INFILTRATION CHARACTERISTICS OF TROPICAL SOILS AT USM ENGINEERING CAMPUS

By

GOH KIM MENG

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ABSTRAK

Kajian ini dijalankan di Kampus Kejuruteraan Universiti Sains Malaysia. Kajian ini meliputi variasi permukaan kadar penyusupan. Tapak ujian ditentukan dengan menggunakan kaedah “geo-grid” terlebih dahulu dan titik kajian ditentukan menggunakan alat GPS(Global Position System). Ujian penyusupan ini dijalankan dengan menggunakan “Double ring”. Satu set data telah diperolehi daripada ujian yang telah dijalankan. Data yang paling penting dalam ini ialah kadar penyusupan awalan dan kadar penyusupan stabil. Analisis telah dijalankan ke atas dua set data ini dengan menggunakan perisian SURFER6 dan GS+. Peta kontor untuk kadar penyusupan awalan dan kadar penyusupan stabil akan diperolehi daripada hasil analysis perisian SURFER6. Perisian GS+ pula digunakan untuk membuat analysis geostatik. Kadar penyusupan awal ialah kadar air mengalir ke dalam tanah pada awal eksperimen dan kadar penyusupan stabil ialah kadar dimana kadar pengaliran air ke dalam tanah sudar mencapai nilai malar iaitu tanah di titik ekperimen sudah mencapai nilai tepu. Bilangan set data yang diambil ialah 50 dan setelah dicampurkan dengan data yang diperolehi pada tahun lepas, ini memberikan 100 set data untuk dianalisis.

ABSTRACT

This study was at University Sains Malaysia Engineering Campus. This study include infiltration test of predetermined geo-grid locations. 50 location were selected for infiltration test. Geostatistical analysis were performed on the infiltration test data to examine the spatial variability of infiltration over the study area. Semivariogram parameters (rang, nugget and sill), were used to characterize the spatial variability of infiltration sales. For the Geostatical analysis GS+ software was uses. Spatial variability map of infiltration rates were prepared using SURFER software. The campus area was classified in two areas namely, disturbed & undisturbed area.

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1.0 INTRODUCTION

1.1 Back Ground

Infiltration is the process by which water arriving at the soil surface enters the soil. This process affects surface runoff, soil erosion, and groundwater recharge. Knowledge of infiltration rates and their spatial variability is required in many disciplines of engineering. The double-ring infiltrometer is often used for measuring infiltration rates.

The infiltration rate of the soil is influenced by various factors depending on the condition of the soil surface, its chemical, physical characteristics, and distribution of water. The rate of entry of water is usually greatest when the soil is dry at the start of watering, but, it decreased as the topsoil became saturated. Infiltration rate are rapid when the water is first applied to the soil, but when the topsoil becomes saturated, the swelling of the clay occours and hence, the infiltration gradually becomes constant. The decrease in infiltration rate with time is mainly due to the depth of wetted zone.

The double ring infiltrometer is a way of measuring saturated hydraulic conductivity of the surface layer, and consists of an inner and outer ring inserted into the ground. Each ring is supplied with a constant head of water either manually or from mariotte bottles. Hydraulic conductivity can be estimated for the soil when the water flow rate in the inner ring is at a steady state.

It works by directing water onto a known surface area due to the parameters of the inner ring. The rate of infiltration is determined by the amount of water that infiltrates into the soils per surface area, per unit of time. Infiltration can be measured by either a single or double ring infiltrometer, with preference usually lying with the double ring because the outer ring helps in reducing the error that may result from lateral flow in the soil.

Soil hydraulic (infiltration) characteritecs varu spatially and temporally form a field scale to a large regional scale and are influenced by both intrinsic (e.g. soil formation process, composition of parent rocks, soil organisms) and extrinsic factors (e.g. regional climate, vegetation, soil management practices, fertilization, etc). Spatial variability causes difficulty in representing a soil with a deterministic or precisely defined set of characteristics and precludes characterization of soil hydrology response. One of the major issues in distributed parameter hydrological modeling is how to estimate attributes of spatially varying soil nutrients

1.2 Objective

The objectives of this study are:

I. To characterize spatial structure of infiltration characteristics of soil under tropical climate in terms of semivariogram parameters.

