Application of Statistical Quality Control Charts and Geostatistics to Soil Quality Assessment in a Semi-Arid Environment of South-Central Iran

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1. Abstract

The research concerns the semi-arid area of Marvdasht in the Fars Province, South central Iran. The area, one of the most productive in Iran, is very susceptible to land degradation due to soil, climatic, topographic, hydrological, and biological conditions. The purpose was to apply control charts to soil quality assessment in particular and to land evaluation in general. The research was carried out taking advantage of an existing full data set, that allowed to test how efficiently control charts can be used to assess the sustainability of land management systems in a semi-arid environment where irrigated wheat has been practiced as a monoculture for centuries. Patterns of variation and distribution of soil variables are analyzed using classical statistics. Statistical quality control charts (SQC) are used to investigate variability in soil properties and control the mean of soil variables. The spatial features are pictured through kriging, a weighted moving average interpolation technique, based on computation, interpretation and modeling of variograms of soil variables. Data layers created by the application of SQC and geostatistics are integrated in a GIS to determine changes in soil qualities. The sustainability of the soil resource is assessed on the basis of the information obtained from the analysis of the changes in soil qualities. In conclusion, statistical quality control charts proved to be efficient for assessing selected soil properties. Control charting can be used in conjunction with geostatistics to map the spatial variation of land qualities in a GIS environment.

Soil quality changes over time. Changes can be identified from variations in soil properties caused by human activities. Data on management-dependent soil properties must be properly analyzed to determine if land management practices and land use have been successful and to decide on future actions. It is through the analysis of such data that management activities can be evaluated and strategies to sustain the use of soil resources can be selected.

Statistical methods such as regression and analysis of variance have been used extensively to analyze soil data and model their variations. However, assessing soil quality may require the use of more than one technique to analyze patterns of variation in its components. Quality control charts are statistical tools that allow such analysis.

They are commonly used in controlling the process variability in manufactured goods and services industry. The statistical basis for their use is well established and several software packages have been developed that allow their construction to be done by computer (Ryan, 1989). Larson and Pierce (1994) suggested that quality control charts could be appropriate statistical tools for assessing changes in soil quality.

The purpose of this study was to apply control charts to soil quality assessment in particular and land evaluation in general. The research mobilized a large data set that allowed to test the efficiency of control charts in assessing the sustainability of land management systems in a semi-arid area of Iran, where irrigated wheat has been practiced as monoculture for centuries.

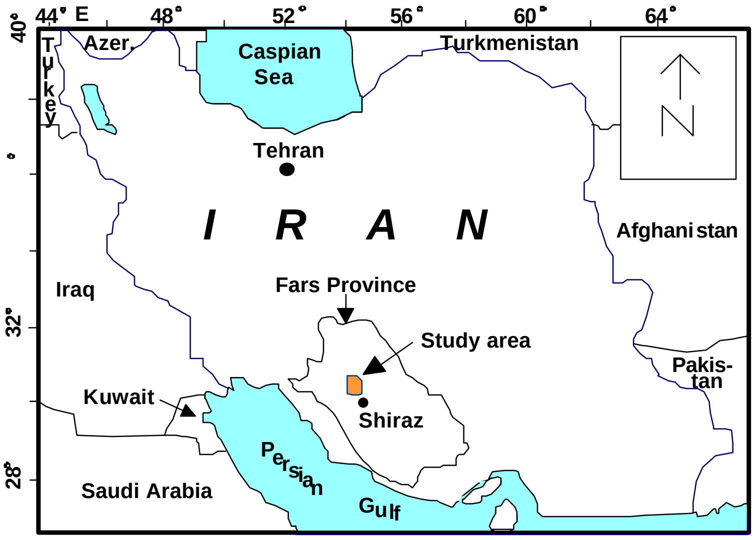
2. Materials and Methods

2.1 Characteristics of the area

The study area, known as the Marvdasht plain, lies in a large valley between mountains in the Fars Province, about 50 km northeast of Shiraz, the provincial capital. The area is located 29° 45′ to 30° 14′ N and 52° 24′ to 52° 48′ E (figure 1).

Average elevation of the plain is 1,580 m asl. The valley is traversed by the Kor river which, soon after leaving the Drudzan dam in the north, enters the Marvdasht plain through which it pursues a meandering course prior to emptying into Lake Bakhtegan, a land-locked complex of saline open water and marshes, 120 km downstream from Drudzan dam.

Figure 1. Location of the study area in the national and regional



context.

Climate is semi-arid, with mild winters and dry and relatively hot summers. In an average year, the area receives about 330 mm of rainfall. Significant precipitation occurs from November to May, while the other five months are very dry. At low elevation, nearly all precipitation falls in the form of rain, while at higher elevations a significant amount occurs in the form of snow. Mean monthly temperature ranges from 3 ^{o}C in January to 29 ^{o}C in July. The mean annual air temperature is about 17 ^{o}C, the mean maximum is 40 ^{o}C and the mean minimum is -6 ^{o}C. Absolute maximum and minimum values of 43 ^{o}C and -15 ^{o}C have been recorded in July 1977 and February 1968, respectively. The relative humidity varies from 23 to 68%, with an average of 58% in winter (48 to 68%) and 27% in summer (23 to 36%). The evaporation rate is very high. The total yearly evaporation, measured from class "A" pan at Marvdasht pilot project area, is 2326 mm (Soil Institute of Iran, 1968). The average evaporation loss is 3.3 mm/day during winter (November to April) and 9.3 mm/day during summer (May to October). The irrigation water is mainly obtained from the irrigation canals of the Drudzan dam and the regulated Kor river flow. Contribution of springs and wells of varying depths to irrigation water is significant.

Quaternary sediments derived from the surrounding sedimentary rocks cover large parts of the study area. Lacustrine sediments are deposited in depressions as mud, clay and siltpans. Rocks in the mountainous areas from which the Kor river and its main tributary Maeen and Sivand rivers draw their water supply, are of sedimentary origin. The middle Cretaceous limestone of the Bangestan group, together with the lower Cretaceous Dariyan-Fahiylan limestone are the most common rock units in the north and northwest of the study area, where most of the Kor alluvium is derived from (NIOC, 1963).

2.2 Sampling method

Collecting soil data depends on the goal for which the soil information is used. This research focuses on land use and land management practices and their effects on land quality. With respect to this, soil population is regarded as that part of the soil which has been cultivated for years ago and will be under cultivation for years to come, i.e. the plow layer, where most of the land management practices take place. The kind of land use is also an important factor that determines whether soil population should be taken as the topsoil, the plow layer, or the whole soil profile down to the rock. Sampling the plow layer for soil quality assessment in relation to soil management practices is justified in the Marvdasht area, because the land use for many years was predominantly irrigated cereals (mostly wheat and barley), with recent incorporation of other shallow-rooted crops such as rice, corn and sorghum. Also off-site effects on land should be taken into account when dealing with sustainable land management (FAO, 1993). The Kor river deposits about 237 thousand tons of sediments on the plain each year. The addition of fine-grained sediments, nutrients and organic matter to land enriches the topsoil, which is incorporated into the plow layer during tillage.

The data set used in this research was prepared by the Agricultural Research Organization of Fars Province, Division of Soils, to assess the fertility condition of soils which have been used for cereal production over centuries. In total, 2,100 observation points were sampled following a systematic sampling scheme. The area was divided into regularly spaced squares of 500 by 500 m and the sampling points were located at grid nodes. The sampling grid was aligned with the topographic map at the scale of 1: 50,000. This was helpful for adjusting the direction and tracking the sampling points. A level was used to give the direction and the sampling points were located by pacing from west to east. Composite samples were taken from topsoil (0 - 25 cm) to obtain average values and minimize the deviations due to factors such as sheet erosion, animal droppings and burning.

Samples were analyzed for determining organic carbon (Walkley-Black method), total nitrogen (Kjeldahl method), available phosphorus (Olsen extraction) and available potassium (1 N ammonium acetate extraction). In addition to grid sampling, 15 soil sites representing the different soil map units were described according to FAO guidelines (1977). Undisturbed soil samples were collected from the topsoil (0 - 25 cm) and subsoil (30 - 50 cm), using cores of 100 cm^3 to determine bulk density.

