Chapter 9
Fundamental Steps for Regional and Country Level Soil Surveys

Norair Toomanian

Abstract The spatial and temporal data and information are essential for decision and policy making within each governing system as well as in conservation and sustainable management programs through the execution of soil surveys. The soil survey data are used to establish national and regional level databases. A unique method of soil survey was executed to map some soil attributes in 300,000 ha of Zayandeh-rud Valley, Isfahan, Central Iran. To establish a powerful database, it is important that soil surveys address the environmental impacts. To do so, the following steps were considered: (1) fundamental factors and processes for landscape formation, (2) evolution pathways of geomorphic surfaces, and (3) mapping of pedologic properties and visualization of collected information. Execution of mentioned steps highlighted some historical facts in study area. It has observed that some geomorphic surfaces have developed before Pleistocene period; the Zayandeh-rud River had three different pathways in Quaternary period; the pedodiversity indices are directly related to soil evolution and time; and the soil evolution pathways in this valley does not follow the convergence pathway of the Jenny's theory. Results also indicate that the digitally extracted continuous maps have the ability to accurately show the spatial distribution of pedologic properties.

Keywords Spatial data • Soil-surveying steps • Pedodiversity • Landscape evolution • DSM

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9.1 Introduction

It is critical to have proper laws for the use, management, and protection of the natural resources. Such legislation is related to the fact that the resources belong to all generations of a nation or country and protects resources against degradation and physical extinction. Soil survey execution, generation of scientifically based soil information, and development of comprehensive database are aimed to address the public interests for sustainable land uses (Capelin 2008). To establish a powerful earth-related database, it is prerequisite that soil surveys must be executed considering performance of all environmental attributes. Soil survey process distinguishes different soil populations and their extent and distribution in the study area and offers fundamental quantitative and qualitative data and information for policy and decision-making processes. Soil data can be pedologic or edaphologic aspects of needed information serving as knowledge bases for different disciplines. Execution of precise soil survey depends on the ability of surveyor to distinguish the processes by which soils are formed, developed, and distributed during the elapsed time and on the precision of their delineation.

Recognition of spatial soil diversity is a fundamental notion of soil mapping at various scales (Yaalon 1998). Owing to the effect of different soil-forming factors and their interaction and interplay of different geomorphic, hydrologic soil-forming processes, the soil cover patterns are basically complex and chaotic nature (Yaalon 1998). In other words, the morphology of the earth surface results from the interaction of the endogenic and exogenic processes.

The processes are scale-dependent, hierarchically structured complex systems which are composed of a large number of heterogeneous components interacting nonlinearly (Hay et al. 2002). The necessity to understand the importance of landscape dynamics, heterogeneity, and environmental changes is the main responsibility of geomorphologic and pedologic studies (Toomanian et al. 2006). There exist different school of contextual approaches for defining the causes and forms of soil distribution in pedology. The emphasis is now on elucidating the cause factors and processes responsible for the observed patterns. In this chapter, different cycles of activities are proposed for execution in traditional (polygon base) or digital soil mapping approaches. Each proposed cycle iteratively recorrects the process of soil population's determination and distinguishes the extent and distribution of soil patches and lastly visualize them in study area. In the following section, basic cycles and associated steps are discussed.

9.1.1 A: Cycle of Landscape Differentiation

It distinguishes the processes which define the soil populations' distribution.

9.1.1.1 Landscape Stratigraphy

The stratigraphic studies start with Butler (1959) and Beattie (1972) works which place emphasis on the soil mantel rather than individual profiles. The soil mantels are formed by sedimentologic (glacial, alluvial, or eolian) processes, or directly on parent rocks, in spatiotemporal positions of landscapes. Soil stratigraphy investigates the distribution and extent of soils having polygenetic development and evolution. Each polygenic soil has been developed in different depositional parent materials and different period of past times (Mackenzie and Austin 1993). In stratigraphic studies, the paleosols (Brewer 1964) are now central context of discussion. Paleosols in different buried, exhumed, and relict positions are formed in the past on any landscape (Beckmann 1984) without any relation with present climatic condition. A paleosoil represents a past period in which it has been developed. Paleosoils are any kind of soil layers formed on different depositional sediments in previous environmental conditions (Mackenzie and Austin 1993). These are mappable unit of unconsolidated sediments (pedologically evolved or not) either on land surface or partially or wholly buried by other layers.

The sedimentologic and pedologic differences of the layers permit the consistent recognition and mapping of these layers. Dating and defining the processes resulting these paleosols and recognizing the relationships between them provide the evidences for deducing soil history (vertical development) and soil evolution (temporal development). Due to above-mentioned causes, soil properties vary spatially depending on the complexity of the way in which soils have been formed. The main tasks of fieldwork in soil stratigraphic studies are to (1) establish that specific soil layers are independent of each other, (2) identify buried soils, and (3) locate the edges or boundaries of pedoderms (Mackenzie and Austin 1993). An understanding of the nature of these surface deposits is required for the management of environmental issues like sand encroachment, land-use planning, and soil and groundwater pollution. Pedostratigraphy is the study of stratigraphic relationships and implications of soils (including buried soils) and paleosols. Soil horizons are morphologically distinct, laterally traceable, and a time marker. The soil stratigraphic relationships are important for determining the geomorphic history of an area (Douglas et al. 2005).

9.1.1.2 Landscape Evolution

The debate on landscape evolution starts with the theory of Davis on geographical cycle. In the William Morris Davis's geographical cycle, the landscapes are seen to evolve through youth, maturity, and old stages. Landscapes are subject of evolution by the influence of different processes; in other words, they are directionally changing, developing, and evolving temporally progressively and/or regressively (Phillips 1999) by different processes; therefore, different ancient landforms (relict, exhumed, and stagnant) are able to form during changing environment of each region.

Process geomorphology studies the processes responsible for landform formation and development. The geomorphic processes have different rates of progression and infer short-term and long-term changes during landforms formation.

Phillips (1999) has offered 11 principles that have immense relevance to geomorphology and may help to reconcile the split between the process and historical aspects of the subject. To have a complete induction from landscape, the understanding of landforms must be based on knowledge of both history and process. Without an understanding of process, history is undecipherable, and without knowledge of history, process lacks a meaningful context. Process and history together lead to better appreciation of forms, behavior, and the earth surface evolution (Huggett 2005). All landscapes are affected by environmental changes. Fluvial system response to environmental change is usually complex. Phillip's principles of earth surface systems promise to help bridge the gap between process geomorphology and historical geomorphology (Huggett 2005).