II. To map the variation in soil hydraulic characteristics in the study area, and

III. To evaluate the effect of land use changes on the variability of infiltration characteristics.

1.3 Scope Research

The scope of this study is to find the spatial variability of infiltration rate inside USM Engineering Campus which is located at about 100° 29.5' South and 100°30.3 North and between 05°0.94' East and 05°08.5 West. This research is to get the information for 50 points inside the campus area which the point are fix at the first and after that, the point will be identified using Global Position System (GPS) survey. After the location of the points were identified, the tests were carried using the double ring infiltrometer. The infiltration rate are been record and the result will be analysis using SUFFER6 to generate the contour map and GS+ to do the geostatical analysis. After the contour map is generated by SUFFER6, the map will be edited by using corelDRAW to insert some more information.

2. LITERATURE REVIEW

2.1 Rainfall Distribution

The seasonal wind flow patterns coupled with the local topographic features determine the rainfall distribution patterns over the country. During the northeast monsoon season, the exposed areas like the east coast of Peninsular Malaysia, Western Sarawak and the northeast coast of Sabah experiences heavy rain spells. On the other hand, inland areas or areas which are sheltered by mountain ranges are relatively free from its influence. It is best to describe the rainfall distribution of the country according to seasons.

2.2 Seasonal Rainfall Variation in Peninsular Malaysia

The seasonal variation of rainfall in Peninsular Malaysia is of three main types:

(a) Over the east coast districts, November, December and January are the months with maximum rainfall, while June and July are the driest months in most districts.

(b) Over the rest of the Peninsula with the exception of the southwest coastal area, the monthly rainfall pattern shows two periods of maximum rainfall separated by two periods of minimum rainfall. The primary maximum generally occurs in October - November while the secondary maximum generally occurs in April - May. Over the northwestern region, the primary minimum occurs in January - February with the secondary minimum in June - July while elsewhere the primary minimum occurs in June - July with the secondary minimum in February.

(c) The rainfall pattern over the southwest coastal area is much affected by early morning "Sumatras" from May to August with the result that the double maxima and minima pattern is no longer discernible. October and November are the months with maximum rainfall and February the month with minimum rainfall. The March - April - May maximum and the June -July minimum are absent or indistinct.

2.3 Soil Background

In Peninsular Malaysia, the basic unit for soil classifications is soil series. Up to now more than 240 soil series have been identified (MARDI, 2002). They are differentiated on the basis of their parent materials, major characteristics, landscape, and mode of formation. At the broadest level, they are divided into mineral or organic soils. Mineral soils are further subdivided as sedentary soils, reworked soils and alluvial soils. The organic soils are differentiated according to the nature of the organic material and its depth.

With regard to their distribution, the sedentary soils are found on undulating land to rolling and hilly terrain (34.2%) and on steep hills and mountains (37.4%). The reworked soils occur on intermediate and higher terraces and pediment (3.3%). The alluvial soils are found on low-lying coastal and river side floodplains (17.8%). The organic soils occur in lowlands, adjacent to the coast (6.0%). The remaining is disturbed urban and mining land(1.3%).

The USM campus mainly consists of alluvium soils with extra added soil to upgrade the strength of the soil.

2.4 Infiltration

Infiltration is the process of water entering the soil profile. When soil is in good condition or has good soil health, it has a stable structure and continuous pores (macro and micro) to the surface. Surface crusting often produces a low infiltration rate resulting from weak soil structure and nonexistent macro pores. Soils that have reduced infiltration have increased water runoff and subsequent erosion. This excess water can contribute to flooding of streams and rivers. In addition, soils that have reduced infiltration become saturated at the soil surface causing anaerobic conditions, which reduce biological activity and increase nutrient deficiencies. If a soil has an infiltration of 1 inch /hour but receives a 2 inch/hour rainfall, that extra inch moves offsite, causing erosion and furthermore not replenishing the soil profile with moisture.