2.3 The data set

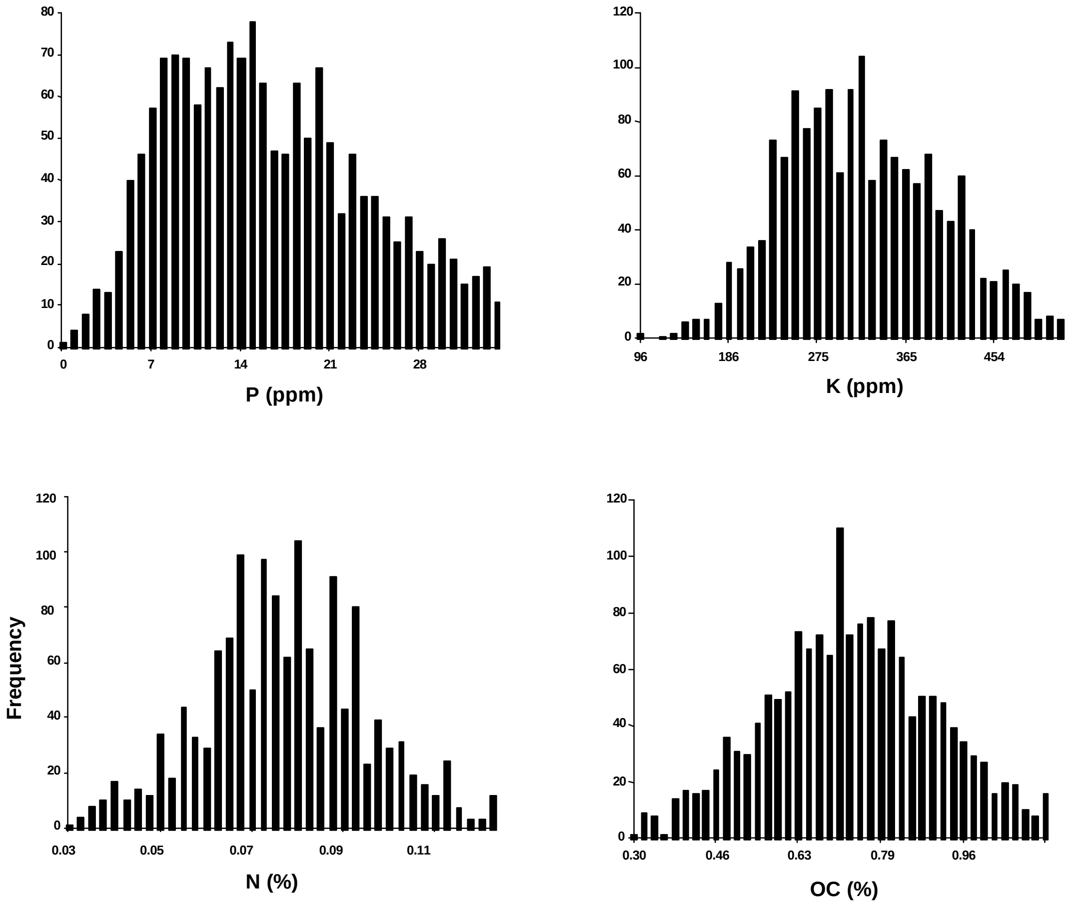


Figure 2. Histograms showing variations of the available P, available K, total N and OC in the soils of the Marvdasht area.

Prior to applying quality control charts, it is necessary to put the data into classes and construct histograms to analyze the pattern of variation in data and see whether or not the data are normally distributed. Specification limits can be displayed on a histogram to show what portion of the data exceeds the established specifications. The histograms of total nitrogen, available phosphorus, available potassium, and organic carbon in soils of the Marvdasht area show that the data sets approximate normality (figure 2).

2.4 Concept of quality control charts

The construction of control charts is based upon statistical principles. The charts used in this research require normal distribution of data. The centerline in figure 3 could represent an estimate of the mean, standard deviation or other statistics. The curve to the left of the vertical axis should be viewed relative to the upper and lower control limits. There is very little area under the curve below the lower control limit (LCL) and above the upper control limit (UCL). This is desirable as areas under a curve for a continuous distribution represent probabilities. Since a process or a property is out of statistical control when a value is outside the control limits, quality control requires that the probability for such an event to occur be small.

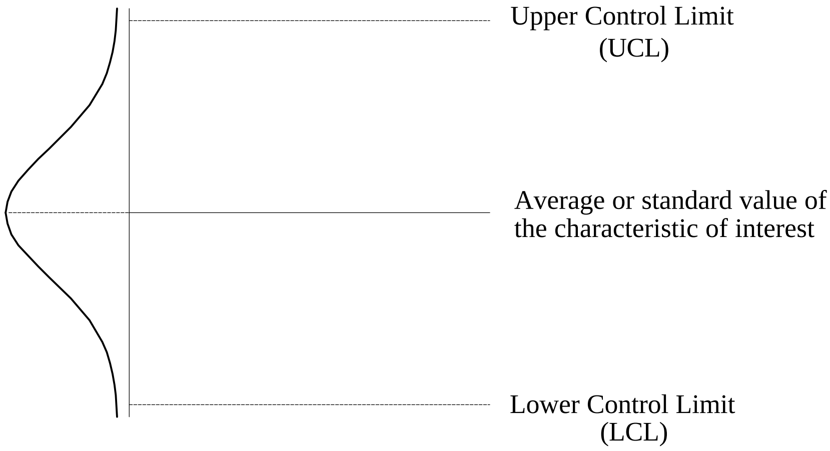


Figure 3. Basic form of a control chart (after Ryan, 1989).

If the objective is to control the process or property mean, μ, and the limits are given as $\mu \pm 3\sigma_x$, the total probability outside the limits is 0.0027 (0.00135 on each side) if X has a normal distribution. In the case of normal distribution and known standard deviation $\sigma_{x,}$ the chance would be 27 in 10,000 of observing a value of the sample mean, $\bar{X}$, outside the limits when the population mean is at μ. It is however unlikely that the distribution will be exactly normal or that the true process or property mean, μ, and σ_x will be known. Therefore, 3-sigma limits are more appropriate than probability limits, since the exact probabilities are unknown. If samples are of at least size 4 or 5, the distribution of $\bar{X}$ will not differ greatly from a normal distribution as long as the distribution of X is reasonably symmetric and bell-shaped. This results from the fact that the distribution of $\bar{X}$ is more normal, in general, than the distribution of *X,* as a consequence of the central limit theorem (Ryan, 1989). The procedure for applying statistical quality control charts to soil quality assessment is given in figure 4.

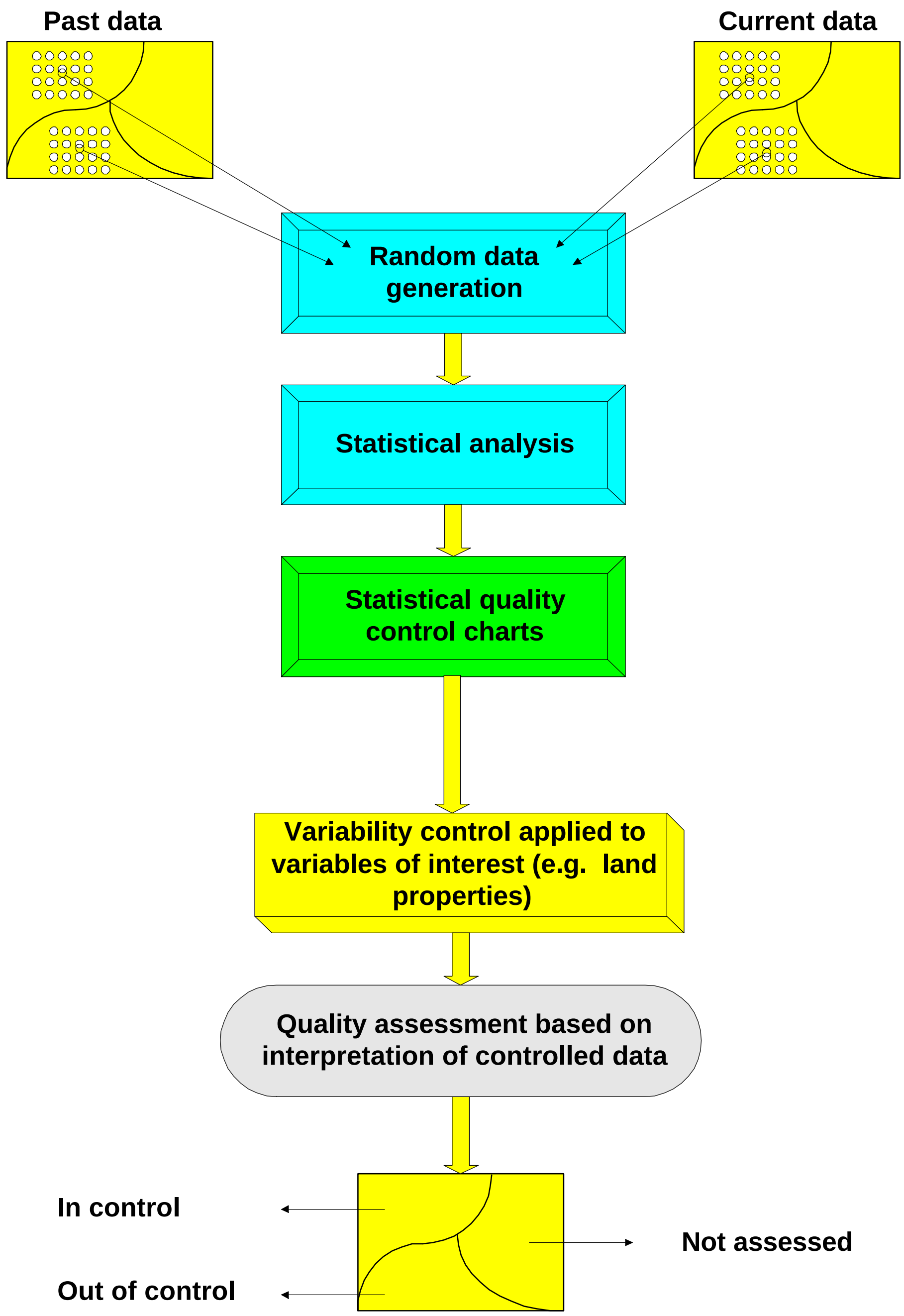


Figure 4. Procedure for the application of statistical quality control charts to soil quality assessment.

