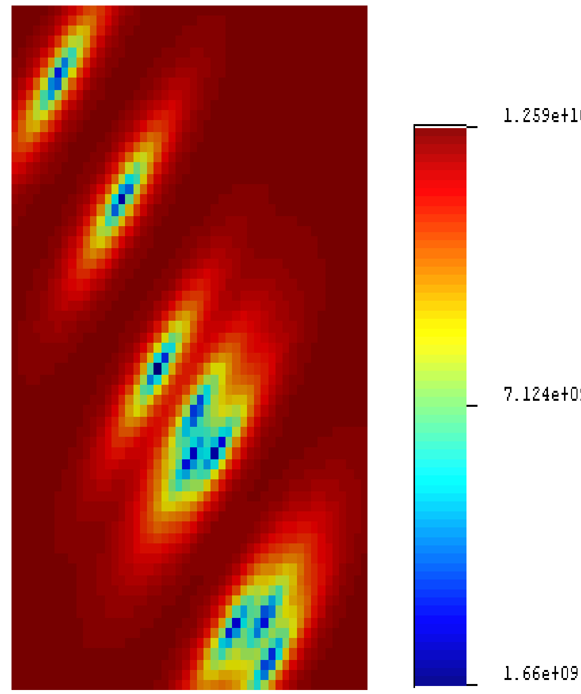


Fig.14 (b) Distribution of variance of Kriged field in Fig.14 (a)

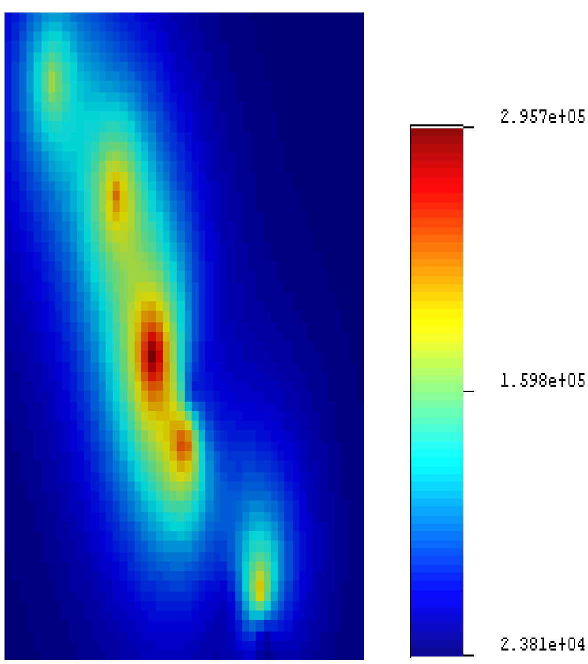


Fig.15 (a) Kriged sediment values for North Region NE monsoon season

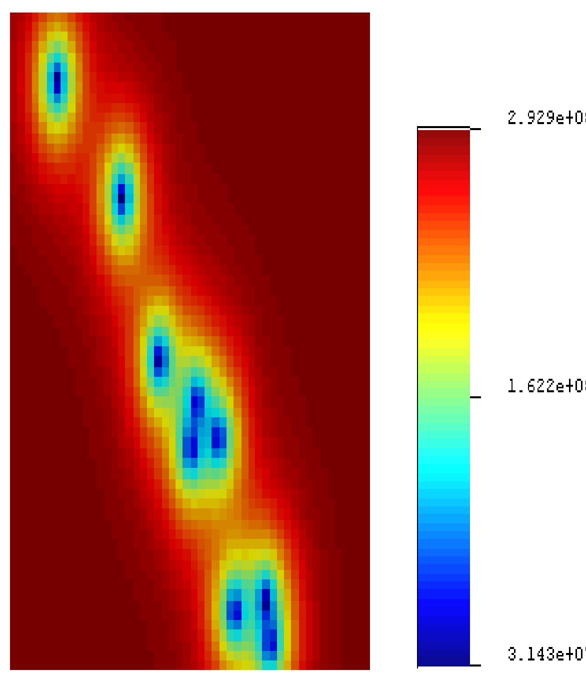


Fig.15 (b) Distribution of variance of Kriged field in Fig.15 (a)