Table 2.1: Infiltration Rates and Classes

(Resource: Journal: USDA Natural Resources Conservation Service, 1998)

Infiltration Rate (min/inch)	Infiltration Rate (in/hour)	Infiltration Class
< 3	> 20	Vary Rapid
3 - 10	6 - 20	Rapid
10 - 30	2 - 6	Moderately Rapid
30 - 100	0.6 - 2	Moderate
100 - 300	0.2 - 0.6	Moderate slow
300 - 1000	0.06 - 0.2	Slow
1000 - 10,000	0.0015 - 0.06	Very Slow
> 40,000	< 0.0015	Impermeable

The double-ring infiltrometer is often used for measuring infiltration rates, and has been described by Bouwer, H. et at., 1986and ASTM et at., 2002. These references contain standard guidelines for conducting double-ring infiltration tests; however, in practice a wide variety of testing methodologies are used.

Ring infiltrometers consist of a single metal cylinder that is driven partially into the soil. The ring is filled with water, and the rate at which the water moves into the soil is measured. This rate becomes constant when the saturated infiltration rate for the particular soil has been reached. The size of the cylinder in these devices is one source of error. A 15-cm diameter ring produces measurement errors of approximately 30%, while a 50-cm diameter ring produces measurements errors of approximately 20% compared to the infiltration rate that would be measured with a ring of an infinite diameter. It has been suggested that a diameter of at least 100 cm should be used for accurate results . However, cylinders of this size become very difficult to use in practice on light soils, because large volumes of water are required to conduct tests on sandy soils with high infiltration rates.

Single-ring infiltrometers overestimate vertical infiltration rates. This has been attributed to the fact that the flow of water beneath the cylinder is not purely vertical, and diverges laterally. This lateral divergence is due to capillary forces within the soil, and layers of reduced hydraulic conductivity below the cylinder. A number of techniques for overcoming this error have been developed (such as a correction procedure that uses an empirical equation) for 15-cm diameter rings. Double-ring infiltrometers minimize the error associated with the single-ring method because the water level in the outer ring forces vertical infiltration of water in the inner ring. Another possible source of error occurs when driving the ring into the ground, as there can be a poor connection between the ring wall and the soil. This poor connection can cause a leakage of water along the ring wall and an overestimation of the infiltration rate. Placing a larger concentric ring around the inner ring and keeping this outer ring filled with water so that the water levels in both rings are approximately constant can reduce this leakage.

The double-ring infiltrometer test is a well recognized and documented technique for directly measuring soil infiltration rates . Bouwer describes the double-ring infiltrometer as often being constructed from thin-walled steel pipe with the inner and outer cylinder diameters being 20 and 30 cm, respectively; however, other diameters may be used.

There are two operational techniques used with the double-ring infiltrometer for measuring the flow of water into the ground. In the constant head test, the water level in the inner ring is maintained at a fixed level and the volume of water used to maintain this level is measured. In the falling head test, the time that the water level takes to decrease in the inner ring is measured. In both constant and falling head tests, the water level in the outer ring is maintained at a constant level to prevent leakage between rings and to force vertical infiltration from the inner ring. Numerical modeling has shown that falling head and constant head methods give very similar results for fine textured soils, but the falling head test underestimates infiltration rates for coarse textured soils.

The ASTM standard describes a procedure for measuring the soil infiltration rate with a double-ring infiltrometer for soil with a hydraulic conductivity between 1×10^{-2} and 1×10^{-6} cm/s (360 mm/h to 0.036 mm/h). The ASTM standard specifies inner and outer diameters of 30- and 60-cm, respectively. There are also some minor differences in the method that is suggested by the standard compared to that described by Bouwer.

The primary objective of this research was to compare falling head and constant head double-ring tests with 15- and 30-cm rings and a constant head test with 30- and 60-cm diameter rings. A secondary objective was to develop a simple device to automatically maintain a constant water level in 15-cm diameter inner ring.