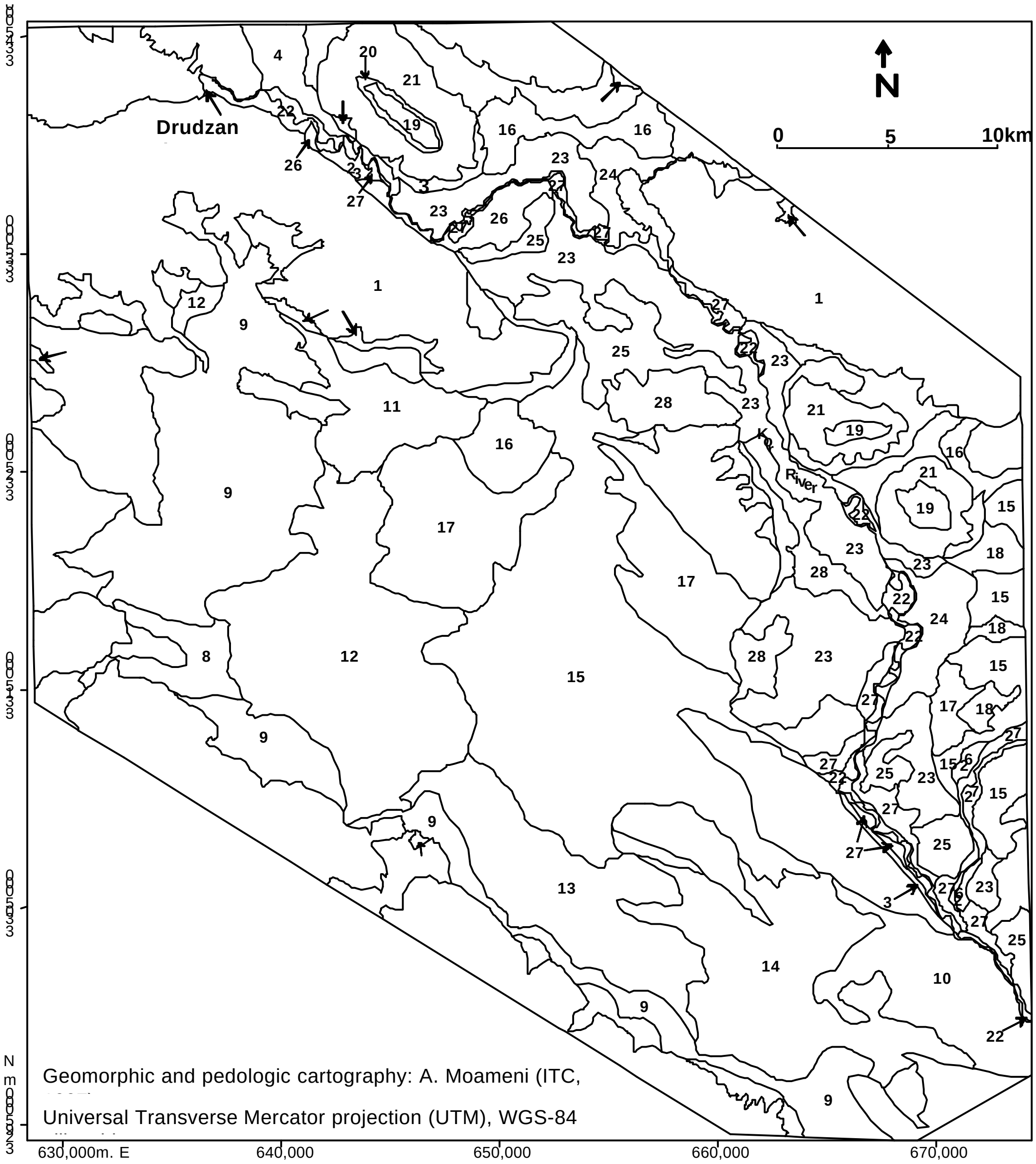


Figure 5. Semi-detailed geopedologic map of Marvdasht

3. Application to Soil Organic Carbon

3.1 Generation of data subsets

Random data subgroups were generated from full data set. First, each sampling point was georeferenced to the standard national topographic map and then assigned a number representing the pair of geographical coordinates of each sampling point. Assigned numbers were used as input data for randomly selecting observation points from the full data set. Random sampling was performed by computer, using statistical software

Table 1 Legend of the geopedologic map of the Marvdasht area

Land-scape	Relief/ Molding	Lithology	Landform	Map unit type	Polypedons Name % Obs.	Inclusions Name%Obs.	Soil map unit
Mountain	High hill	Massive limestone	Structural surface	Consociation	Rock outcrop80 Lithic Xerorthents20		1
	High hill	Marly limestone	Slope facet complex	Association	Bare rock70 Lithic Xeric Haplocalcids30		2
Piedmont	Fan	Alluvio-colluvium	Apical part	Consociation	Typic Xerorthents85 Lithic Xerorthents15		3
			Distal part	Consociation	Xeric Haplocalcids80 Typic Xerorthents20		4
		Alluvium	Torrential stream deposit	Consociation	Typic Xerorthents50 Typic Xerofluvents50		5
	Erosional glacis	Alluvio-colluvium		Association	Xeric Haplocalcids40 Typic Xerorthents30	Lithic Xerorthents 15 Typic Xerofluvents 15	6
	High glacis	Alluvio-colluvium		Consociation	Xeric Haplocalcids 70 Lithic Xeric Haplocalcids20	Typic Xerorthents 10	7
	Middle glacis	Alluvio-colluvium		Consociation	Xeric Haplocalcids 65 Typic Xerorthents35		8
	Lower glacis	Alluvium		Consociation	Xeric Haplocalcids 80 Sodic Xeric Haplocambids 15	Typic Xerofluvents 5	9
			Salt affected	Association	Xeric Natrargids 60 Sodic Aquicambids 30	Xeric Aquicambids10	10
	Lacustrine depression	Lacustrine	Depression, wet	Association	Gypsic Haplosalids 40 Xeric Aquicambids 30 Sodic Xeric Haplocambids 30		11
			Depression, salt pasture	Consociation	Sodic Xeric Haplocambids 75 Xeric Aquicambids 20	Xeric Haplocalcids 5	12
			Depression, marsh creek zone	Consociation	Sodic Xeric Haplocambids 80 Xeric Aquicambids 20		13
			Depression, wet & saliferous	Association	Xeric Natrargids 40 Sodic Xeric Haplocambids 30 Xeric Aquicambids 30		14

Land-scape	Relief/ Molding	Lithology	Landform	Map unit type	Polypedons Name % Obs.	Inclusions Name%Obs.	Soil map unit
Piedmont	Flash-flood fan	Alluvium	Central part	Association	Xeric Haplocambids70 Aquic Haplocambids 20	Fluventic Aquicambids1 0	15
			Depression , wet	Consociation	Xeric Aquicambids 65 Sodic Xeric Aquicambids30	Gypsic Haplosalids 5	16
			Depression , moderately salt affected	Consociation	Xeric Aquicambids 50 Sodic Xeric Aquicambids45	Fluventic Aquicambids 5	17
			Central part, severely salt affected	Consociation	Typic Aquisalids 80 Aquic Haplargids20		18
Plateau	Mesa	Limestone		Association	Lithic Xerorthents40 Rock outcrop 40 Typic Xerorthents20		19
	Scarpment	Massive limestone	Vertical scarp	Consociation	Bare rock 100		20
	Debris talus	Colluvium		Consociation	Rock outcrop 85 Lithic Xerorthents10	Typic Xerorthents5	21
Valley	Floodplain	Alluvium	Pointbar complex	Consociation	Xerifluventic Haplocambids65Xeroflu vents 35		22
	High terrace	Alluvium	Levee/overf low mantle complex	Consociation	Xeric Haplocambids 50 Xeric Aquicambids50		23
			Levee/overf low mantle complex, eroded	Association	Xeric Haplocambids 60 Xerertic Haplocambids30	Xeric Aquicambids 10	24
	Upper middle terrace	Alluvium	Levee/overf low mantle complex	Consociation	Xerifluventic Haplocambids50 Xeric Haplocambids 30	Xeric Haplocalcids 20	25
	Lower middle terrace	Alluvium	Levee/overf low mantle complex	Consociation	Xerifluventic Haplocambids75	Xeric Haplocalcids 25	26
	Lower terrace	Alluvium	Levee/overf low mantle complex	Consociation	Xerifluventic Haplocambids60 Fluventic Haplocambids 30	Xerofluvents10	27
	Depression	Alluvium	Overflow basin	Consociation	Xerertic Haplocambids50 Xeric Aquicambids 40	Sodic Xeric Aquicambids 10	28