Landscape evolution is governed by a balance of forces: on the one hand, vertical tectonic movements resulting from the interaction between lithospheric plates and, on the other, erosion and deposition controlled by a range of processes whose relative importance depends on local climatic conditions, vegetation, and rock type (Kaufmann 2003). Different processes during geologic time, such as tectonic movements and erosion deposition sequences, affect the nature of landscape evolution. Local climate condition controls the vegetation and the rate of erosion and deposition. Climate changes immensely affect on nature of geomorphic and hydrologic processes to form specific landforms. In the other hand, evolutionary sequences of landscape formation are responses to changes of hydrologic, geomorphologic, and pedogenic processes. Consequently, tectonic activities, hydrologic and geomorphic processes, and climatic changes govern the landscape evolution and the soil development. All of these changes are reflected and recorded in soil profiles during its developing periods. The proxy records of historical events and environmental changes are kept in soil layers. Study of the relationship between these proxy data (pedogenic and geogenic) and their formative processes helps us to reconstruct the sequence of historical events that has formed the landscape and confirms its evolutionary pathways. As a good source of information, the soil paleo-environmental proxy records are used in different scientific disciplines for reconstructing the historic sequences of concerned studies. Paleosoils can provide much more information concerning the evolution of landscapes in every region.

9.1.1.3 Landscape Stratification

During soil development phase, soil horizons are produced that are superimposed onto landforms and parent materials. Sequential and temporal erosion and deposition (eolian and fluvial) can remove, truncate, and/or bury soil horizons. Spatial and/or temporal landscape stability permits initial and subsequent soil development. Thus, most landscapes are a mosaic of various-aged landforms, parent materials, soils, eroded deposited segments, and geomorphic surfaces. Surficial soils, buried soils, and paleosols (globally polygenic), therefore, are a unique portion of the geomorphic and stratigraphic record in a region (Douglas et al. 2005). The defining and delineating of these patches of landscapes which have different origin and characterization is called stratification. This step is being done via various methods within soil-surveying approaches. Traditionally, land system and physiographic definitions were mostly used to stratify, which newly has changed to geomorphic bases (Zinck 1988). But because earth crust is formed by scaled and hierarchical processes, to stratify the land surface, there is a great need of a geomorphologic taxonomic hierarchy to define the way of their formation (the history of formation and responsible processes). Additionally, there is a great need to establish universally accepted procedures to delineate the defined geomorphic taxa. In general, a solid structure for defining and stratifying the geoforms is lacking. Obviously, some authors have tried to follow a sort of structure, but none of them were successful (Farshad 2006). The problem is that geomorphology is quite a controversial subject and that a real taxonomic classification is lacking, whereas some other disciplines such as botany and soils have succeeded to establish one (Farshad 2006). A systematic hierarchy has been proposed (Zinck 1988) in concordant with USDA Soil Taxonomy to define different geoforms in any region. This structure and its fundamental contexts are defined in Farshad (2006). A three level geomorphic taxonomy has also been proposed by USDA-NRCS which is now being used within the soil-surveying steps (Schoeneberger and Wysocki 2008; Schoeneberger et al. 2002).

The classic cartographic method of delineating the landscape patches is the air photo interpretation (API), and if this method is combined with a proper geomorphic taxonomy, it is still considered as one of the best landscape-stratifying methods. The digital terrain modeling (DTM) is a mathematical (or digital) approach to delineate the terrain surface (Li et al. 2005). Recently, soil scientists and hydrologists have tried to digitally stratify the landscape (Drãguþ and Blaschke 2006). They have used the methods described by Hengl and Reuter (2009) which are geomorphometric approaches. The required data for the digital terrain modeling is either obtained from field survey (use of conventional surveying instrument or GPS), from stereo pairs of aerial (or space) images using photogrammetric techniques, or from the digitization of the existing topographic maps (Farshad et al. 2005).

9.1.2 B: Cycle of Soilscapes Differentiation

It distinguishes the diversity of soil types and soil evolution pathways in each geomorphic unit. A geomorphic surface, smallest division of geoforms, is a geomorphic unit which is formed by a unique process within a defined span of time (Ruhe 1975). As a consequence, the soils formed by one process but in different time spans are considered as different geomorphic surfaces. It is assumed that the soils developed under one geomorphic process should have uniform distribution in defined geoform; however, the influences of minor differences in soil-forming factors (parent material, spatially different orientation and distribution of soil particles, minor spatially differences of environmental conditions) and minor spatially differences in the operation of soil-forming processes and execution of different history on minute part of soil profiles lead to the formation of somehow different soils (Phillips 2001). To conclude, to what extent the sampling scheme has defined the soil populations and how accurate soil types can be delineated, and also to find out that soils have evolved convergent or divergent evolution pathways, the pedodiversity analyses should be carried out in each geomorphic surface. In case of more diversity, complimentary samples should be taken.

9.1.2.1 Pedodiversity Analysis

Pedodiversity is a way of showing soil variation in an area or category (McBratney 1992) usually using soil taxa. Different diversity indices are presented in literature (Ibanez et al. 1995). Most of them used entropy bases to simulate the biodiversity essentials in pedology. From a methodological point of view, the different ways of measuring diversity may be grouped into three classes (Magurran 1988): (1) indices of richness (number of objects in the site, i.e., a count of the number of biological species or soil types known to occur in a defined sampling unit), (2) object abundance models (these models describe the distribution of objects abundance), and (3) indices based on proportional abundance of objects (in this case, diversity is defined in terms of a function of the number of different objects and their relative abundance or cover) (Ibanez et al. 1995). The definition of pedodiversity, indices, and its usage in pedology are defined by various workers (Ibanez et al. 1995, 1998; Martin and Rey 2000; Guo et al. 2003; Phillips and Marion 2005; Toomanian et al. 2006).

The application of diversity analysis to geomorphology and soil has recently attracted attention (Ibanez et al. 1998, 2005; Guo et al. 2003; Saldana and Ibanez 2004; Phillips and Marion 2005). Soil Taxonomy is hierarchically based on breaking the soil continuum into discrete ranges of soil types and bodies (soilscapes) which, in the lowest level, could be considered as individual soil species that are produced through natural development processes (Ibanez and De Alba 1999; Guo et al. 2003). Relationships between species richness and area have long been used in biogeography and biodiversity studies. This approach has also been adapted to soils (Ibanez et al. 1995, 1998; Phillips 2001, 2005; Guo et al. 2003). Using this diversity approach, soil-type complexity in a category or defined area or polygon can be shown. Using the diversity indices, it is possible to show the increasing or decreasing rate of entropy in soil pedogenesis among different levels of geomorphic hierarchical levels or area (Phillips 2001; Toomanian et al. 2006).

9.1.3 C: Cycle of Predicting Soil Patterns in Study Area

Soil surveys are conducted to distinguish and map the distribution of soil types using various sampling scheme suitable to the study area and objective of survey. The mapping is accomplished by predicting soil types in the area of interest through traditional or pedometrics methods. Traditional soil-surveying paradigm was based on interpretative ability of experts to mentally relate the soil–landscape relationship concept with the initial soil-forming processes and environmental factors to extract soil distribution in a completely subjective manner; however, this method is now subject to some criticisms (Zhu et al. 2001).

During the last decades, quantitative methods of describing, classifying, and studying the spatial distribution pattern of soils in a more objective manner have been developed to address the criticism using pedometrics. This is the application of mathematical and statistical methods for the quantitative modeling of soils, with the purpose of analyzing its distribution, properties, and behavior. The definition covers quantitative mathematical and statistical measurements and predictions of soil-related modules and roughly pedology. “In this sense, pedometrics deals with uncertainty in soil-related problems due to deterministic or stochastic variation, vagueness and lack of knowledge of soil properties and processes.”