2.4.1 Implications for forest productivity and surface water quality

Variation of infiltration rates with landscape position influences the amount, distribution, and routing of overland flow. Knowledge of runoff patterns gives land managers the opportunity to affect changes that optimize water use efficiency and reduce the risk of water quality impacts. Three previously reported studies measured infiltration rates using double ring sprinkling, single ring and tension infiltrometers on soils at varying landscape positions. Although large variation in infiltration rates was observed among measurement techniques, upland and side slope soils (Nixa and Clarksvilleet al., 1977) had consistently lower infiltration rates compared to the soil in the valley bottom (Razort et al., 1994). A conceptual understanding of watershed runoff is developed from these data that includes infiltration excess runoff from the Nixa and Clarksville soils and saturation excess runoff on the Razort soil. Management of the soil water regime based on this understanding would focus on increasing infiltration in upland soils and maintaining the Razort soil areas in forest. Forest productivity would be enhanced by increasing plant-available water in upland soils and decreasing flooding on the Razort soil. Surface water quality would be improved by reducing the transport of potential water contaminants from animal manure applied to upland pastures. Characterization of the spatial relationships of surface runoff generation has been an active area of research for several decades (Betson and Marius, 1969, Dunne and Black, 1970, Anderson and Burt, 1978 and Bernier, 1985). Locations within watersheds with differing infiltration characteristics have been referred to as variable-source areas, partial area contributions, or hydrologically-active areas, all of which refer to the nonuniform occurrence of surface runoff in response to precipitation. Often, the distinction is made between areas where runoff is generated when precipitation occurs at a rate greater than the soil's infiltration rate (infiltration excess runoff) and areas where runoff occurs because the soil is saturated to the surface (saturation excess runoff). Spatial variation of surface soil hydraulic properties therefore influences the amount and distribution of infiltration and the routing of overland flow following precipitation events.

Nonuniform infiltration within a watershed leads to differences in plant-available water stored in the root zone and influences the partitioning between evaporation from the soil and plant transpiration (Luxmoore and Sharma, 1980, Luxmoore, 1983, Kachanoski and De Jong, 1988 and Grayson et al., 1997). In addition to fiber production, forested watersheds provide several important ecosystem functions including the production of clean water suitable for municipal, industrial, and agricultural uses. Water moving through the root zone or across the soil surface also transports sediment, nutrients, pesticides, and pathogens that may be delivered in quantities that impair ground or surface waters. Understanding the spatial variation of infiltration within watersheds is therefore critical to developing and implementing management practices that optimize plant-available water and minimize nonpoint source pollution (Or and Hanks, 1992, Gburek and Sharpley, 1998 and Walter et al., 2000).

2.4.2 Importance of natural and manipulated landscapes

Water infiltration into soil is an important aspect of both natural and manipulated landscapes. While simple in concept, it is difficult to identify or directly measure the relative importance of several pathways water can take as it penetrates the soil surface. Soil aggregation, porosity, surface connected pores produced by roots and fauna, and the stratification of organic matter can all play a role. Our ability to make useful recommendations on the effects of different types of tillage, minimum disturbance seeding, addition or subtraction of surface residues, soil inversion, and other soil manipulations depends on improving our understanding of the exact mechanisms by which water infiltrates under different circumstances. For example, tillage can cause rapid, significant physical changes, which can also be detrimental to the functioning of soil biota such as arbuscular mycorrhizal fungi (Wright et al., 1999).

2.4.3 Infiltration Rate

The infiltration rate of the soil is influenced by various factors depending on the condition of the soil surface, its chemical, physical characteristics, and distribution of water (U. S. Salinity Laboratory Staff, 1954). Stern (1980) reported that the rate of entry of water was greatest when the soil was dry at the start of watering, but, it decreased as the topsoil became saturated. FAO (1988) also reported that the infiltration rate was rapid when the water is first applied to the soil, but when the topsoil becomes saturated, the swelling of the clay is caused and hence, the infiltration gradually becomes constant (Donen and Westcot, 1988; McNeal and Coleman, 1973). The decrease in infiltration rate with time is mainly due to the depth of wetted zone. The metric potential gradient tends to zero and steady at the approximate hydraulic conductivity of the soil (Hillel, 1971). However, cracks developed in dry soil are closed by swelling of clay particles and the volume of water passing through decreases sharply with time due to filling of the cracks (Kosmas and Moustakes, 1991). Oster (1999) reported that, in order to grow crops, farmers must maintain adequate physical properties by using various combinations of crop, soil, water, and tillage practices. The primary properties of concern are water and air movement into and through soil, and the ability to prepare seed beds with a tilth that fasters seed germination, a critical step in crop growth. Furthermore, hydraulic conductivity must be adequate so that salts can be removed from the root zone through leaching.

