Chapter 12
Remote Sensing and GIS for Geomorphological Mapping

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Abstract Geomorphology is the study of the landforms, their processes, form and sediments at the surface of the earth. Geomorphological maps are very effective tools in management of land resources and help in various types of resources inventory, mapping and management. Running water, wind, glaciers, karst and sea waves are powerful erosional and depositional agents, which are acting over a long period of time and produce systematic changes leading to sequential development of landforms. The traditional mapping approaches emphasized qualitative interpretation, as frequently dictated by the inherent limitations associated with fieldwork, paucity of digital data and lack of prior field/geographic experience and domain knowledge. Recent advances in remote sensing, geographic information system (GIS) and availability of satellite-based digital elevation models and developments in numerical modelling capabilities enhance the ability to understand the surface processes more clearly in the field of geomorphology. Geomorphological mapping and analysis of various processes using advance tools like remote sensing and GIS act as preliminary tools for land resources inventory, mapping and management, geomorphological and geological risk management, as well as providing baseline data for other applied sectors of environmental research such as landscape ecology, soil science, hydrology and forestry, etc.

Keywords Remote sensing · Geomorphological mapping · Fluvial landforms · Aeolian landforms · Karst landforms · Glacial landforms · Coastal landforms

12.1 Introduction

Geomorphology is the scientific study of the geometric features of the earth's surface. Although the term is commonly restricted to those landforms that have developed at or above sea level, geomorphology includes all aspects of the interface

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between the solid earth, the hydrosphere and the atmosphere. Geomorphological mapping plays an important role in understanding the earth surface processes, geochronology, natural resources, natural hazards and landscape evolution (Blaszczynski 1997; Bishop and Shroder 2004; Smith et al. 2011; Reddy 2012). Geomorphological processes comprise the physical and chemical interactions between the earth's surface and the natural forces acting upon it to produce landforms. Several related landforms together make up landscapes, and each landform has its own physical shape, size and materials and is a result of the action of certain geomorphic processes and agent(s). Actions of most of the geomorphic processes and agents are slow, and hence, the results take a long time to take shape. The efficiencies of these processes are determined by such variables as geology, climate, vegetation, base level and human influences. Due to changes in climatic conditions and vertical or horizontal movements of landmasses, either the intensity of processes or the processes themselves might change leading to new modifications in the landforms. Landform evolution implies stages of transformation of either a part of the earth's surface from one landform into another or transformation of individual landforms after they are once formed. A geomorphological map can act as a preliminary tool for land management and provides baseline data to other applied sectors of environmental research such as landscape geology, geography, soil science, hydrology, forestry, ecology, environmental sciences, etc. (Cooke and Doornkamp 1990a; Dramis et al. 2011).

Geomorphological mapping plays an important role in understanding earth surface processes, geochronology, natural resources, natural hazards and landscape evolution (Blaszczynski 1997; Reddy et al. 2004; Bishop and Shroder 2004). It involves the partitioning of the terrain into conceptual spatial units/entities based upon criteria that include morphology (form), genetics (process), composition and structure, chronology, environmental system associations (land cover, soils, ecology), as well as spatial topological relationships of surface features (landforms). Geomorphological mapping has been based upon integration of multidisciplinary information from the field, remotely sensed data and cartographic map products. Regional-scale geomorphology and physiographic analysis and mapping (Baker 1986) were based upon the interpretation of photography and smaller-scale maps to classify terrain types/features at the regional (physiographic) scale. Detailed geomorphological mapping is being carried out based on surveying and other *in-situ* measurements, although detailed large-scale geomorphological maps did not exist for many areas. These traditional mapping approaches emphasized the qualitative interpretation, as frequently dictated by the inherent limitations associated with fieldwork, paucity of digital space–time data and human a priori field/geographic experience and domain knowledge.