9.2 Materials and Methods

The study area is located in the central basin of Iranian plateau (Fig. 9.1). This area includes 0.3×10^6 ha of Zayandeh-rud Valley. The geologic infrastructure of the area is mainly Cretaceous limestone, Mesozoic shale, and sandstone. Erosion and deposition processes, especially in the late Tertiary and early Quaternary, have been the main geo-formation processes in the area. After uplifting of Zagros Mountains (Alpine Orogeny), the Zayandeh-rud River downcut its bed, forming the terraces along its path to the Gavkhuni marsh in the eastern part of the study area. The salinity of soils simultaneous with aridity increases eastwardly while altitude decreases in that direction. Ascending water table, extreme drought, increase in salinity, and some human activities resulted in high rate of wind erosion. The eolian deposition is now covered all eastern part of the study area. The methods considered in various steps of this study are used in the following sequence.

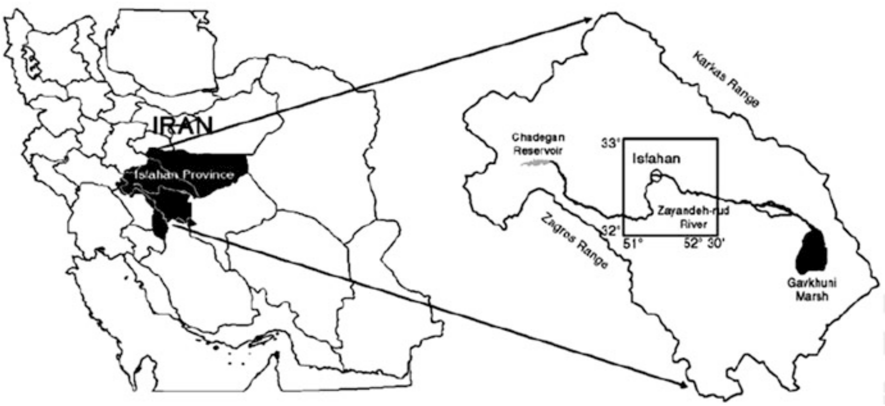

Fig. 9.1 The study area in central Iran

9.2.1 Landscape Stratification

Having geomorphic knowledge in mind and considering the topography, geology, land use, and vegetation cover, the study area is stratified by API method. In this context, the geomorphic taxonomy is one of the most needed subjects. The API differentiated geomorphic patterns (nested geomorphic hierarchy) based on their formation processes, general structure, and morphometry. The terminology of interpreting legend was based on Zinck (1988). A four-level geomorphic hierarchy is used to break down the complexity of different landscapes in the study area. In the lower level of the hierarchy, the geomorphic surfaces, which were formed by a unique process during a specific geologic time, were defined. The principle of this technique is to search for edges, or discontinuities, by breaking down the neighborhood of adjacent areas into subgroups that are internally as homogeneous as possible. In API, the hierarchy of field geographical organization was delineated on air photos (1:55,000). The cartographic scale of these geomorphic surfaces was of a reconnaissance soil survey (1:100,000–1:250,000). Stereoscopically interpreted air photos of the study area were imported into a geographic information system (GIS) environment, and after ortho-photo geo-referencing, geomorphic surfaces were mapped and glued via on-screen digitization.

9.2.2 Field Check and Soil Sampling

The delineated geomorphic surface map overlaid on a registered color composite image was used in the field to check the boundaries and to allocate sampling points within delineations.

9.2.2.1 Sampling

A purposive soil sampling method based on the extent of geomorphic surfaces and direction of changing gradients like slopes was used for proportional sampling throughout the study area excluding mountains and rocky hills. A total of 191 soil profiles were excavated and classified using Keys to Soil Taxonomy (Soil Survey Staff 2003), and their genetic horizons were sampled. The samples were analyzed for important physical and chemical characteristics using standard USDA procedures (Soil Survey Staff 1996). Already existing data from 66 profiles in the study area was also used for digital mapping of soil properties.

9.2.3 Landscape Stratigraphy and Evolution

The geologic (tectonic, fault, etc.) and paleoclimatic history of the area is considered to differentiate the soil layers. The stratigraphic layers are distinguished by landform unconformities in margins of geoforms formed by unique geomorphic processes. Landscape evolution is also defined by relating the soil layers to find the precedence or recency of layers which were formed by different deposition processes. This enables us to find whether a geoform has passed different historic evolutionary sequences compared with other points within each geomorphic surface. This was critical when eolian deposits were covering the surface of the most part of Segzi playa.

9.2.4 Pedodiversity Analysis

In this study, taxonomic diversity at the family level and genetic diversity at horizon level is investigated; both are important soil individual entities for diversity analysis. Pedodiversity indices including Shannon K-entropy, richness, and evenness for each geomorphic category were calculated in each category (Guo et al. 2003). To calculate the diversity indices in each landscape, the number of profiles belonging to a given landscape and the total number of profiles in the study area were considered. The number of different objects or entities including soil families and horizon sequences in a certain ecosystem or predefined territory and geomorphic categories was considered as richness of species. The diversity indices are measured by relative abundance of soil families to total sampled points in geomorphic units (Ibanez et al. 1995; Phillips 2001). The proportional abundance of objects is the most frequently used method to estimate the diversity. Evenness is another index which refers to the relative abundance of each object in a defined area. Logically, when the evenness of objects is equally probable, the diversity is highest when the richness of comparing units is the same (Ibanez et al. 1995).

9.2.5 C: Cycle of Predicting Soil Patterns in Study Area

Execution of survey, i.e., the interpolation of soil classes and attributes in unsampled points of study area, could be executed by using methods described in *Soil Survey Manual* (Soil Survey Division Staff 1993) or through mapping the distribution of soil types or attributes using quantitative pedometric approaches. In this study, digital soil mapping of some soil attributes was accomplished.

9.3 Results and Discussion

In soil-surveying methods, regardless of the approach used, three fundamental steps must be accurately undertaken. The first is the landscape evolution which should be defined to show how the geoforms are developed and what evolutionary history they had. Second, the complexity of soil types in each geoform and the cause of diversity