Soil physical conditions, such as slow re-distribution, compaction and poor aeration, and traffic ability are often the consequences of low hydraulic conductivity. The conditions can occur quickly in the salt affected soil when the salinity is too low to compensate for the effects of exchangeable sodium on soil properties. Oster and Jayawardane (1998) reported that infiltration rates, hydraulic conductivities, and soil tilth decrease with decreased soil salinity and with increasing exchangeable sodium. At the soil surface, infiltration rates and soil tilth are particularly sensitive to salt and exchangeable sodium levels. The mechanical impact and stirring action of the irrigation water, or rain, combined with the freedom for soil particle movement at the soil surface can result in low infiltration rate when the soil is wet, and cause hard, dense soil crusts when the soil is dry. Crusts can block the emergence of seedlings. Tillage of crusted soil can result in hard soil clods that are particularly difficult to reduce in size when the clod is dry. Extensive tillage can be required to prepare a seed bed with sufficient tilth to assure adequate seed contact with soil for seed germination. Morin and Benyamini (1977) suggested that when water is applied to the soil surface at a rate exceeding infiltration rate, whether through rainfall or by irrigation, some enters the soil, while the remainder either accumulates on the surface or is carried as runoff. Generally, infiltration rate is high during the initial stage of soil wetting but decreases exponentially with time to approach a constant rate. Two main factors are responsible for this decrease: (1) a decrease in the matric potential gradient, which occurs as infiltration proceeds, and (2) the formation of a seal or crust at the soil surface. Soils in semi-arid and arid regions, where the organic matter content is usually low, soil structure is unstable, and sealing is major factor determining the steady-state infiltration rate.

2.4.4 Infiltrability

The infiltrability or infiltration capability of a soil is usually referred to as the infiltration flux of water at the soil surface, per unit area at a unit time, under unlimited water supply and standard atmospheric pressure (Brooks et al., 1997 and Hillel, 1998). This parameter is determined by the soil properties and determines the amounts of water entering into the soil and running off of the hill slope.

The infiltration capability is of importance in scientific researches in the fields such as hydrological processes, crop water availabilities, irrigation system design and scheduling as well as management, soil erosion and soil water and solute transport processes, etc (Brooks, 1997; Vijay, 1988).

The infiltration capability of a soil determines the surface runoff, while runoff is closely related to the flood prediction, reservoir water resources estimation, irrigation water allocation, runoff induced pollutants transportation, etc. (Brooks, 1997). The soil infiltration capability also determines the amount of water getting into soil profile under a given rainfall condition. The infiltrated water is either recharged as the groundwater or transferred into soil water available to crops, which influences the irrigation scheduling. Runoff as influenced by infiltration process is the driving force responsible for soil erosion (Hillel, 1998 and Jiang, 1997).

The infiltration capability of soil is a function of soil texture, structure, soil profile moisture distribution (Hillel, 1998 and Scott, 2000). It has a very high value at the initial when soil is dry, and decreases with time of the infiltration process and approaches a final constant, the steady infiltration rate. Only when the water supply to the soil surface reaches or exceeds the infiltration capability does the actual infiltration rate equal to the infiltration capability of the soil. This is the basis for measuring the infiltration capability of a soil.

A commonly used method for infiltration rate measurement is rainfall simulator or sprinkler. Peterson and Bubenzer, 1986 and Ogden et al., 1997 reported the detailed procedures for measuring soil infiltration rate with sprinkle rainfall simulator. Yuan et al. (1999) developed a portable dripper rainfall simulator for field infiltration/runoff measurement. Many more or less similar work have been reported in the literatures. This kind of method has its limitation: the very high infiltration capability of the soil cannot be determine due to the limitation of water supply.

Many reported the double ring infiltrometer, such as Bouwer (1986). The double ring method uses a Mariotte bottle for its water supply. The infiltrated amount of water is automatically replaced, so that the complete transient process of infiltration capability can be determined.

The double ring method requires the soil surface be more or less flattened and leveled. It is not applicable to (steeply) sloped soil surface. To level a sloped surface to suit the double ring application would inevitably disturb the structure of the surface soil and the continuity of the slope. Furthermore, the double ring method cannot take into account the impacts of rain drop splashes and the soil erosion on infiltration capability. Numerous studies (Helalia et al., 1988, Morin and Van Winkel, 1996 and Levy et al., 1994) showed that both raindrop splash and soil erosion cause crusting or sealing at soil surface through soil pores filled with washed in particles and/or deposition of eroded materials, which inevitably results in significant reduction in soil infiltration capability and induces higher runoff rate. Yuan et al. (1999) reported that double ring infiltrometer, as compared with sprinkler method, overestimated the steady infiltration rate of a loess soil by 1.43–1.78 times. No data is yet available as how much higher the double overestimates the transient rate at initial state of infiltration, since there is no sound method with which the early soil infiltration capability can be determined. Therefore, the research on the transient process of infiltration capability on sloped soil surface as influenced by raindrop splash, runoff, and soil erosion is of great importance to many related researches and applications.