Traditionally, terrain and landform mapping was undertaken by utilizing topographical map, aerial photographs and field surveys (Dent and Young 1981; Pain 1985). Aerial photographs are used as remote sensing data in terrain mapping programmes in British Columbia (Slaymaker 2001) and landslide mapping in Hong Kong (Dai and Lee 2002) and fieldwork for large- and medium-scale mapping (Mantovani et al. 1996). The satellite images are unique resources for geomorphological mapping. Different spatial information such as land cover, hydrology and digital elevation model (DEM) integrated in a GIS allows interpretation and analysis of geomorphological features more precisely than satellite data alone. Application of various image enhancement techniques could significantly improve the visual interpretability of an image by increasing the apparent distinction between the features on the land (Sabins 2000). Digital image processing techniques such as generation of false colour composites (FCC), band ratioing and principal component analysis (PCA) help to evaluate geological, structural and geomorphologic characteristics of the terrain. Many researchers have also used Landsat datasets for identification of terrain features, landform, geology and geomorphology (Verstappen 1977; Kayan and Klemas 1978; Pain 1985; Bocco et al. 2001). Recent advances in geospatial technologies, which include remote sensing, GIS, global positioning system (GPS), digital elevation models as well as developments in numerical modelling of surface processes, have revolutionized the field of geomorphology mapping and analysis of the processes (Shroder and Bishop 2003; Bishop and Shroder 2004).

12.2 Geomorphological Processes

A geomorphological process includes the interactions between physical components of the atmosphere, the earth (lithosphere) and water (hydrosphere) with the biological communities of plants and animals and especially humans that modify landforms. The landforms are produced by a consequence of the interaction of relative uplift (endogenetic) on the earth's surface and down wearing (exogenetic) by weathering and erosional processes. The struggle between these opposing processes is reflected at any particular point in time by the landforms that appear on the earth. The processes, which influence the characteristics of landforms, are activity of running water (fluvial) and moving ice (glaciers), work of underground water (Karst), the transport and deposition of dust and sand by wind (aeolian), beach and shoreline processes that involve the mechanics and effects of waves and current (littoral) and the study of mass movement of material through downhill creep of soil/rock and by landslide and mud flows. Detailed study of these processes form a base for classification of landforms, which is a major aspect of geomorphological mapping.

12.3 Evolution of Landforms

Changes on the surface of the earth owe mostly to erosion by various geomorphic agents. Of course, the process of deposition too, by covering the land surfaces and filling the basins, valleys or depressions, brings changes in the surface of the land. Deposition follows erosion, and the depositional surfaces too are ultimately subjected to erosion. Running water, groundwater, glaciers, wind and sea waves are powerful erosional and depositional agents shaping and changing the surface of the earth aided by weathering and mass wasting processes. These geomorphic agents acting over long periods of time produce systematic changes leading to sequential development of landforms. Each geomorphic agent produces its own assemblage of landforms, and each geomorphic process and agent leaves their distinct imprints on the landforms they produce. The study of evolution of landforms will reveal the process and agent, which has made or has been making those landforms. As the geomorphic agents are capable of erosion and deposition, two sets – erosional or destructional and depositional or constructional – of landforms are produced by them. The distinct landforms develop by the action of each of the geomorphic agents depending upon especially the type and structure, i.e. folds, faults, joints, fractures, hardness and softness, permeability and impermeability, etc. come under structure of rocks. There are some other independent controls like (i) stability of sea level, (ii) tectonic stability of landmasses, and (iii) climate, which influence the evolution of landforms. Any disturbance in any of these three controlling factors can upset the systematic and sequential stages in the development and evolution of landforms.