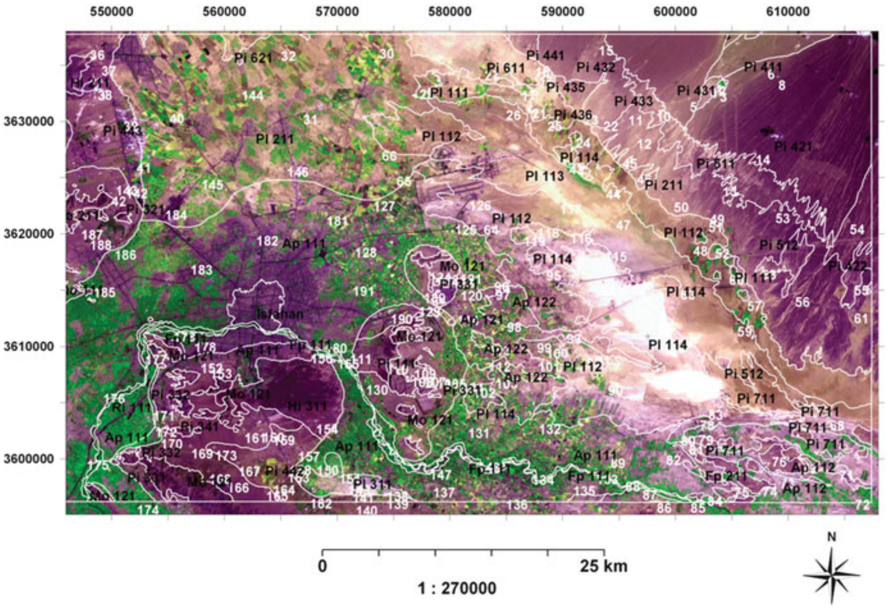

Fig. 9.2 Delineated geomorphic units in study area with its hierarchic code (*black*) and studied points (*white*)

should be distinguished. Third, iterate the stratification process and sampling design with the incorporation of landscape evolution results and pedodiversity analysis. This enables the surveyor to be sure that all soil-type populations have been accounted in soil mapping process.

9.3.1 Air Photo Interpretation

Through photo interpretation, the knowledge of soil–landscape relationships, geology, topography, and geomorphologic factors affecting the soil formation of the study area was considered. In the first attempt, the API has distinguished seven kinds of landscapes and 46 geomorphic surfaces in the study area. The delineated surfaces resulted from photo interpretation, and the legend of interpretations is shown in Fig. 9.2 and Table 9.1, respectively. The drawn delineations for all geomorphic surfaces in the field were checked, and corrections were inserted in the GIS map of the landforms. Upon the processes ruling the formation and development of all soil types, the sampling scheme was designed and the soil profiles described. The soil samples were analyzed and amount of all the soil attributes measured.

Table 9.1 Legend of delineated geomorphic surfaces before inserting the landscape evolution results

No	Landscape	Landform	Lithology[a]	Geomorphic surfaces	Code
1	Mountain	Dissected ridge	Marly limestone (K4, K2) and shale	Structured surface	Mo 111
2	Mountain		Marly limestone (K4, K2)	Structured surface	Mo 121
3	Mountain	Rock pediment	Eroded calcareous and dark shale	Scarp slope	Mo 211
4	Hill land	Dissected ridge	Basal conglomerate (OMC)	Slope facet complex	Hi 111
5		Eroded ridge	Dissected dark-gray shale	Structured surface with braded stream	Hi 211
6		Rocky high hill	Remnant of shale (J)	Slope facet complex	Hi 311
7	Piedmont	Pediment	Remnant of shale (J)	Slope facet complex	Pi 111
8		Flash flood fan delta	Quaternary alluvium	Outwash sediment finer and white	Pi 211
9				Outwash sediment (coarser)	Pi 212
10		Alluvial fan	Alluvium of OM, OMC	Apical part	Pi 311
11			Alluvium of dark-gray shale	Apical part, slope facet complex	Pi 321
12			Alluvium of marly limestone	Slope facet complex	Pi 331
13				Slope facet complex, cultivated	Pi 332
14			Alluvium of marly limestone	Active fan	Pi 341
15		Bahada	Alluvium of OM, OMC, Ev	Middle part	Pi 411
16			Alluvium of andesite, granodiorite	Apical part	Pi 421
17				Apical part (extremely braded drainage)	Pi 422
18			Alluvium of foraminifera limestone	Apical part, with dense drainage network	Pi 431
19				Middle part	Pi 432
20				Distal part, with dense drainage network	Pi 433
21				Distal part with dense drainage network, finer	Pi 434
22				Distal part calcareous	Pi 435
23				Distal part, salt crusted, gypsiferous	Pi 436
24			Alluvium of K4, K2, Tn	Middle part with parallel drainage pattern	Pi 441
25				Middle part with less drainage	Pi 442
26				Distal part with dense drainage network	Pi 443
27		Dissected old bahada Alluvium of foraminifera limestone	Paleoterrace, undulating plateau	Pi 511	

(continued)

Table 9.1 (continued)

No	Landscape	Landform	Lithology[a]	Geomorphic surfaces	Code
28				Paleoterrace, with braded intense network	Pi 512
29		Old bahada	Fine marly gypsiferous sediments	Piedmontal terrace, flat, salty fine alluviums	Pi 611
30			Fine marly alluvium	Piedmontal terrace, distal part, fine alluviums	Pi 621
31		Rolling old bahada	Coarse, gypsiferous alluvium	Paleoterrace, gypsic plateau	Pi 711
32	Alluvial plain	Alluvial flat, river terraces	Zayandeh-rud river alluviums	Cultivated terraces	Ap 111
33				Playa/river terraces, cultivated, salty	Ap 112
34			Old river sediments	Meandering complex facet	Ap 121
35				Cultivated old river terrace	Ap 122
36	Flood plain	Lowest river terrace	Recent alluviums	Channel margin alluvium, cultivated	Fp 111
37				Channel margin alluvium, cultivated, salty	Fp 112
38	Seasonal drain	Recent alluviums systems	Salty gleyed fine alluviums	Fp 211	
39	River	River sediments	Recent gravelly alluviums	Channel sediments	Ri 111
40	Playa	Segzi basin	Alluvio-lagoonary fine sediments	Wet zone, flat, salty, cultivated	Pl 111
41				Wet zone, flat, very salty	Pl 112
42				Soft clay flat, with drained groundwater	Pl 113
43				Soft clay flat, gypsiferous, extremely salty	Pl 114
44		Borkhar basin	Alluvial fine sediments, slightly salty	Soft clay flat, cultivated	Pl 211
45		Margh basin	Alluvio-lagoonary fine sediments	Puffy ground, lagoonary, gypsiferous	Pl 311
46		Jarghuye basin	Alluvial fine sediments, salty	Soft clay flat, cultivated	Pl 411

[a]K2 – Red conglomerate and sandstone with a yellow sandy dolomite bed at the top and intercalations of dolomite beds locally
K4 – Gray limestone containing orbitolinas and ammonites
Tn – Dark-gray shale with intercalations of lenticular limestone (containing corals and Heterstridium) and sandstone (Naiband formation)
OMC – Basal conglomerate
J – Shale containing ammonites, with intercalations of conglomerates, sandstone, radiolarite sandstone, and volcanics
OM – Foraminiferal limestone (Qom formation)
Ev – Tuff breccia and andesitic volcanics