Table 2. Random subgroup data for topsoil (0 - 25 cm) organic carbon content

Subgroup →	**1 U 4**	**2 U 11**	**3 U 12, U 13**	**4 U 14**	**5 U 15**	**6 U 16**	**7 U 17**	**8 U 18**	**9 U 22, U 26, U 27**	**10 U 23**	**11 U 24**	**12 U 25**	**13 U 28**
x_1	0.87	0.67	0.42	0.46	0.99	0.66	0.5	0.7	0.93	0.51	1.03	1.06	1.39
x_2	0.85	0.71	0.78	0.48	0.87	0.72	0.81	0.7	0.71	0.42	0.63	0.8	0.99
x_3	0.93	1.49	0.9	0.98	0.36	0.82	0.48	0.98	0.45	0.59	0.8	0.48	0.71
x_4	0.91	1.8	0.65	0.74	1.66	0.57	0.71	0.93	1.02	0.76	0.8	0.71	0.044
x_5	1.1	1.44	0.61	0.52	0.55	0.88	0.99	0.41	0.71	0.73	0.64	0.86	0.56
x_6	0.77	1.49	0.5	1.05	0.55	1.06	0.65	1.41	1	0.4	1.23	0.85	0.81
x_7	0.66	0.93	0.67	0.87	0.89	0.42	0.8	1.2	0.45	0.83	1	0.64	0.51
x_8	0.91	0.9	0.47	0.98	1.27	0.93	0.5	0.72	0.82	1.02	0.89	0.98	0.8
x_9	0.61	1.6	0.47	0.89	0.28	0.88	1	0.73	1.15	1.02	0.94	1.15	0.56
x_{10}	0.66	0.83	0.88	0.81	1	0.32	1	0.54	0.47	0.64	0.54	0.82	0.33
x_{11}	1.04	0.99	0.67	1.08	0.73	0.66	0.95	0.98	0.54	0.66	0.92	1.06	0.91
x_{12}	0.86	1.49	0.81	0.9	0.73	0.67	0.91	0.56	1	0.74	0.8	0.45	0.38
x_{13}	0.85	0.81	0.6	0.9	1.27	0.72	1.1	0.97	0.82	0.68	0.57	1.06	0.58
x_{14}	0.98	0.88	0.9	0.81	0.54	0.66	0.68	0.97	0.31	0.46	0.8	1.11	0.99
x_{15}	0.77	0.81	0.74	1.04	0.55	0.8	1.1	0.73	0.67	0.51	0.48	0.88	0.25
x_{16}	0.88	0.81	0.75	0.74	0.58	0.57	0.79	0.54	0.59	0.88	1.01	0.88	0.74
x_{17}	0.77	0.81	0.6	0.74	1.16	0.67	0.81	0.7	0.95	0.74	0.76	0.8	1.2
x_{18}	0.77	0.88	0.89	0.55	0.99	1.01	0.76	0.97	0.42	0.74	1.03	0.74	0.71
x_{19}	0.91	0.78	0.92	1.04	0.55	0.19	1.33	0.48	0.84	0.39	0.59	0.86	0.77
x_{20}	0.81	0.57	0.88	1	0.7	0.74	0.78	0.56	0.45	0.68	0.54	0.59	0.82
$\overline{X}$	0.85	1.03	0.71	0.83	0.81	0.7	0.83	0.79	0.72	0.67	0.8	0.84	0.7
R	0.49	1.23	0.5	0.62	1.38	0.87	0.85	1	0.84	0.63	0.75	0.7	1.35
S	0.12	0.37	0.16	0.2	0.35	0.22	0.22	0.26	0.25	0.19	0.21	0.2	0.32

U = Unit (i.e., soil map unit); x_1 to x_{20} = Observations per subgroup (soil map unit); $\overline{X}$ = Sample mean; *R* = Sample range; *S* = Sample standard deviation

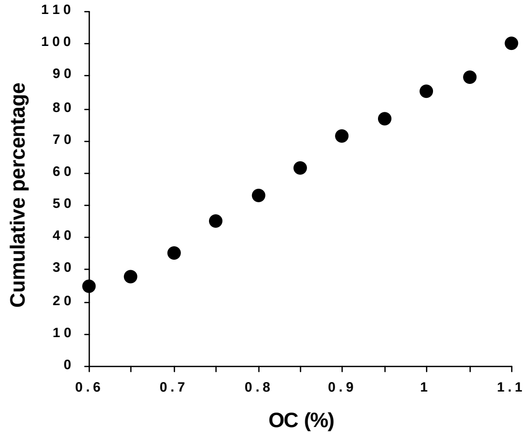


Figure 6. Cumulative frequency plot of data from table 2.

package (Microsoft Corporation, 1996). In total, 13 subgroups with 20 observations per subgroup were obtained, each subgroup being the average of four random data subsets.

The random data set generated for soil organic carbon (OC) content is shown in table 2. Generally, each subgroup corresponds to a map unit on the geopedologic map of the area (figure 5 and table 1). Exceptionally, subgroups 3 and 9 contain more than one map unit to obtain the minimum number of observations required (table 2). The purpose was to have enough observations to obtain a good estimate of the variability and the mean of OC in each soil map unit. Table 3 shows the summary of sample statistics for data on soil OC content, generated by random sampling from the full data set pertaining to the 13 selected subgroups (corresponding to 16 out of 28 map units on the geopedologic map of the area). Before charting, it is needed to know how close the distribution of data values approaches normality (Gaussian distribution). Figure 6 shows a cumulative frequency plot of 260 topsoil OC values. Most of the cumulative frequencies plot in a straight line, indicating that the distribution of the data approximates normality. The skewness of the data sets and the difference between mean and median are both low, thus close to normality. This is desirable because the construction of statistical quality control charts relies, at the first place, on random or near-random data.

Table 3 Statistical summary of subgroup data in table 2

1 (Map unit 4)		**2 (Map unit 11)**		**3 (Map units 12,**		**4 (Map unit 14)**	
Mean	0.85	Mean	1.03	Mean	0.71	Mean	0.83
Standard Error	0.03	Standard Error	0.08	Standard Error	0.04	Standard Error	0.04
Median	0.86	Median	0.88	Median	0.71	Median	0.88
Mode	0.77	Mode	0.81	Mode	0.9	Mode	0.74
Standard Deviation	0.12	Standard Deviation	0.37	Standard Deviation	0.16	Standard Deviation	0.2
Sample Variance	0.02	Sample Variance	0.13	Sample Variance	0.03	Sample Variance	0.04
Kurtosis	0.05	Kurtosis	-0.72	Kurtosis	-1.21	Kurtosis	-0.69
Skewness	0	Skewness	0.86	Skewness	-0.25	Skewness	-0.66
Range	0.49	Range	1.23	Range	0.5	Range	0.62
Minimum	0.61	Minimum	0.57	Minimum	0.42	Minimum	0.46
Maximum	1.1	Maximum	1.8	Maximum	0.92	Maximum	1.08
Sum	16.91	Sum	20.69	Sum	14.11	Sum	16.58
Count	20	Count	20	Count	20	Count	20
Largest(1)	1.1	Largest(1)	1.8	Largest(1)	0.92	Largest(1)	1.08
Smallest(1)	0.61	Smallest(1)	0.57	Smallest(1)	0.42	Smallest(1)	0.46
Confidence	0.06	Confidence	0.17	Confidence	0.08	Confidence	0.09
5 (Map unit 15)		**6 (Map unit 16)**		**7 (Map unit 17)**		**8 (Map unit 18)**	
Mean	0.81	Mean	0.7	Mean	0.83	Mean	0.79
Standard Error	0.08	Standard Error	0.05	Standard Error	0.05	Standard Error	0.06
Median	0.73	Median	0.7	Median	0.81	Median	0.73
Mode	0.55	Mode	0.66	Mode	0.5	Mode	0.7
Standard Deviation	0.35	Standard Deviation	0.22	Standard Deviation	0.22	Standard Deviation	0.26
Sample Variance	0.12	Sample Variance	0.05	Sample Variance	0.05	Sample Variance	0.07
Kurtosis	0.33	Kurtosis	0.56	Kurtosis	0.02	Kurtosis	0.25
Skewness	0.73	Skewness	-0.6	Skewness	0.26	Skewness	0.7
Range	1.38	Range	0.87	Range	0.85	Range	1
Minimum	0.28	Minimum	0.19	Minimum	0.48	Minimum	0.41
Maximum	1.66	Maximum	1.06	Maximum	1.33	Maximum	1.41
Sum	16.22	Sum	13.95	Sum	16.65	Sum	15.78
Count	20	Count	20	Count	20	Count	20
Largest(1)	1.66	Largest(1)	1.06	Largest(1)	1.33	Largest(1)	1.41
Smallest(1)	0.28	Smallest(1)	0.19	Smallest(1)	0.48	Smallest(1)	0.41
Confidence	0.16	Confidence	0.1	Confidence	0.1	Confidence	0.12
9 (Map units 22,26,27)		**10 (Map unit 23)**		**11Map unit 24)**		**12 (Map unit 25)**	
Mean	0.72	Mean	0.67	Mean	0.8	Mean	0.84
Standard Error	0.06	Standard Error	0.04	Standard Error	0.05	Standard Error	0.04
Median	0.71	Median	0.68	Median	0.8	Median	0.86
Mode	0.45	Mode	0.74	Mode	0.8	Mode	1.06
Standard Deviation	0.25	Standard Deviation	0.19	Standard Deviation	0.21	Standard Deviation	0.2
Sample Variance	0.06	Sample Variance	0.03	Sample Variance	0.04	Sample Variance	0.04
Kurtosis	-1.24	Kurtosis	-0.44	Kurtosis	-0.75	Kurtosis	-0.43
Skewness	0.06	Skewness	0.23	Skewness	0.19	Skewness	-0.34
Range	0.84	Range	0.63	Range	0.75	Range	0.7
Minimum	0.31	Minimum	0.39	Minimum	0.48	Minimum	0.45
Maximum	1.15	Maximum	1.02	Maximum	1.23	Maximum	1.15
Sum	14.3	Sum	13.4	Sum	16	Sum	16.78
Count	20	Count	20	Count	20	Count	20
Largest(1)	1.15	Largest(1)	1.02	Largest(1)	1.23	Largest(1)	1.15
Smallest(1)	0.31	Smallest(1)	0.39	Smallest(1)	0.48	Smallest(1)	0.45
Confidence	0.12	Confidence	0.09	Confidence	0.1	Confidence	0.09