12.4 Geomorphological Mapping

Recognizing the importance of geomorphological mapping, the 18th Congress of the International Geographical Union (IGU) held at Rio de Janeiro in 1956 and 19th Congress of IGU held at Stockholm in 1958 formed a subcommission on geomorphological mapping to (1) introduce and develop a standardized methodology of geomorphological mapping, (2) adopt a uniform system to ensure compatibility and (3) demonstrate the applications of geomorphological mapping in local and regional economic planning in order to facilitate a rational utilization of the earth's surface (Gilewska 1966; Gilewska and Klimek 1968). In 1968, IGU developed Unified Key mapping system for international detailed geomorphological mapping (Demek et al. 1972; Unified Key 1968) and subsequently Unified Key developed for geomorphological mapping at medium scale (Demek and Embleton 1978). During the same time, the International Institute for Aerial Survey and Earth Sciences (ITC) also published an international mapping system for various landscapes (Verstappen and Van Zuidam 1968) and presents information about morphometry/morphography, processes/genesis, age and lithology. The legend and manual for geomorphological mapping was published in 1971 and 1972, respectively (Bashenina et al. 1971; Demek et al. 1972). Demek et al. (1972) suggested that a large-scale geomorphological map could have a scale of 1:10,000–1:50,000 and occasionally up to 1:100,000. UNESCO (Anonymous 1976) suggested a scale of 1:5000–1:10,000 to qualify a map as 'large-scale'. Demek and Embleton (1978) reported that geomorphological mapping should describe the surface of earth's crust and its contact with the hydrosphere, the atmosphere, the pedosphere and the biosphere. Cooke and Doornkamp (1990b) reported that large-scale maps form the strongest scientific source of geomorphological information and are the best explanatory presentation of landforms and landscape development. Klimaszewski (1990) suggests that a detailed geomorphological map should mainly present the landforms, while information on lithology and hydrography should be supplements.

In geomorphological survey, mapping and classification, the morphogenetic and morphodynamic criteria are extensively used (Verstappen and van Zuidam 1968). In fact, the interaction between form and process is the core of geomorphology (Evans 1998), and form characteristics are key components of geomorphological systems (Ahnert 1998). Lane et al. (1998) in his extensive review underlined the importance of the form in the relief assessment for a variety of purposes. Verstappen (1983) noted that four different types of data could be collected for mapping landforms that include morphographic, morphogenetic, morphometric and morphochronologic information. Many authors noted that land cover or land systems (Cooke and Doornkamp 1990b), hydrology (Gustavsson et al. 2006), surface materials, lithology and structure (Gustavsson 2006), morphometry and morphography (Gustavsson et al. 2006; Fookes et al. 2007), sediment-transfer cascades (Chorley and Kennedy 1971; Shroder and Bishop 2004), surface-process regimes (Cooke and Doornkamp 1990b) and chronology (mapping the age of landforms) should be part of geomorphological mapping activity.

In detailed geomorphological mapping, it may be appropriate to use contours as a base for mapping surface form. Surface features can then be superimposed, providing full detail of the shape of the terrain. Slope length and direction are usually important in geomorphological mapping to distinguish the features like cliffs, upslopes, downslopes, concave or convex units. Surface materials would typically be incorporated in the geomorphological map. They may be mapped according to type or grade, or may incorporate relevant features such as the extent of jointing or fracturing to understand the slope stability or groundwater resources. Other features such as soil depth, porosity, permeability or strength may also be shown depending on the specific purpose of the study. The surface processes are generally mapped indirectly by means of interpreting landform and surface materials. The type of landform and symbol used will therefore differ markedly, according to the types of process operating in the region of interest. The age of a landform is often difficult to ascertain. It is generally more useful in the interpretation of long-term landscape evolution than in applied settings. However, in some contexts, the age may be a useful proxy for different material properties. In some cases, land system mapping is used at regional to national scales for a variety of purposes, including terrain evaluation, resource evaluation, route-corridor alignment, hazard assessment or avoidance and conservation planning. The approach depends on the evaluation of patterns of topography, soils and vegetation that recur within a particular landscape (Cooke and Doornkamp 1990a). The land system is divided into units and then elements or facets.