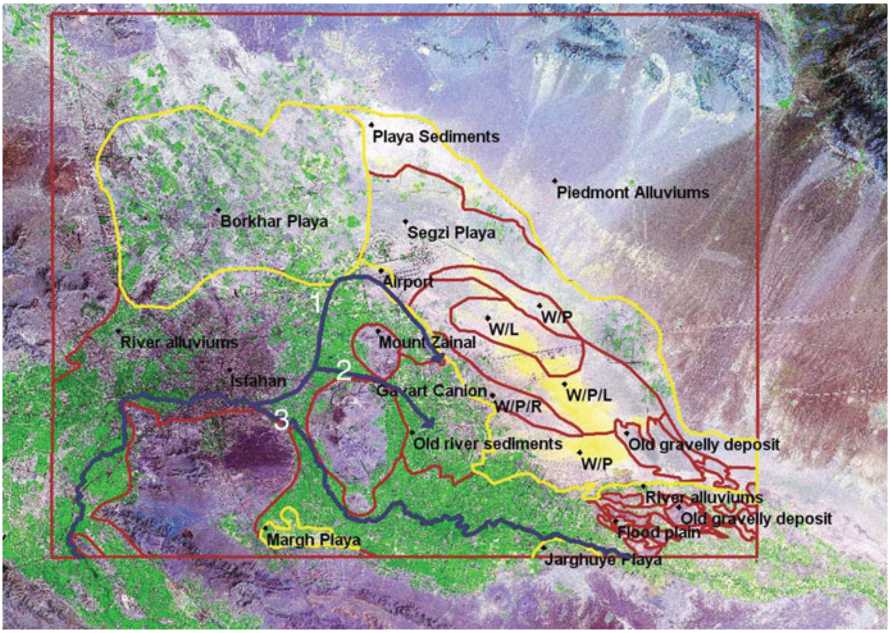

Fig. 9.3 Different zones of parent materials delineated upon landscape evolution. The sequential river pathway changes are shown with *1*, *2*, *3*

9.3.2 Landscape Evolution

Soil profile descriptions proved that the delineations are more complex in Segzi playa than those determined by API method (underneath differences were not distinguished by API). In this playa, different hydrologic and geomorphic processes have created some heterogeneous parent materials. These heterogeneous parent materials were formed by intermittent sedimentation of eolian, lagoonal, and river alluvial layers which have been laid during the Tertiary and Quaternary. These geomorphic variations were not detected by API method because the surface of these map units has been covered by uniform eolian materials. The distribution map of these parent materials was resulted from upscaling of the profile data (Fig. 9.3). Overlaying the parent materials mapped on air photo interpreted delineations inferred more details in some geomorphic surfaces (API map and legend), which are presented in Table 9.2.

The evidences recorded in geologic and geomorphic units and soil profiles of the study area have shown different critical evolutionary steps in Zayandeh-rud Valley formation which are sequentially shown in Fig. 9.4. The inherited proxy records of past environmental changes are used to reconstruct the past evolutionary history during late Tertiary and Quaternary. These evidences and proxies are used to find the sequential steps of landscape evolution in study area.

Table 9.2 Legend of delineated geomorphic surfaces which was changed after inserting the landscape evolution results

Landscape	Landform	Lithology	Geomorphic surfaces	Code
Piedmont	Bahada	Alluvium of foraminiferal limestone	Distal part, with dense drainage network (Pi 433)	Pi 433
			Fine	Pi 4331
			Coarse	Pi 4332
Alluvial plain	River terraces	Old river sediments	Meandering complex facet (Ap 121)	Ap 121
			Fine/coarse	Ap 1211
			Fine	Ap 1212
Playa	Segzi basin	Alluvio-lagoonary fine sediments	Wet zone, flat, very salty (Pl 112)	Pl 112
			Playa	Pl 1121
			Windy/playa	Pl 1122
			Windy/playa/old river	Pl 1123
			Windy/playa/lagoon	Pl 1124
			Soft clay flat, with drained groundwater (Pl 113)	Pl 113
			Playa	Pl 1131
			Playa/lagoon	Pl 1132
			Windy/playa	Pl 1133
			Windy/playa/old river	Pl 1134
			Windy/playa/lagoon	Pl 1135
			Soft clay flat, gypsiferous, extremely salty (Pl 114)	Pl 114
			Playa	Pl 1141
			Playa/lagoon	Pl 1142
			Windy/playa	Pl 1143
			Windy/playa/lagoon	Pl 1144
	Margh basin	Alluvio-lagoonary fine sediments	Puffy ground, lagoonary (Pl 311)	Pl 311
			Windy/playa/lagoon	Pl 3111
			Playa/lagoon	Pl 3112

9.3.3 Pedodiversity Analysis

The diversity indices for each geomorphic surface were calculated using the total number of profiles studied in the area of unit and the number of profiles belonging to each soil family within that unit. Table 9.3 shows the pedodiversity indices in some geomorphic surfaces which have more diversity. This seems to be due to simultaneous increasing of the richness and evenness through this hierarchical downscaling method. Although using the result of landscape evolution in study area decreases the diversity indices (Table 9.4) and subdivided some geomorphic units, but there remain some high diversity indices in these geomorphic

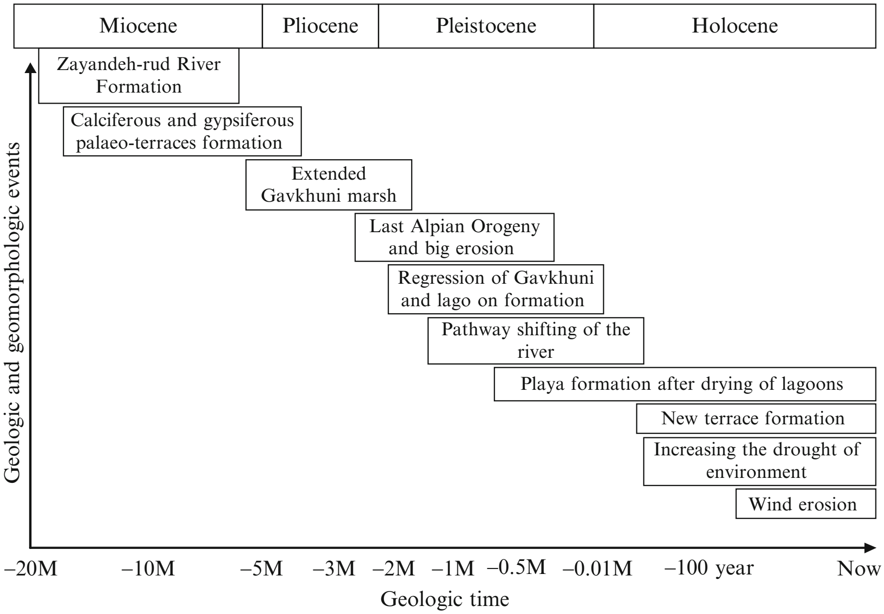

Fig. 9.4 Sequences of landscapes evolved during time

units. This increasing rate of diversity through geomorphic and taxonomic hierarchies confirms the existence of divergent soil evolutionary pathway in this area.