2.4.5 Condition of infiltration

Infiltration rates are influenced by several factors (Morgan and Rickson, 1986). It varies with soil texture (the size of the soil particles), soil structure (the arrangement of the soil particles) and rainfall intensity. Table 2.2 shows the variation of infiltration rates with the soil type. The infiltration rate is high in sand and low in clay as the clay has small particles and the soil structures are complex as well.

Table 2.2 Basic Infiltration for various soil types

Soil type	Basic infiltration rate (mm/hour)
sand	less than 30
sandy loam	20 - 30
loam	10 - 20
clay loam	5 - 10
clay	1 - 5

The soil texture influences infiltration rate by the presence of cracks and the number of bio pores it contains. McKeague et. Al., 1986 presented some guidelines for estimating hydraulic conductivity form soil morphology which indicated in table 2.3

Table 2.3: Morphological descriptions and corresponding values of saturated hydraulic conductivity for soils with and loamy texture but different structural properties and pore content (from McKeague et al., 1986)

Hydraulic conductivity (mm/h)	Soil Description
1.5-5.0	Massive to weak coarse block or prismatic non compact loamy or clayey material with tightly-accommodated peds (if any), <0.02% channels >0.5mm, and few very fine voids visible with a hand lens
5.0-15	Structure less loamy material, friable, bulk density 1.5+?- Mg/M3, not compact, with <0.02% channels
15-50	Either moderately packed loamy to clayey material with weakly developed pedality (adherent partly-formed peds); 0.02%-0.1% channels >0.5mm, some of which traverse the horizon or Moderate medium to coarse blocky loamy or clayey material with firm dense peds, < 0.02% channels (= to 15 biopores/m2 of 4mm diameter)
50-150	Either approximately 0.1-0.2% channels >0.5mm, at least half of which extend through the horizon, <0.02% large (>5mm) channels, structure less or weak structure; texture finer than fine sandy loam, if not compact Or moderate fine medium blocky with weakly adherent peds or moderate to strong medium to corse blocky,;<0.1% channels extend through the horizon; texture finer than sandy loam, if not comnpact

In table 2.2, six different morphological descriptions of loamy soil are given, together with corresponding values for saturated hydraulic conductivity. The soils have the same texture but differ with respect to the number of bio pores or level of aggregation and structural development.

It is evident that such large differences in hydraulics conductivity will result in large differences in the amount of runoff generated during a particular storm. If the soil is wet; the rate of infiltration would be equal to the saturated hydraulics conductivity of the soil.

Table 2.4: Basal areas for different vegetation types (from McKeague et. al., 1986)

Land use or cover	Hydrological condition	Percentages basal area rating
Fallow (after row crop)	-	0.10
Fallow (after sod)	-	0.30
Row crops	poor	0.10
	good	0.20
	poor	0.20
Small grain	good	0.30
	poor	0.20
Hay (legumes)	good	0.40
	poor	0.40
Hay (sod)	good	0.60
	excellent	0.80
	poor	0.20
Pasture or range	fair	0.30
(bunch grass)	good	0.40
	poor	0.40
Temporary pasture (sod)	fair	0.50
	good	0.60
Permanent pasture or	poor	0.80
meadow (sod)	good	1.00
Woods and forest	-	1.00

For dry soil, time for runoff generation may be even larger, as the time taken to wet the soil to saturation varies. This also implies that the delay in time before runoff occurs is longer for soils with high hydraulics conductivity. Typical values of basal area given in Table 2.4. the hydrological condition for soil with high percentages of basal area leads to high infiltration rates and probably it is by no means clear, to reduction in the amount of rain reaching ground after interception by the vegetation canopy.