12.5 Geomorphological Mapping at Different Scales

The issue of spatial and temporal scale in geomorphological mapping is well known (Quattrochi and Goodchild 1997; Tate and Atkinson 2001; Sheppard and McMaster 2004). Obviously, practical issues of scale are associated with data representation, collection, analysis, modelling and presentation. Spatial scales are varied and include concepts of *geographic scale,* which represents aerial coverage or the size of objects, *cartographic scale,* which represents aerial distribution and detail of information presented, *measurement scale,* which represents the smallest area over and which data can be collected or represented to maintain distinguishable parts of an object, *operational scale,* which represents the scale at which processes, feedback mechanisms and systems operate and *computational scale*, representing the scale at which data are analysed. Dikau (1989) and Brändli (1996) proposed hierarchical level, which essentially describes a vertical structure of levels, and that a subsystem at any level is spatially constrained by a higher level. It can be used to describe the complexity of scale associated with a landscape, and the theory has been proposed as a basis for modelling and geomorphological mapping. Fookes et al. (2007) underlined that the detail that can be shown and the form of representation of specific features in geomorphological mapping will depend on the scale of map to be drawn. The map scale will in turn be determined by the aim and type of study carried out and may vary from a regional assessment at 1:1,00,000 scale or coarser resolution to detail mapping or detailed plan at 1:2000 scale.

12.6 Remote Sensing in Geomorphological Mapping

Recent developments in remote sensing and GIS have vastly improved the accuracy in mapping of several geomorphological variables. With the advent of digital image processing, GIS and GPS, it is now possible to map the geomorphological features in greater details than before and to interpret them for newer information. Further, use of digital remote sensing, GIS and digital elevation models (DEM) in geomorphological mapping is cost-effective and time efficient (Batten 2001; Bocco et al. 2001). Reddy and Maji (2003) reported that analysis of IRS-ID LISS-III data in conjunction with distinct lithological units, drainage pattern and contour information improves the capability in delineation and characterization of geomorphological units. Remote sensing data has been used in the analysis of terrain mapping and geomorphic features by the analysis of colour composites (Pain 1985; Novak and Soulkellis 2000; Bocco et al. 2001). The false colour composites, i.e. blue, green and red bands of Landsat (with bands 7, 5 and 4), display good contrast for analyses of landform (Pain 1985). Verstappan (1977) used Landsat ERTS-1 band 5 and 7 data and concluded that some landform types were better distinguished than others, mainly because of variations on the correlation between geomorphic units and vegetation. Band 7 of Landsat ERTS-1 was the most valuable for identifying geologic formations, tectonic fault lines and geomorphology slope contrast (Kayan and Klemas 1978). Pain (1985) used Landsat MSS for landform mapping in Australia and existing land use classification as a reference. Bocco et al. (2001) concluded that application of Landsat data helps to quickly identify and map terrain features at reconnaissance scale (1:250,000) and semi-detailed (1:50,000) levels.

Recent advances in remote sensing and GIS, as well as developments in numerical modelling of surface processes, have revolutionized the field of geomorphology (Shroder and Bishop 2003; Bishop and Shroder 2004). The synoptic view provided by satellite remote sensing offers technologically the appropriate method to map distinct landforms. Geospatial technologies can be used to address some of the conceptual issues such as heterogeneous surface composition with fuzzy classification membership (Warner and Shank 1997), indeterminant boundaries and features (Burrough 1989; Usery 1996; Burrough et al. 2000; Smith et al. 2000; Deng and Wilson 2008), hierarchical organization and spatial analysis using object-oriented technology (Ralston 1994; Brändli 1996; Schmidt and Dikau 1999), scale dependence of properties and patterns using geostatistics (Tate and Wood 2001) and objective mapping using different analytical approaches such as descriptive statistics, inferential statistics, artificial intelligence and analytical reasoning technologies. Geomorphological maps can act as a preliminary tool for land management and geomorphological and geological risk management, as well as providing baseline data for other applied sectors of environmental research such as landscape ecology, forestry or soil science (Cooke and Doornkamp 1990a; Dramis et al. 2011; Paron and Claessens 2011). Many authors used remote sensing data in geomorphological mapping in fluvial, arid, glacial, karst and coastal environments.

12.7 Geomorphological Mapping in India

In India, under national mission on geomorphological and lineament mapping on 1:50,000 scale, ISRO-National Remote Sensing Agency (presently known as National Remote Sensing Centre) and Geological Survey of India (GSI) have developed a new genesis-based three-level classification system (Anonymous 2009). In this system, the first level addressed the genetic aspect (origin) of landforms, the second level grouped the landforms on the basis of their broad current processes, and the third level provided the actual mapped landforms. In India many authors used both aerial photographs and satellite remote sensing data in geological, geomorphological and structural mapping (Krishnamurthy and Srinivas 1995; Reddy et al. 2004). Detailed information on various geomorphological properties can be extracted accurately from high-resolution satellite data and large-scale aerial photographs. Further detailed information can be generated on geomorphological units and their characteristics in GIS.