In Ap 111 and Ap 121 units (Table 9.3), the general trend of increasing the diversity indices from order to subgroup is not the same as the others. In most part of the Ap 111 mapping unit, where intensive cultivation has been carried out, the argilification (clay illuviation) was the only soil-forming process leading to local convergence soil development. The only factor responsible for differentiating the undeveloped soils in Ap 121 mapping unit is irregular sedimentation of fine and coarse materials by meandering older Zayandeh-rud channel. Ibanez et al. (1990, 1994) have used this method to show how the evolution of fluvial systems induces an increase in pedo-geomorphological landscape complexity. Ibanez et al. (1995) studied the diversity of soil mapping units of Spain and reached to the same conclusion. Saldana and Ibanez (2004) stated that an increase in soil heterogeneity through a geomorphic hierarchy verifies the existence of divergent soil evolution. However, in the units in which the amounts of diversity indices were high, the complementary sampling was conducted to reduce the probable inaccuracies.

The relationship between K-entropy and time or soil evolution was studied in Zayandeh-rud River terraces. This river has three different terraces along its path to Gavkhuni marsh. The entropy measured in these terraces (lower, middle, and upper) significantly increases from lower to upper terraces (Fig. 9.5) indicating the positive relationship between the K-entropy and time or soil evolution in the absence of any variation in climate, parent material, and topography. In the lower terrace, Torriorthent was the only developed soil great group. In the middle terrace,

Table 9.3 Pedodiversity indices measured for diverse units before inserting the landscape evolution results

Code	Total	Family classification (Soil Taxonomy 2003)	%	*S*	*H′*	H_{max}	*E*
Pi 321	6	Loamy-skeletal, mixed, thermic, typic haplocalcids (143-142-186)	50				
		Sandy-skeletal, mixed, thermic, typic torriorthents (187)	16.66	4	1.24	1.386	0.895
		Loamy-skeletal, mixed, thermic, typic torriorthents (42)	16.66				
		Loamy-skeletal, mixed, thermic, typic haplogypsids (188)	16.66				
Pi 331	23	Fine-loamy, mixed, thermic, typic calciargids (166-165)	8.7				
		Loamy-skeletal, mixed, thermic, calcic argigypsids (169-159-153-122)	17.5				
		Fine-loamy, mixed, thermic, typic torriorthents (156)	4.3				
		Loamy-skeletal, mixed, thermic, typic haplogypsids (104, 168)	8.7				
		Loamy-skeletal, mixed, thermic, typic haplocalcids (106-107-108-109)	17.5				
		Fine-loamy, mixed, thermic, typic calcigypsids (189-130)	8.7	11	2.27	2.4	0.95
		Loamy-skeletal, mixed, thermic, typic calciargids (160-152- 105)	13				
		Loamy-skeletal, mixed, thermic, typic torriorthents (161)	4.3				
		Fine-silty, mixed, thermic, typic torriorthents (121)	4.3				
		Fine-silty, mixed, thermic, typic calcigypsids (190)	4.3				
		Loamy-skeletal, mixed, thermic, typic calcigypsids (123-124)	8.7				
Pi 442	8	Coarse-loamy, gypsic, thermic, typic haplogypsids (20)	12.5				
		Loamy-skeletal, mixed, thermic, typic torriorthents (167-173)	25				
		Loamy-skeletal, mixed, thermic, typic haplogypsids (157)	12.5				
		Loamy-skeletal, mixed, thermic, typic calcigypsids (158-163)	25	6	1.73	1.79	0.97
		Fine-loamy, mixed, thermic, typic calciargids (164)	12.5				
		Loamy-skeletal, mixed, thermic, typic calciargids (162)	12.5				

(continued)

Table 9.3 (continued)

Code	Total	Family classification (Soil Taxonomy 2003)	%	*S*	*H′*	H_{max}	*E*
Pi 512	8	Coarse-loamy, gypsic, thermic, typic haplogypsids (11, 61)	25				
		Fine-loamy, gypsic, thermic, leptic haplogypsids (12)	12.5				
		Loamy-skeletal, gypsic, thermic, typic haplogypsids (50, 53)	25	6	1.73	1.79	0.97
		Fine-silty, mixed, thermic, leptic haplogypsids (13)	12.5				
		Coarse-loamy, mixed, thermic, typic haplosalids (49)	12.5				
		Fine-loamy, mixed, thermic, typic haplogypsids (56)	12.5				
Ap 111	27	Fine, mixed, thermic, typic haploargids (128-129-131-133 88-175-125-150-176-182-136-137-174-180-181-183-185-191)	66.7				
		Fine-silty, mixed, thermic, typic haplocambids (82-84-87-132)	14.8				
		Loamy-skeletal, mixed, thermic, typic haplocalcids (171)	3.7	6	1.11	1.79	0.62
		Fine, mixed, thermic, typic haplocambids (89-135)	7.4				
		Fine, mixed, thermic, typic torriorthents (111)	3.7				
		Fine-loamy, mixed, thermic, typic torriorthents (178)	3.7				
Ap 121	7	Coarse-loamy, mixed, thermic, typic torriorthents (112)	14.286				
		Fine-silty over sandy, mixed, thermic, typic torriorthents (103)	14.286				
		Fine-silty, mixed, thermic, typic torriorthents (99)	14.286				
		Loamy-skeletal, mixed, thermic, typic torriorthents (101)	14.286	7	1.946	1.946	1
		Fine, mixed, thermic, typic torriorthents (114)	14.286				
		Coarse-silty, mixed, thermic, typic torriorthents (120)	14.286				
		Fine-silty over sandy, mixed, thermic, typic haplocambids (97)	14.286				
Fp 111	6	Coarse-silty, mixed, thermic, typic torriorthents (134- 147- 148-179)	66.67	2	0.636	0.69	0.92
		Loamy-skeletal, mixed, thermic, typic torriorthents (177-155)	33.33				

(continued)

Table 9.3 (continued)

Code	Total	Family classification (Soil Taxonomy 2003)	%	S	H′	H_{max}	E
Pl 112	13	Fine, mixed, thermic, gypsic haplosalids (43, 66, 69, 48)	30.77				
		Fine, mixed, thermic, typic haplosalids (60-51)	15.4				
		Fine-silty, mixed, thermic, gypsic haplosalids (25, 92, 93)	23	6	1.67	1.79	0.93
		Fine, mixed, thermic, calcic haplosalids (64-116)	15.4				
		Loamy-skeletal, mixed, thermic, gypsic haplosalids (91)	7.75				
		Fine, mixed, thermic, gypsic haplosalids (126)	7.75				
Pl 113	11	Coarse-silty, gypsic, thermic, gypsic haplosalids (26)	9.1				
		Fine, mixed, thermic, gypsic haplosalids (70, 78, 59, 80, 118, 47, 68, 117)	72.7	4	0.885	1.39	0.64
		Fine-silty, mixed, thermic, typic haplosalids (95)	9.1				
		Fine-silty over sandy, mixed, thermic, gypsic haplosalids (83)	9.1				
Pl 114	7	Fine, mixed, thermic, gypsic haplosalids (44, 62, 63, 94, 119)	71.43				
		Fine, mixed, thermic, calcic haplosalids (115)	14.285	3	0.796	1.1	0.72
		Fine-silty, mixed, thermic, gypsic haplosalids (90)	14.285				
Pl 211	12	Fine-silty, mixed, thermic, typic haplocambids (30)	8.3				
		Fine, mixed, thermic, typic torriorthents (40-127)	16.74				
		Fine-silty, mixed, thermic, typic haploargids (31)	8.3				
		Fine-silty, mixed, thermic, typic calciargids (184)	8.3	8	1.9	2.08	0.91
		Fine, mixed, thermic, typic haploargids (146)	8.3				
		Fine-silty, mixed, thermic, gypsic haplosalids (29)	8.3				
		Fine, mixed, thermic, typic haplosalids (65)	8.3				
		Fine, mixed, thermic, typic calciargids (145-144-34-32)	33.46				