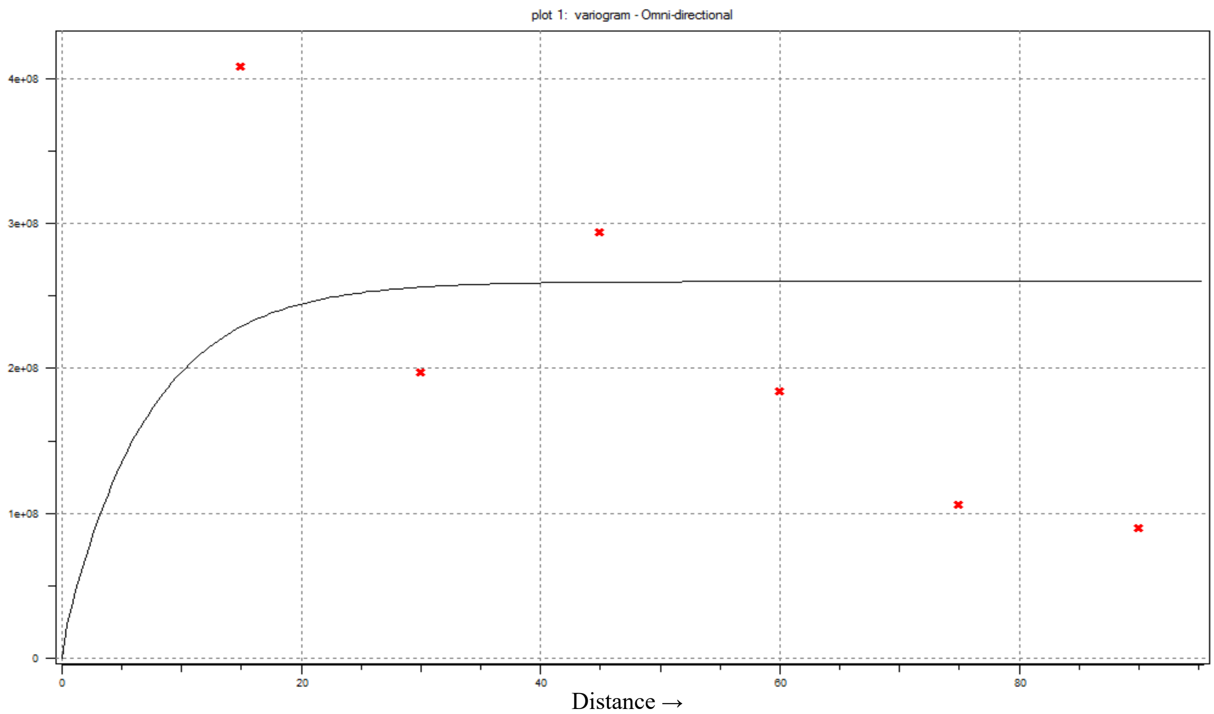


Fig.16 Variogram model South region for SW monsoon

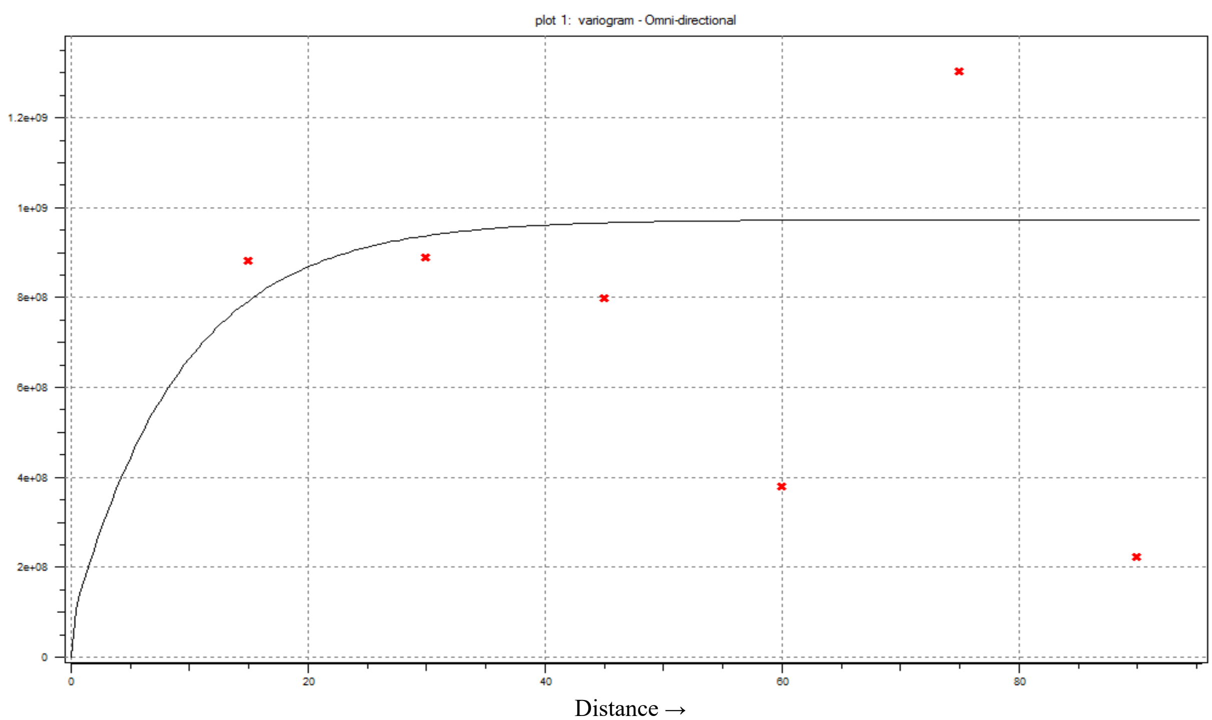


Fig.17 Variogram model South region for NE monsoon