2.4.6 Spatial Variability of Infiltration

Soil, as a natural resource, has variability inherent to how the soil formation factors interact within the landscape. However, variability can occur also as a result of cultivation, land use and erosion. Spatial variability in soil attributes as a result of land degradation due to erosion. Spatial variability of soil properties has been long known to exist and has to be taken into account every time field sampling is performed. There have been reports of spatial variability of soil properties, mostly affecting crop yield, since the beginning of this century, but a comprehensive tool to analyse spatial variability was not available until 1971. It is called geostatistics and has been intensively used in soil science and other agronomic properties during the last two decades.

2.5 Geostatistical Analysis

GS+ is a GeoStatistical Analysis and Mapping program that allows you to quickly and efficiently measure and illustrate spatial relationships in geo-referenced data. GS+ analyzes spatial data for autocorrelation and then uses this information to make optimal, statistically rigorous maps of the area sampled. Geostatistical analysis included examining spatial variability nature of the soil engineering properties by determining semivariogram parameters namely the sill, nugget and range, establishing best fitted semivariogram models for the soil properties, and computing maps of distribution of soil engineering properties over the study area using the method of kriging. Geostatistics was defined as" the application of the formalism of random functions to the reconnaissance and estimation of natural phenomena" by G. Matheron, who introduced the theory of regionalized variables for mining applications. The technique of geostatistics is used to create of model of spatially correlated random variables based on samples, and then estimate values at unsampled locations using the model. The application of geostastics is relatively new, limited by a lack of infiltration using semivariogram seems to be more informative and this aspect has not yet fully explored. A property is called auto correlated or spatially dependent if the probability of similar data values is higher for neighbouring sample points than points far from each other. This spatial is differentiating using the semivariance which is one of the geostatistical characters. In an h-Scattergram the individual values that make up a semivariance pair (the head value and the tail value) are plotted against each other for all the points that make up a variogram lag class. Like variance cloud graphs, h-Scattergrams are very useful for discovering outliers that can skew the average semivariance value for a particular lag class. By placing the mouse on top of individual points you can determine which pairs of points in the data set are suspect.

h-Scattergrams are specific to both direction (isotropic or a specific anisotropic direction) and to a particular lag class. h-Scattergrams are created by clicking on a point in a variogram or autocorrelogram in either the Autocorrelation Analysis window or the Variogram window. The List Values command lists numeric values for the cloud pairs in a separate h-Scattergram Listing window

2.5.1 Statistical methods

When data are sampled in such a way as to allow for the application of geostatistical analysis, the spatial dependence, according to VIEIRA et al. (1983) can be evaluated by examining the semivariogram, which can be calculated using this equation,

$$\gamma(h) = \frac{1}{2N(h)} \sum \left[Z(x_i) - Z(x_i + h) \right]^2$$

where N(h) is the number of pairs of values $Z(x_i)$, $Z(x_i+h)$ separated by a vector h. If the semivariogram increases with distance and stabilises at the a priori variance value, it means that the variable under study is spatially correlated and all neighbours within the correlation range can be used to interpolate values where they were not measured. Semivariograms may be scaled by dividing each semivariance value by a constant such as the square of the mean and the variance value, as it was suggested by Vieira et al. (1997).

When semivariograms are calculated using equation 1, the result is a set of discrete values of distances along with the corresponding semivariances. Because any geostatistical calculation will require semivariances for any distance within the measured domain, there is a need to fit a mathematical model which would describe the variability. VIEIRA (2000) describes the model fitting process and the cross validation of the fitted models. In this paper, the semivariograms used were all fitted to the spherical model, which is

$$\gamma(h) = C_0 + C_1\left[\frac{3}{2}\frac{h}{a} - \frac{1}{2}\left(\frac{h}{a}\right)^3\right], h \leq a$$

$$\gamma(h) = C_0 + C_1, h > a$$

where C_0 is the nugget effect, C_1 is the structural variance and a the range of spatial dependence. These are the three parameters used in the semivariogram model fitting. Models were fit using least squares minimization and judgement of the coefficient of determination. Whenever there was any doubt on the parameters and model fit, the jack knifing procedure was used to validate the model, according to VIEIRA (2000).

Using the values interpolated by the kriging method, contour or tri-dimensional maps can be precisely built, examined and compared for each of the crop yield and soil properties variables.