13 (Map unit 28)			
Mean	0.7	Range	1.35
Standard Error	0.07	Minimum	0.04
Median	0.73	Maximum	1.39
Mode	0.99	Sum	14.05
Standard Deviation	0.32	Count	20
Sample Variance	0.1	Largest(1)	1.39
Kurtosis	0.35	Smallest(1)	0.04
Skewness	0.05	Confidence Level(95.0%)	0.15

3.2 Construction of quality control charts

There are many possible alternatives for constructing quality control charts. *R* charts (*R* for range) are used in controlling the property variability. The 3-sigma limits used to establish the control limits of the *R* chart are obtained from: $\bar{R} \pm 3\,\hat{\sigma}_R$, where $\bar{R}$ is the average of the subgroup ranges and $\hat{\sigma}_R$ is the estimated (population) standard deviation from *R*. The limits can be shown to be equal to $D_3\bar{R}$ for the lower control limit (LCL) and $D_4\bar{R}$ for the upper control limit (UCL). D_3 and D_4 are the values obtained from dividing the average of the ranges by a constant such that the resulting statistic is an unbiased estimation of σ (Ryan, 1989). The values of constants D_3 and D_4 for different subgroup sizes are tabulated with the assumption of normal distribution. For the data in table 2 with 13 subgroups, $\bar{R}$ = 0.862. The control limits are: LCL = $D_3\bar{R}$ = 0.273*0.862 = 0.23; UCL = $D_4\bar{R}$ = 1.727*0.862 = 1.48. The control chart constructed for soil organic carbon content, using the data in table 2, is given in figure 7.

Also *S* charts (*S* for standard deviation) can be established to verify the variability of the soil OC content. As with other standard control charts, the control limits for *S* charts are 3-sigma limits obtained from: $\bar{S}$ = ± 3 $\hat{\sigma}_S$, where $\bar{S}$ is the average of the subgroup standard deviations and $\hat{\sigma}_S$ is the estimate of the standard deviation of *S*. The control limits for S charts are: UCL = $B_4\bar{S}$ and LCL = $B_3\bar{S}$. For the data in table 2, $\bar{S}$ = 0.236 and the

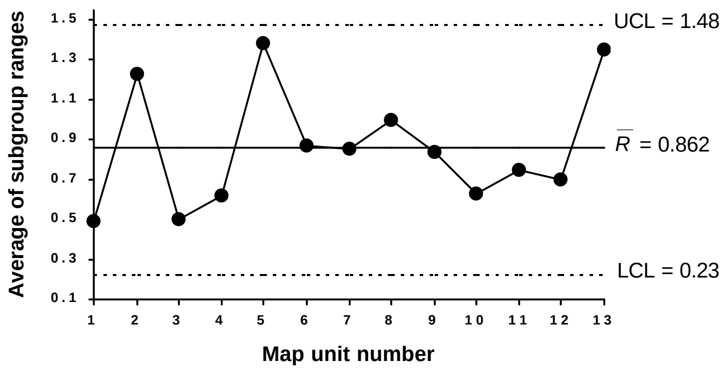


Figure 7 *R* chart for soil organic carbon content.

values of B_4 and B_3 are 1.66 and 0.342, respectively. The control limits are calculated as: UCL = 1.66*0.236 = 0.39; LCL = 0.342*0.236 = 0.08. The constructed *S* chart is shown in figure 8.

If, instead of analyzing the standard deviation controlled by an *S* chart, the objective is to investigate whether or not the mean of a soil property (or soil process) is in a state of statistical control, then an $\bar{X}$ chart ($\bar{X}$ for mean) is constructed. The control limits for an

$\bar{X}$ chart are obtained from $\bar{\bar{X}} \pm 3\,\hat{\sigma}_{\bar{X}}$, where $\bar{\bar{X}}$ is the overall average of the subgroup averages, and $\hat{\sigma}_{\bar{X}}$ denotes an estimate of the standard deviation of the subgroup averages. The control limits for an $\bar{X}$ chart can be written as: $\bar{\bar{X}} \pm A_2\bar{R}$. The values of the constant

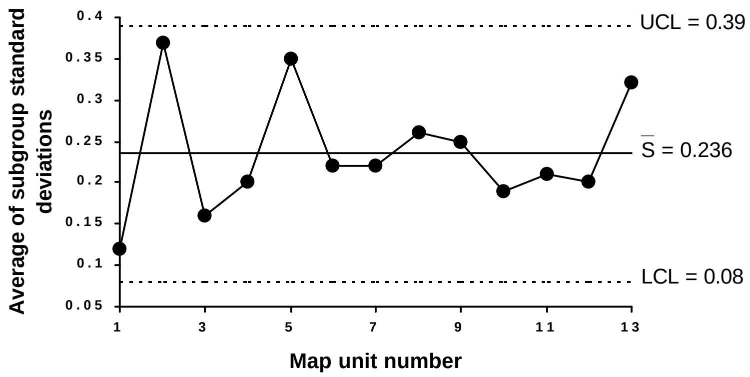


Figure 8. ***S* chart for soil organic carbon.**

A_2, calculated on the assumption of normal distribution, are available for different subgroup sizes in especially prepared tables (Ryan, 1989). The value of $\bar{\bar{X}}$ for the data in table 2 is 0.791. The control limits are calculated as: $\bar{\bar{X}} \pm A_2\bar{R} = 0.791 \pm 0.274(0.862)$, so that LCL = 0.55 and UCL = 1.03. The $\bar{X}$ chart obtained from data in table 2 is shown in figure 9.

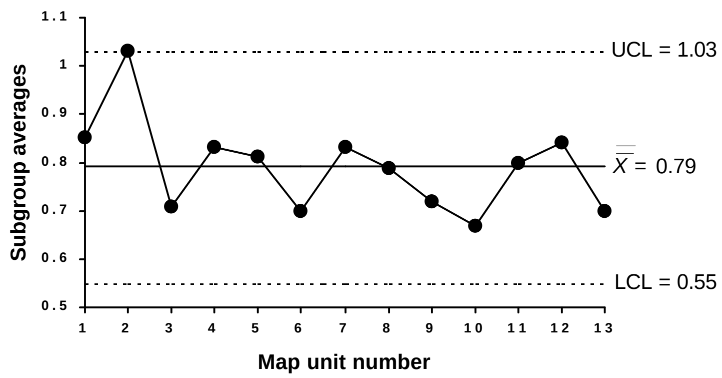


Figure 9. **$\bar{X}$ chart for soil organic carbon.**

S and *R* charts are used to verify property variability and the $\bar{X}$ chart indicates whether the property mean is in control. Whatever chart (*R* or *S*) is selected to control the property dispersion, all points for the data in table 2 plot inside the control limits, indicating that the soil OC variability is in a state of statistical control, i.e. soil OC variability has stabilized at 3-sigma level. This is true for the property mean, although subgroup 2 (map unit 11) lies just on the UCL (figure 9). But this reflects only the present status of the soil OC content in the study area; it does not indicate whether the level of OC is appropriate or not for the crops being cultivated or to be introduced, because limits do not correspond to target values. The present mean value of soil OC is 0.79%, which is far below the acceptance value for this dynamic, management-dependent soil property. Even the UCL of 1.03 is not close to the adequacy level required for good performance of the soil processes controlled by the OC content.

3.3 Standards for soil quality assessment

In control charting for soil quality assessment, distinction should be made between control limits computed on the basis of statistical procedures and target control limits (acceptance or sufficiency standards). Had the data plotted in table 2 been obtained, for example, by measuring consecutive units on an assembly line in a factory producing a certain type of metal rod with known diameter, specification limits of 3-sigma would have been appropriate for assessing the process variability and the process mean based on statistics. This is because the limits are determined from engineering specifications, based on the acceptance limits (or standards) established for the metal rod diameter to be assessed. The use of standards in conjunction with control charts has been largely discussed (Ryan, 1989). For example, if a machine can be adjusted so that the length of a bolt should be exactly 5 cm, the center line of an $\bar{X}$ chart representing length values should be set at 5, rather than some statistical value of $\bar{\bar{X}}$. Likewise, standards of soil quality are needed to determine what is good or bad and to find out if soil management systems are functioning at acceptance levels of performance (Doran and Parking, 1994). The UCL and LCL for soil quality assessment should be set based on known or desired tolerance levels, or based on the mean variance obtained from past performance, or known through some other means (Larson and Pierce, 1994).

Construction of control charts and interpretation of the results obtained should be carried out taking into account the type of soil process or property being investigated. For soil OC content for example, LCL can be designed on an average value reflecting a minimum level, beyond which management practices cannot be sustained. The desired value can be set based on proposed critical levels of soil OC content for optimum performance of soil management practices found in the literature. There is no consensus on what optimal OC levels should be used. Sys *et al*. (1991) suggested four different scales for soil OC content rating, from which an average scale was derived for the purpose of this study (table 4).

Table 4. Rating of soil OC content

Land suitability	Soil OC content (%)
S1	> 2
S2	0.8- 2
S3	<0.8

For controlling the soil property mean related to OC content, the values of 0.8 % and 2% were adopted as LCL and UCL respectively, and an $\bar{X}$ chart was constructed based on these acceptance limits (figure 10). Subgroups 3, 6, 9, 10 and 13 plot below the LCL, while other subgroups lie just on this limit. Those map units plotting outside the LCL are out of control, and the reason for this should be investigated. It is a signal of poor performance of soil processes related to soil OC, which can be attributed to land management practices and land use in the area.