12.8 Geomorphological Classification and Legend Systems

Geomorphic classification is the categorization and description of the nature, origin and development of landforms. The framework of classification system is that a geomorphic unit can be classified based collectively on its origin and development (process), on its general structure and shape (landform), on measurements of its dimensions and characteristics (morphometry) and on the presence and status of process overprinting (geomorphic generation). In the past, a number of classification systems have been devised, in which a general objective has been to describe and group landforms according to the processes that shaped or influenced them. In addition, some classification systems incorporate the stage of development of landforms as an aspect of their evolutionary development through geologic time and take into consideration the lithology of rocks, the attitude of strata, the presence of faults and joints and factors of broad influence, including regional uplift and climatic change. The geomorphic classification system also needs to be hierarchical in order to address related landforms at various scales; to illustrate the relationships to both higher-order and more finite geomorphic processes, landforms and landform components; and to link at all scales (USDA 1993). The taxonomic schema for describing landform patterns includes how they were formed, the environment in which they were formed and their composition.

In the early twentieth century, a large number of symbols and legends have been developed for geomorphological mapping. The concepts and cartographic conventions created basically related to the terrain configuration of the surveyed region and the scientific focus and aim of the map. Obviously, more complex terrains have the greater diversity of symbols and colours (Verstappen 2011). In general geomorphological maps and their legend systems can be differentiated into maps showing a single aspect of geomorphology, most commonly morphology, and analytical maps that encompass the full information of a landscape including processes, morphogenesis and even lithology (Knight et al. 2011; Verstappen 2011). An overview of different legend systems is provided by Otto et al. (2011), and it highlights how different countries have developed their own systems, either formally or informally, to suit their own needs. Most of the interest in geomorphological mapping has centred on the development of various mapping systems for use in environmental management (Cooke and Doornkamp 1974); the most detailed systems have been developed in Europe, where different countries utilize different procedures. Despite attempts at international standardization (Demek 1972; Demek and Embleton 1978), the major problem remains the correlation and harmonization of various mapping schemes.

12.9 Geomorphological Mapping in Different Environments

Geomorphological mapping involves the partitioning of the terrain into conceptual spatial units/entities based upon criteria that include morphology (form), genetics (process), composition and structure, chronology, environmental system associations (land cover, soils, ecology), as well as spatial topological relationships of surface features (landforms). Landform elements are commonly described by five main attributes: slope, topographic position, dimension, 'mode of geomorphological activity' and 'geomorphological agents' (Klingseisen et al. 2007). The genesis of landforms due to various geomorphic agents like fluvial, arid, glacial, karst and coastal is briefly discussed below.

12.9.1 Geomorphological Mapping in Fluvial Environment

The surface run-off starts commonly in the form of a thin sheet of water in motion – rain wash/sheet wash. This accumulates and begins its downward journey; it becomes a stream. Further down a number of streams unit to form a river. Along its seaward course, a river produces a few tributaries and developed a river system gradually. The water flowing in a river erodes the land, brings about its chemical decay, denudes the country rocks, transports the rock debris and finally deposits the transported material under favourable conditions. The fluvial cycle operates in three well-defined stages. At the stage of 'youth', the flowing water predominantly erodes and tributaries gradually develop. At the stage of 'maturity', the long profiles of rivers are attained equilibrium, drainage system is well evolved, and the power of erosion is also much reduced and is balanced with its transporting capacity. At the stage of 'old', the river valley becomes very wide due to lateral cutting, and the process of erosion becomes extremely slow while deposition phase dominates. The country is reduced to a '*peneplain*', which is a region of low relief exhibiting very gentle undulations. Isolated hillocks made up of harder, durable and resistant rocks occur here and there on the peneplains, which are known as monadrocks, and they are the remnants of the pre-existing country.