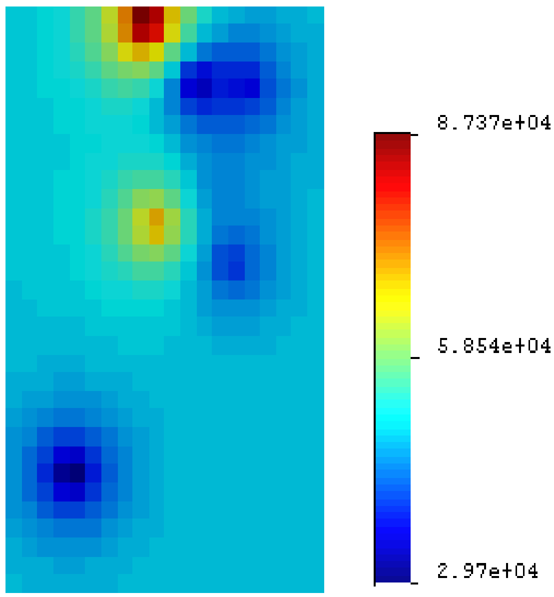


Fig.18 (a) Kriged sediment values for South Region SW monsoon season

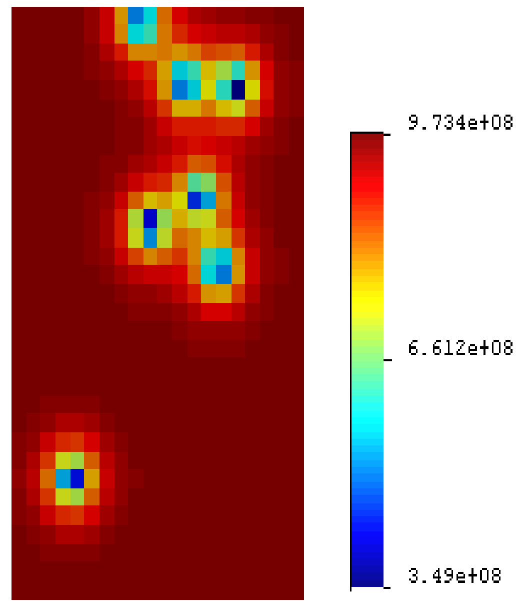


Fig.18 (b) Distribution of variance of Kriged field in Fig.18 (a)