From previous section, the value of $\bar{\bar{X}}$ for the data in table 2 is 0.79. The lower acceptance limit (0.8) coincides almost with $\bar{\bar{X}}$, which is an estimation of μ, the population mean, i.e. the mean of all the values of topsoil OC content in the study area.

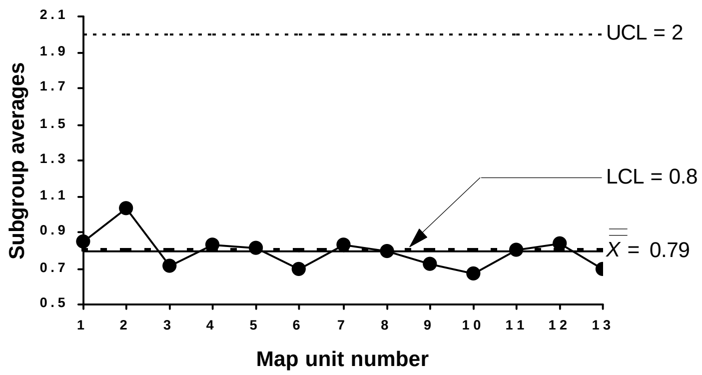


Figure 10. $\bar{X}$ **chart based on acceptance limits for soil OC.**

4. Application To Other Soil Properties

4.1 Phosphorus

The interpretation values, selected as sufficiency levels, for soil available phosphorus (P) are given in table 5 (EUROCONSULT, 1989) and the random subgroup data for P in table 7. To construct the control chart, the LCL was based on an empirical sufficiency

Table 5. Rating of available potassium (3% $H_2C_2O_4$) and available phosphorus (Olsen method)

Rating	Available K (ppm)	Available P (ppm)
Extremely high	-	>20
Very high	>320	15 - 20
High	240 - 320	10 - 15
Moderately high	160 - 240	-
Medium	120 - 160	5 - 10
Moderately low	80 - 120	-
Low	40 - 80	0 - 5
Very low	<40	-

Table 6. Random subgroup data for topsoil (0 - 25 cm) available phosphorus

Subgroup →	1 U 4	2 U 11	3 U 12, U 13	4 U 14	5 U 15	6 U 16	7 U 17	8 U 18	9 U 22, U 26, U 27	10 U 23	11 U 24	12 U 25	13 U 28
x_1	20.2	4.5	11.8	17.4	5.8	37.2	8.8	13	43.9	34	5	13.8	14
x_2	16.2	9.9	7.8	11.4	6.2	47.2	20	10.8	32	5	41	27	13.4
x_3	22.2	23.2	22	5.4	25.8	20.2	16.8	15.4	7.2	48.6	39.2	22.6	13.6
x_4	15.1	23.2	11.8	25.2	11.6	15.3	14.6	14.8	29.5	8	34.2	19.6	32.4
x_5	9.2	11	24	22	15.8	33	43.2	31	32	4.4	5	7	10.8
x_6	16.2	11	23.3	27.4	6.6	7.6	2	14.8	25.5	31.8	41	14.2	21.8
x_7	24.2	23.2	18.6	45.2	39.4	29.8	23	25.8	49.6	8.4	26.2	27.2	18.2
x_8	33.2	15.7	22	12.7	20	26.6	22.2	7.4	9.4	10	12.4	24	40.6
x_9	13.2	4.5	31.4	22.8	33.6	15.2	10.2	11	49.6	20.8	54.2	7	19.4
x_{10}	22.2	7.9	14.4	23	20.4	16.4	4	13	11.9	16.2	7	7	9.4
x_{11}	16.2	20	19.4	9.4	33.6	22	43.2	10	31	32.4	31.6	15.2	10.4
x_{12}	15.1	17.5	30.2	22.8	20.8	26.6	7.3	4.2	17.8	5.2	24.4	13.7	27.8
x_{13}	10.4	10.9	30.2	35	13.8	11	8.5	17.4	9	14.8	5	14.2	25.4
x_{14}	12.6	14.2	19.4	12.7	24.2	16.8	16	4.4	12.2	22.6	18.2	19.2	19
x_{15}	20.2	23.2	36.2	22	39.4	23.2	33	11	1.6	20.6	12.4	6.2	25.8
x_{16}	22.2	8.5	24	27.4	6.2	33	56	4.6	31	5	17.4	27.6	20.2
x_{17}	16.2	7.9	30.2	4.7	24.6	16.8	33	4.4	13.8	33.8	28.2	7.7	10.4
x_{18}	24.2	11.9	20.6	27.7	17.6	21.4	12.1	17.4	12.8	18.2	61.4	4.7	20.2
x_{19}	6	10.9	19.4	46.2	6.2	44	9.6	15.8	8.7	31.8	43	13.8	10.4
x_{20}	12.6	15.7	24.8	17	39.4	49.6	33	14.8	49.6	2.6	43	19.6	10.2
$\bar{X}$	17.38	13.74	22.08	21.87	20.55	25.65	20.83	13.05	23.91	18.71	27.49	15.57	18.67
R	27.2	18.7	28.4	41.5	33.6	42	54	26.8	48	46	56.4	22.9	31.2
S	6.292	6.219	7.292	11.38	11.81	11.92	14.87	6.878	15.61	13.08	17.02	7.535	8.474

U = Unit (i.e., soil map unit); x_1 to x_{20} = Observations per subgroup (soil map unit); $\bar{X}$ = Sample mean; R = Sample range; S = Sample standard deviation

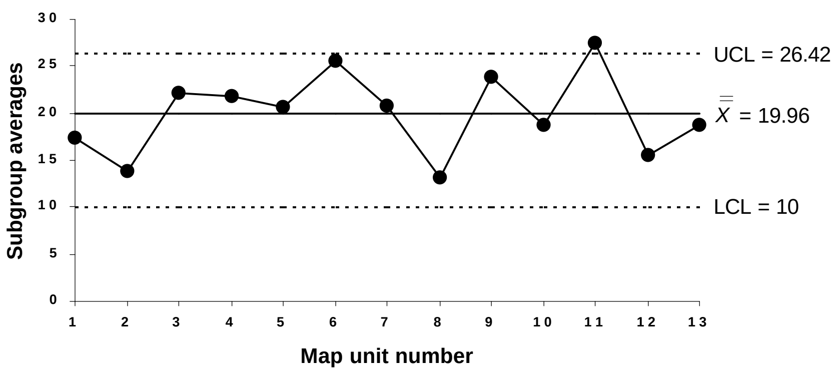


Fig. 11 $\bar{X}$ chart for soil available phosphorus

level of 10 (from table 5), while the UCL of 26 was computed from 3-sigma level (figure 11). All subgroups (except subgroup 11) plot inside the control limits. Thus the overall land use system is performing satisfactorily, which may be due to high application of fertilizers among other management practices.

4.2 Potassium

To construct the control chart, the LCL was set based on a sufficiency level of 160 (from table 5), while the UCL of 412.9 was established based on computation. Most of the subgroup averages plot inside the control limits, which indicates that natural soil fertility supplies potassium at a satisfactory level (table 7 and figure 12). Because potassium fertilizers are not extensively used in the area, high potassium levels in the soils may be attributed to potential soil fertility (i.e., soil mineral composition). Although soil and water management practices and land use can have considerable effects on available potassium, most soils in the study area have adequate potassium for normal growth of main crops.

Table 7. Random subgroup data for topsoil (0 - 25 cm) available potassium

Subgroup →	1 U 4	2 U 11	3 U 12, U 13	4 U 14	5 U 15	6 U 16	7 U 17	8 U 18	9 U 22, U 26, U 27	10 U 23	11 U 24	12 U 25	13 U 28
x_1	424	788	444	340	308	320	336	260	200	460	352	324	294
x_2	490	252	386	450	440	280	204	476	226	490	332	258	272
x_3	280	788	322	220	320	420	384	476	328	322	356	366	378
x_4	478	600	444	376	390	330	300	382	252	486	440	404	272
x_5	560	284	424	460	440	140	240	382	348	576	344	336	248
x_6	300	436	176	442	390	340	220	326	456	270	360	272	392
x_7	392	788	252	340	340	520	414	430	252	386	428	396	384
x_8	308	788	284	376	360	230	288	472	314	340	364	320	192
x_9	478	568	198	282	308	374	252	318	200	418	340	324	508
x_{10}	308	176	380	288	308	520	252	288	354	258	366	240	214
x_{11}	418	600	176	340	248	340	292	318	364	294	328	396	248
x_{12}	330	788	320	500	272	230	228	326	384	324	366	272	508
x_{13}	560	192	236	500	390	270	322	476	262	392	492	324	340
x_{14}	244	314	252	470	360	374	240	430	364	306	460	332	260
x_{15}	300	600	344	280	250	140	246	380	226	304	258	448	360
x_{16}	300	362	240	420	436	240	324	396	324	440	292	376	272
x_{17}	300	370	267	316	294	140	252	312	314	458	268	230	192
x_{18}	362	1180	350	386	390	310	396	140	348	232	268	326	294
x_{19}	300	1180	332	334	418	320	272	140	256	354	316	280	294
x_{20}	418	314	261	470	250	280	320	312	256	386	360	208	192
$\bar{X}$	377.5	568.4	304.4	379.5	345.6	305.9	289.1	352	301.4	374.8	354.5	321.6	305.7
R	316	1004	268	280	192	380	210	336	256	344	234	240	316
S	95.87	298.9	83.64	81.59	65.03	107.2	60.03	99.08	68.71	90.4	62.56	63.98	93.06