Table 9.4 Pedodiversity indices[a] measured for diverse units after inserting the landscape evolution results

Unit	*N*	Family classification (Soil Taxonomy 2003)	%	*S*	*H′*	H_{max}	*E*
Ap 1211	6	Coarse-loamy, mixed, thermic, typic torriorthents (112)	16.666				
		Fine-silty over sandy, mixed, thermic, typic torriorthents (103)	16.666				
		Fine-silty, mixed, thermic, typic torriorthents (99)	16.666				
		Loamy-skeletal, mixed, thermic, typic torriorthents (101)	16.666	6	1.79	1.79	1.00
		Fine, mixed, thermic, typic torriorthents (114)	16.666				
		Coarse-silty, mixed, thermic, typic torriorthents (120)	16.666				
Pl 1121	7	Fine, mixed, thermic, gypsic haplosalids (43, 66, 69, 48)	57.000				
		Fine, mixed, thermic, typic haplosalids (60-51)	28.600	3	0.96	1.10	0.87
		Fine-silty, mixed, thermic, gypsic haplosalids (25)	14.400				
Pl 1132	3	Fine-silty over sandy, mixed, thermic, gypsic haplosalids (83)	33.333	2	0.64	0.69	0.93
		Fine, mixed, thermic, gypsic haplosalids (78, 59)	66.666				
Pl 1142	3	Fine, mixed, thermic, calcic haplosalids (115)	33.333	2	0.64	0.69	0.93
		Fine, mixed, thermic, gypsic haplosalids (62, 63)	66.666				

[a] *S* (richness) – number of soil types in the reference area; *H′* – negative entropy or diversity Index of the population; *E* (evenness) – relative abundance of each soil type among the others; H_{max} – richness when all objects in reference area are equiprobable; *N* (total number of soil types)

Haplocambids have formed, whereas in the upper terrace, Haplosalids and Haplargids have been developed. These findings are in agreement with those of Saldana and Ibanez (2004), and Phillips (2001) on river terraces. The increase in K-entropy from younger to older soil cover in such condition is expected in a chaotic system (Phillips 2001). In this case, dynamic instabilities and chaos in pedogenesis result in the magnification of initial differences and effect of perturbations to produce an increasingly diverse soil cover (Phillips 1999, 2001).

Another testable hypothesis is examining the regional geomorphic evolution. It is accomplished by plotting the calculated K-entropies within geomorphic surfaces versus the ranked age of these units. It has been found that the soils are more developed on older geomorphic surfaces compared with those on younger ones. The relationship between K-entropy and richness of soil types versus the relative age of geomorphic surfaces are presented in Fig. 9.6. This, in turn,

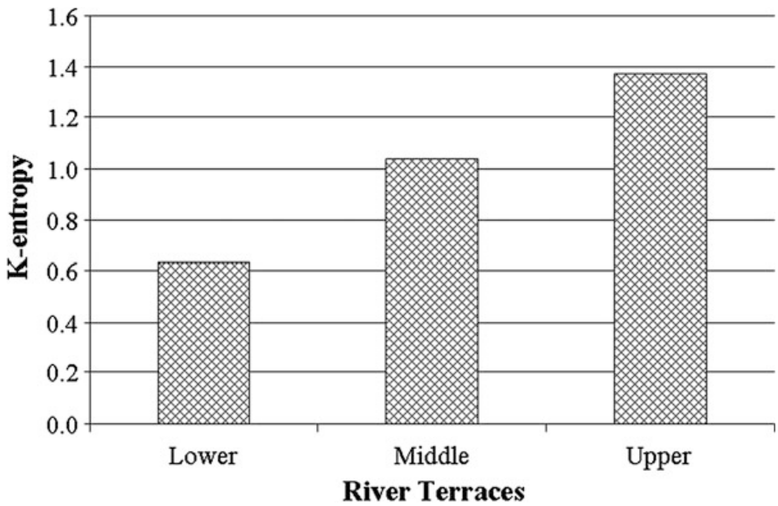

Fig. 9.5 Comparison of the diversity in river terraces

indicates that, in the study area, the soil pedogenesis follows a chaotic and divergent pathway, similar to what has been reported earlier (Ibanez et al. 1990; Phillips 2001).

9.3.4 Predicting Soil Patterns

In this study, attempts have been made to map the thickness of A and B horizons (cm) and clay amount in subsurface layer. The target variables are produced and assessed. Figure 9.7a presents the thickness and its estimating error maps of A horizon. The estimated standard error map shows the quality of calculated thicknesses of "A" horizon in the study area (Fig. 9.7b). The standard error in sparsely sampled area is 7.5–15 cm and in intensely sampled areas is 6–6.7 cm. It means that the most of the studied area has been predicted with error around 7 cm thicknesses for "A" horizon. The unsampled area (mountains and some rocky hills) are masked (white areas in the map) (Fig. 9.8) shows the relation of predicted depths of "A" horizon by undertaken digital soil mapping method with landforms stratified by manual API approach. As it shows, the model could differentiate the landforms and predict the proper depth for "A" horizon in study area. The predicted and standard error maps of other variables are not shown. The estimated error for the thickness of B horizons is mostly between 42 and 55 cm, which are considerable. The estimation error of some points in this map is 160 cm; this is due to low sampling intensity, weak relationships of this variable with predictors, and weak relationships of this horizon formation with current environmental condition (the most of B