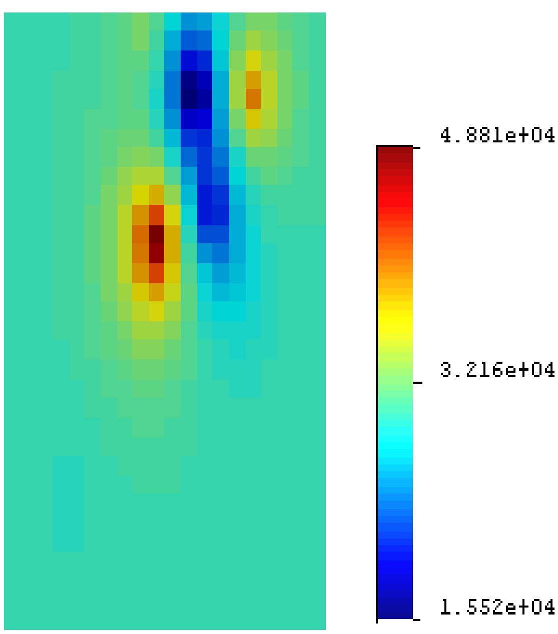


Fig.19 (a) Kriged sediment values for South Region NE monsoon season

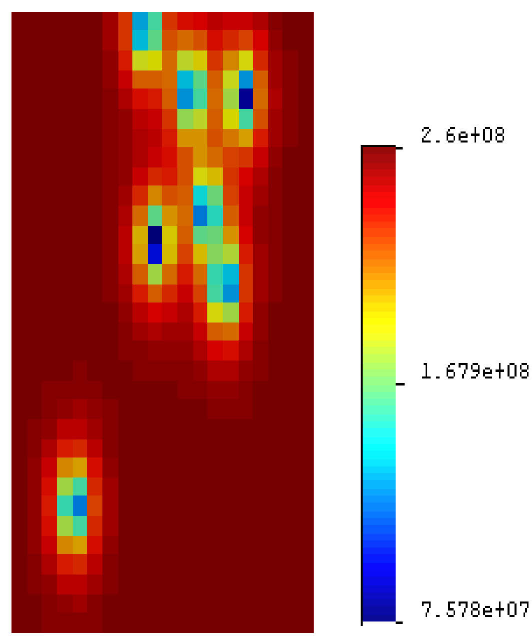


Fig.19 (b) Distribution of variance of Kriged field in Fig.19 (a)

DISSCUSSIONS:

Spatial analysis of the study area from N to S is categorized into three cases based on regional and seasonal variations. Case 1 study contains total region including North and South regions, Case 2 contains North and South regions separately and Case 3 contains both cases 1&2 with seasonal variations.

Case 1: Sediment data of full region is located as a grid in Cartesian system with longitude in x-axis and latitude in y-axis, has the mean of 138497 and variance of 1.15e10. Based on these values empirical variogram is calculated and with sill of 1.15e10 exponential variogram model is fitted. Variogram shows the half of the points is very close the model which represents spatial correlation and decreases as the separation increases. This model is used in simple kriging with median value to interpolate the surface at other location in the grid.

Case 2: Sediment data of North and South region is located based on latitude and longitude. The mean of North and South regions are 184538 and 79281.9 respectively, variance of North and South region are 1.49e10 and 1.54e9, exponential variogram model is fitted to north and south regions. North region has high spatial structure compared to South region. Kriged North region has high sediment yield than South region.

Case 3: Seasonal variation such as SW monsoon and NE monsoon (post monsoon) for case 1&2 is considered QQ-plot and PP-plot shows normal distribution as the data points are close to 45^0line. Scatter Plot of seasonal variation for full region, North region and South region gives the positive coefficient of correlation as 0.37, 0.703 and 0.455 respectively, these values shows that North region data is 70%, South region data is 45% and Full region is 37% correlated.

Mean and variance values are tabulated below.

Region	Mean		Variance	
	SW monsoon	NE monsoon	SW monsoon	NE monsoon
North and South	112178	26309.4	1.01e10	2.5e8
North	160998	23537.8	1.21e10	2.83e8
South	49408.4	29873.5	9.03e8	2.28e8

These values show that NE monsoon for North region gives less spatial correlation and high for South region. Kriging for SW monsoon gives high sediment yield than NE monsoon

CONCLUSION:

Spatial analysis of study area with region variations gives less spatial structure compared to both seasonal and regions variation. North region has 70%, South region has 45% and Full region has 37% of correlation seasonally. North region has comparatively good spatial correlation seasonally. Full region sediment data values variance varies 12% for SW monsoon and 97% for NE monsoon. North region sediment values variance varies 13% for SW and 98% for NE monsoon. South region sediment values variance varies 41% for SW and 85% for NE monsoon which gives SW monsoon data can be better predicted than NE monsoon for North region.

The analysis of sediment yield data over long periods is helpful in investigating and understanding the distributional characteristics and pattern of sedimentation in river basins. These parameters vary with space and time. Sediment yield is one major problem arising in the design of hydraulic structures. It varies both in spatial and temporal variables. A study on spatial analysis of sediment data and ability to predict the sediment values at the gauged stations of river flow using geostatistics. A report of the works carried in this direction using the long term data record of sediment for the rivers of Kerala State is presented.

Geostatistics is a powerful tool to help us characterize spatial variability. Geostatistical tools like QQ-plots, PP-plots, scatter plots, variogram analysis, kriging and simulations are used for the presented analyses. The sediment data has been partitioned into regional zones as well as seasonal basis to investigate variabilities. Variogram analyses and Kriging exercises have been carried using mean annual data of sixteen rivers from Kerala over a period of about 20 years.

The study revealed that maximum spatial correlation in North Region compared to South region. Also, seasonal variation is observed between SW monsoon and Post monsoon periods. Based on seasonal variation SW monsoon has more sediment concentration compared to NE monsoon (post monsoon). The differences may be due to differences in rainfall and topographical characteristics.

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