U = Unit (i.e., soil map unit); x_1 to x_{20} = Observations per subgroup (soil map unit); $\bar{X}$ = Sample mean; *R* = Sample range; *S* = Sample standard deviation

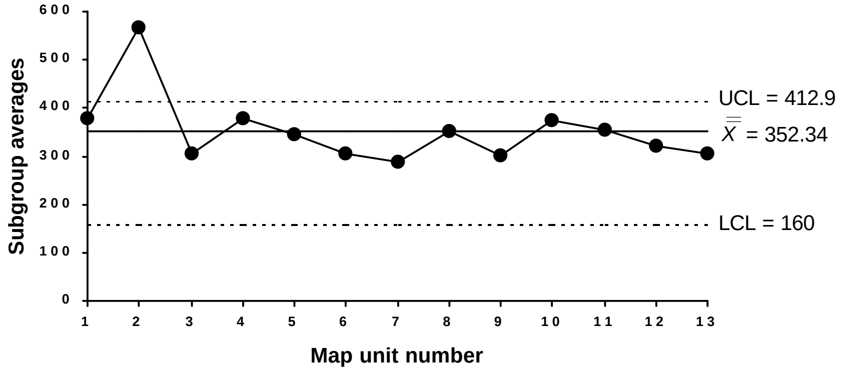


Fig. 12 $\bar{X}$ chart for soil available potassium

4.3 Nitrogen

The $\bar{X}$ chart constructed for assessing the soil quality controlled by nitrogen availability is given in figure 13. The control limits are established based on the sufficiency levels given in table 8 (EUROCONSULT, 1989). In all the soil map units assessed, the total N content is far below the lower sufficiency level adopted, with only minor spatial variations.

Table 8. Rating of total nitrogen (N)

Rating	Total N (%)
Very high	>0.300
High	0.226 - 0.300
Medium	0.126 - 0.225
Low	0.050 - 0.125
Very low	<0.050

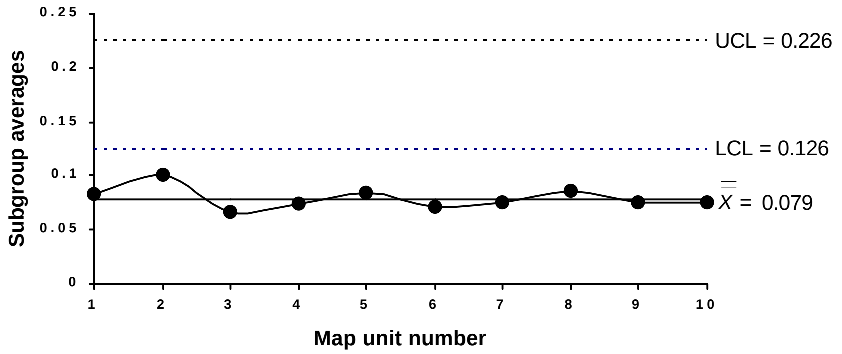


Figure 13. $\bar{X}$ chart for total nitrogen.

Table 9. Random subgroup data for topsoil (0 - 25 cm) total nitrogen

Subgroup →	1 U 4	2 U 11	3 U 12,U 13	4 U 14	5 U 16	6 U 17	7 U 22, U 26, U 27	8 U 23	9 25	10 U 28
x_1	0.076	0.095	0.084	0.079	0.088	0.076	0.069	0.099	0.061	0.07
x_2	0.077	0.08	0.065	0.032	0.13	0.085	0.098	0.074	0.079	0.07
x_3	0.095	0.09	0.065	0.066	0.081	0.058	0.098	0.08	0.084	0.095
x_4	0.085	0.08	0.056	0.052	0.052	0.084	0.07	0.099	0.092	0.07
x_5	0.085	0.058	0.084	0.076	0.073	0.056	0.088	0.085	0.066	0.069
x_6	0.067	0.16	0.065	0.076	0.102	0.07	0.095	0.069	0.092	0.07
x_7	0.094	0.195	0.068	0.069	0.074	0.075	0.06	0.105	0.044	0.095
x_8	0.067	0.091	0.043	0.091	0.105	0.07	0.056	0.099	0.038	0.031
x_9	0.077	0.19	0.078	0.107	0.039	0.08	0.05	0.078	0.098	0.085
x_{10}	0.09	0.195	0.09	0.077	0.039	0.078	0.069	0.073	0.066	0.039
x_{11}	0.094	0.08	0.078	0.069	0.085	0.058	0.088	0.084	0.085	0.07
x_{12}	0.081	0.053	0.07	0.074	0.105	0.095	0.074	0.081	0.081	0.099
x_{13}	0.104	0.084	0.069	0.107	0.101	0.067	0.123	0.095	0.099	0.039
x_{14}	0.081	0.067	0.065	0.072	0.081	0.067	0.057	0.081	0.079	0.09
x_{15}	0.076	0.091	0.059	0.077	0.039	0.05	0.07	0.088	0.059	0.109
x_{16}	0.067	0.09	0.055	0.084	0.105	0.045	0.123	0.083	0.076	0.085
x_{17}	0.073	0.053	0.045	0.072	0.074	0.083	0.057	0.083	0.079	0.103
x_{18}	0.091	0.078	0.08	0.038	0.102	0.071	0.059	0.09	0.081	0.039
x_{19}	0.09	0.095	0.055	0.102	0.11	0.078	0.036	0.088	0.075	0.091
x_{20}	0.101	0.084	0.055	0.074	0.101	0.077	0.077	0.083	0.084	0.099
$\bar{X}$	0.084	0.1	0.066	0.075	0.084	0.071	0.076	0.086	0.076	0.076
R	0.037	0.142	0.047	0.075	0.091	0.05	0.087	0.036	0.061	0.078
S	0.011	0.046	0.013	0.019	0.026	0.013	0.023	0.01	0.016	0.024

U = Unit (i.e., soil map unit); x_1 to x_{20} = Observations per subgroup (soil map unit); $\bar{X}$ = Sample mean; *R* = Sample range;*S* = Sample standard deviation

4.4 Bulk density

Soil physical properties are both expensive and time-consuming to measure. In most cases, it is not possible to form subgroups due to the lack of data. Thus, physical properties must be frequently charted using individual observations rather than subgroups. A chart constructed from individual observations is known as *X* chart. Like the $\bar{X}$ chart, an *X* chart operates with standard limits based on interpretation values for management-dependent soil properties.

Soil bulk density (BD) has been given different interpretations (EUROCONSULT, 1989; Sys *et al*., 1991; Boulding, 1994). Boulding (1994) regarded BD as an indicator of a restrictive layer, which significantly reduces soil water and permeability or increases excavation difficulty. From an agricultural point of view and for soil classification and mapping purposes, the ratings forwarded by the USDA Soil Classification Staff (SCS, 1983), quoted in Boulding (1994), seem to be practical. The bulk density, at which resistance to root penetration is high, varies with soil texture. The following rating is suggested (table 10).

Table 10 Rating of bulk density (BD)

Textural family	Bulk density
Sandy	>1.85
Coarse-loamy	>1.8
Fine-loamy	>1.7
Coarse-silty	>1.6
Fine-silty	>1.5
Fine	>1.35

The soil textures in the study area are mostly fine silty and fine. Adopting 1.35 as LCL and 1.5 as UCL for assessing the soil processes related to bulk density in a semi-arid condition seems to be justified (figure 14). Limiting values are used to assess BD, while sufficiency values were used for the other properties.

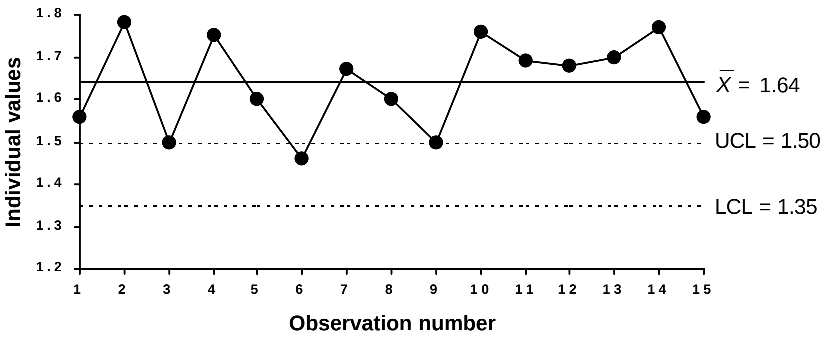


Figure 14. $\bar{X}$ chart for soil bulk density at 15 sites.

5. Discussion

5.1 Indicator properties

Organic matter is a very important soil constituent. It affects the physical, chemical and biological properties of soils. Organic matter increases the water-holding capacity of soils and promotes the development of stable soil structure by increasing granulation. Chemically, it is a source of plant nutrients, especially nitrogen (N) and sulfur (S). The total N content is a function of soil organic matter content (Tan, 1996). The $\bar{X}$ chart constructed for soil OC can provide essential information about soil properties that are in various ways related to OC. However, control charts should be constructed (on the basis of random data) and soil process variability and soil process mean associated with indicator properties should be investigated for each individual soil property of interest, to detect limiting factors.