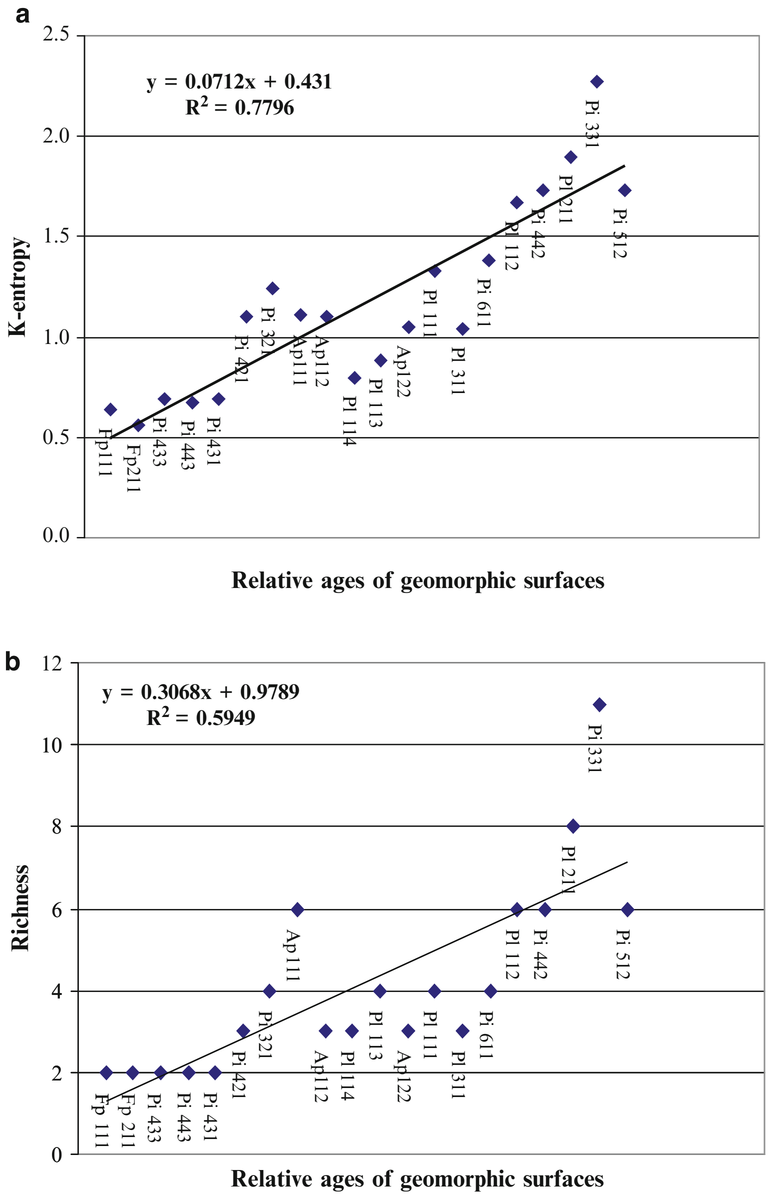

Fig. 9.6 Relation between the diversity (**a**) and richness (**b**) of geomorphic units with age

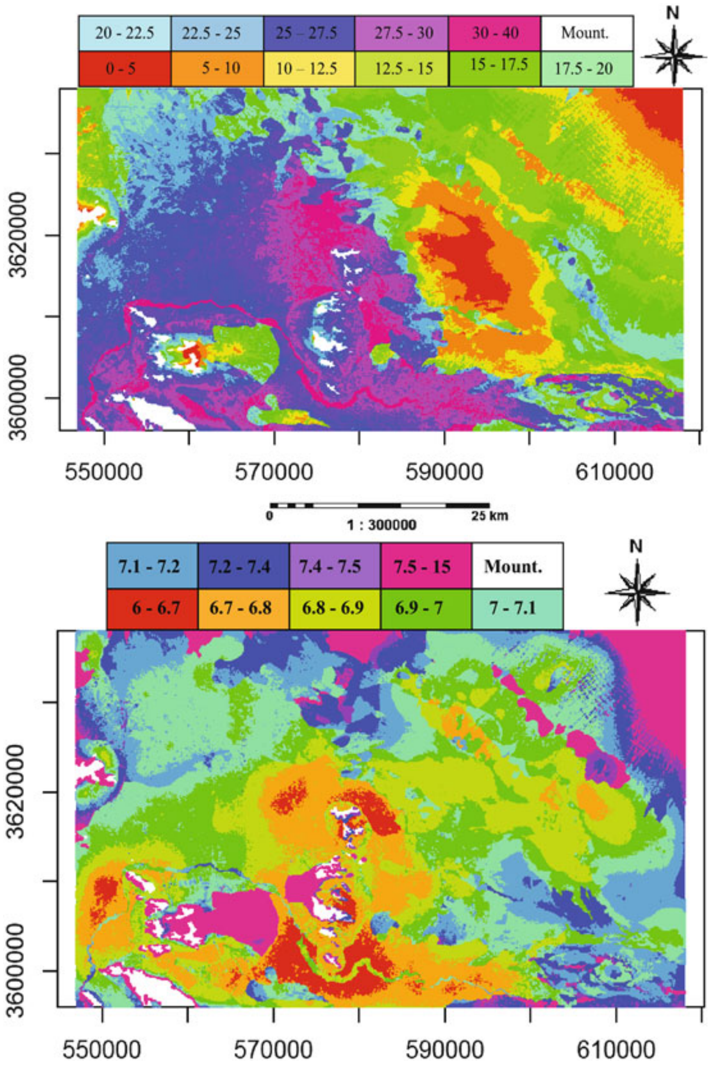

Fig. 9.7 Extracted map of "A" horizon depth (**a**) and the error of prediction in each pixel of study area (**b**)

horizons are developed under different paleoclimatic conditions). Interpolating the clay amount (%) in second layer was carried out on transformed asin $y^{1/2}$ (arc sin of square root of target variable y) data. Therefore, due to nonlinearity of back transformation of kriging variance, it was hard to calculate the standard error image in this case, but instead the lower and upper confidence interval boundaries of predicted variance was calculated for a 0.975 probability, $\hat{Y}_{UK} \pm 1.96\,\mathrm{sqrt}(\mathrm{Var}_{UK})$, to present the boundary interval maps.

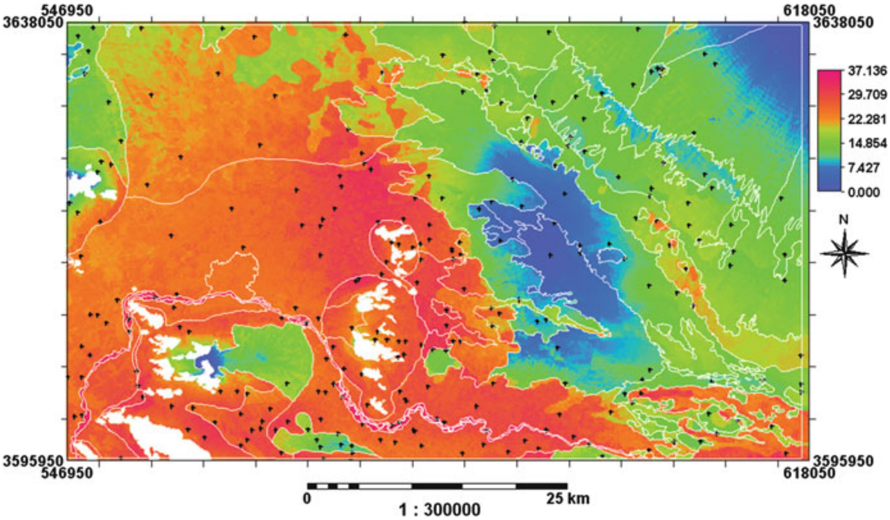

Fig. 9.8 Predicted depths (cm) of "A" horizon compared with delineation of geomorphic surfaces

9.4 Conclusions

It is concluded that incorporating the upper mentioned steps in any soil survey sequences upgrades the quality of survey and increases the accuracy and precision of extracted maps. It also enables to highlight the localities which need more sampling points to account the distribution of minute soil types.

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