The control chart given in figure 10 reveals that topsoil OC content is one of the factors limiting the sustainability of the agricultural activities in the area. Similarly for available nitrogen (figure 13), all subgroups cluster around $\bar{\bar{X}}$ (the average of subgroup averages), which is far below the lower acceptance control limit. In the case of soil bulk density (figure 14), most of the sites plot outside the UCL and $\bar{X}$ lies far beyond the UCL, which indicates that the property mean is out of control. This is undesirable and calls for investigating the causes. The soil and water management systems have to be either improved or changed to bring soil property mean in control. In a similar manner, other soil physical and chemical properties can be charted and evaluated to assess human-induced soil degradation. However, it would be difficult to keep a particular process characteristic in control without some knowledge of the factors affecting that characteristic. Soil available water content, for example, depends on many other soil properties such as clay content, type of clay mineralogy, bulk density, total soil porosity, among others. Investigating the weak performance of a particular property, such as available water content, in controlling the soil quality needs acquiring adequate information about the status of the other related factors. Quality control charts can be applied to each factor separately, to investigate soil condition with respect to the variability of individual (causative) factors. But control charts alone cannot produce statistical control of soil quality. Application of control charts to soil quality assessment can indicate whether or not statistical control is being maintained and provide other signals that should be used to detect the causes of soil quality deterioration through analytical determinations. The problem of poor performance of soil quality indicators should be investigated within the context of human activities, such as land use and land management systems.

Control charting might reveal that some properties are out of control, while others are not. In the present study area, for example, organic content, nitrogen and bulk density are close to or below the LCL. In contrast, phosphorus and potassium are well in the control range. Thus a few limiting factors might be decisive in determining agricultural sustainability. These are indicators of poor land management, which must be removed to secure sustainability.

5.2 Minimum data set

This research benefited from a very large data set, collected for other purposes. For example, 1,752 organic carbon values were available. From this existing data population, only small samples were randomly taken: 20 values for each of 16 selected map units, thus a total of 260 values representing only 15% of the total data set. The question that arises is: what is the minimum number of observations needed to construct quality control charts of a similar level of confidence? Figure 15 shows the polynomial line fitted to the means calculated from an increasing number of observations (from 1 to 30), randomly selected from the total population of values. With 12 observation points, the fitted line becomes less wavy and the differential of the means (i.e., the difference between the mean of the full data set and the mean of the selected observation points) approaches zero. This is also the case of the estimated mean based on the randomly selected observation points. Therefore, a minimum of 12 observation points per soil map unit would be required for charting soil properties.

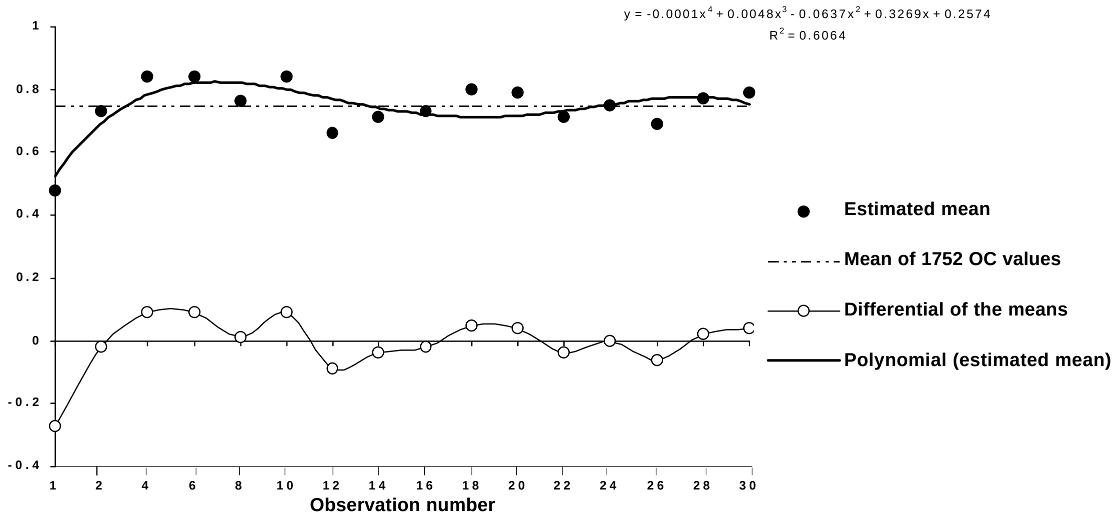


Fig. 15 Minimum data set per soil map unit

5.3 Spatial interpolation

Other important questions that may arise are: what is the magnitude of the problem and how is the geographical distribution of the problem-areas? To answer these questions, appropriate tools are needed, such as spatial interpolation techniques that allow mapping the extent and spatial variability of the limiting factors. From a land management point of view, this not only provides information about the geographical distribution of the problem-areas, but also gives necessary clues to the magnitude of the efforts and investments needed to solve the problem.

Mapping the spatial variation of the management-dependent soil variables was carried out with a full data set, including 2,100 measured values of OC, total N, available K and available P for all locations. For the locations on the right bank of the Kor river, soil electrical conductivity and pH were measured as well.

The variograms of individual soil variables were analyzed separately. Spatial patterns of soil variables were portrayed based on the parameters of sample variograms for each variable. The variable values were both interpolated and extrapolated by ordinary kriging.

As an example, the contour map showing the spatial variability of soil OC content is given in figure 16. In the largest part of the area, the OC content falls in the range from 0.1 to 0.6% which is far below the threshold values required for sustainable wheat cultivation.

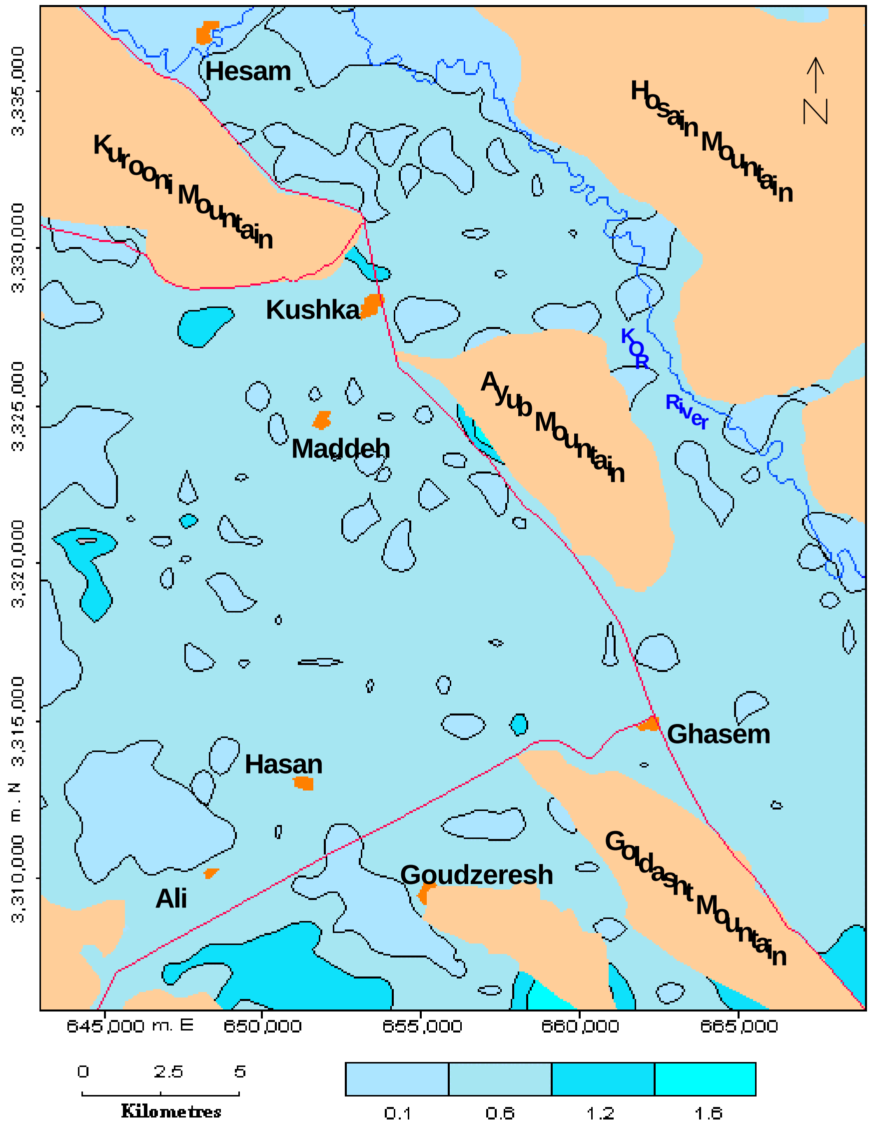


Figure 16. Contour map of soil OC values (%).

This is in agreement with the results obtained through the application of statistical control charts which demonstrated that, as far as soil OC content is concerned, soil quality is out of control (figure 10). In a similar way, the spatial variability of other soil variables was mapped. The results obtained from the application of control charts and the contour maps produced through the application of geostatistics were used as data layers and integrated in a geographic information system, to obtain information about management-dependent soil properties. Not only degradation but also improvements of soil condition under irrigated wheat were highlighted.

6. Conclusion

Statistical quality control charts proved to be efficient for assessing selected soil properties. The approach presented in this research for soil quality assessment is based on statistical procedures that can be used for land evaluation, through quantification of land qualities, to minimize human judgment. Both biophysical and socio-economic aspects of land, if quantified through random sampling procedures, can be evaluated using quality control charts. Suitability rating can be carried out, first by establishing acceptance (threshold) limits for the optimum performance of desired land utilization types and then by constructing statistical quality control charts for land qualities of interest.

Control charts can be used in conjunction with geostatistics, to map the spatial variation of land qualities in a geographic information system and obtain information about the sustainability of land management systems and the effects of land use on land quality and vice versa.

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