12.9.1.1 Geomorphological Processes in Fluvial Environment

The important fluvial processes of running water are hydraulic action, abrasion, attrition, solution, transportation and deposition. *Hydraulic action* is basically breaking down of the rock masses essentially due to continuous impact of water moving with appreciable velocity along the channel. *Abrasion* is the process of wear and tear of rock material. *Attrition* is the process of mechanical breakdown of the transported rock fragments due to impact among themselves. Abrasion and attrition always work together and produce fine rock particles, which ranges in size from boulder–pebbles to silt–clay and are readily transported downstream along with flowing water. *Transportation* can be defined as the size and amount of load, and the velocity of stream determines their transporting power. Transportation power is directly proportional to the sixth power of stream velocity. However, *deposition* occurs primarily during the periods of low flow and form various depositional landforms.

12.9.1.2 Fluvio-denudational Landforms in Fluvial Environment

Stream Capture Drainage progressively or abruptly diverted from one basin to another as a stream is beheaded by headward erosion. It is a progressive movement of drainage network towards headward side of terrain through the activity of erosion by drainage streams. In this process parallel streams formed at different elevation with different base levels (drainage captures by lower stream). Some streams have structural advantage, i.e. degrading more rapidly in softer rock than the hard rock.

Plateau A plateau is an extensive, elevated region with a fairly flat top surface. Plateaus are generally dominated by a structure of horizontal rock layers. Many striking plateaus exist in the deserts and semiarid regions of the world. Colorado Plateau of the United States is a tectonically uplifted desert plateau, where streams and their tributaries respond to uplift by cutting narrow and steep-sided canyons.

Canyon In the upper part of the course, the process of erosion becomes very conspicuous in downcutting the valley floor. Therefore, the river passes through a narrow but deep valley, which may develop in softer rocks known as 'gorge' or 'canyon'. Numerous waterfalls and rapids also develop on the upper parts. The canyon walls consist of horizontal layers of alternating resistant and erodible rocks; differential weathering and erosion exert a strong influence on the canyon walls. Canyons in these areas tend to have stair-stepped walls, with near-vertical cliffs marking the resistant layers, and weaker rocks form different slopes.

Mesa Weathering and erosion will eventually reduce the extent of a caprock until only flat-topped, steep-sided mesas remain. A mesa has a smaller surface area than a plateau and is roughly as broad across as it is tall. Mesas are relatively common landscape features in Deccan Plateau region of India.

Butte Due to erosional processes of the caprock from all sides, a mesa may be reduced to a butte, which is a similar, flat-topped erosional remnant but with a smaller surface area than a mesa. Mesas and buttes in a landscape are generally evidence that uplift occurred in the past and that weathering and erosion have been extensive since then. Variations in the form of the slope extending down the sides of buttes, mesas and plateaus are related to the height of the cliff at the top, which is controlled by the thickness of the caprock in comparison to the size of landform features.

12.9.1.3 Fluvio-depositional Landforms in Fluvial Environment

Natural Levees During floods streams commonly overflow their channels, and when this water retreats, ridge-like deposits of silt and clay are formed along the fringes of the flooded channels known as 'natural levees'. Flood plain is the portion of a river valley, which is readily submerged underwater during floods. Slough are depressions upon the flood plains of meandering rivers due to the tendency of the overflowing water to follow a shorter course. The process of repeated filling up and cutting of channels upon the valley floors is known as 'braiding'.

Alluvial Fans In the earlier stages of development of a river valley, its transverse profile is 'V' shaped. With maturity of the river, its width increases in comparison with its depth, and the transverse profile is modified to a more or less flat base with gently sloping *abutments*. Accumulation of boulders and pebbles at a point where running water enters into the plains are known as 'alluvial fans', where rock fragments are arranged in a radiating fan-like pattern.

Oxbow Lakes Streams and rivers never follow a straight course. They move in curved, more or less zigzag paths, and the curvature along the course is known as meanders. Meanders are present since running water has the tendency to follow the direction of maximum slope of the landforms. During the later stages, however, the meanders become more conspicuous due to deposition of sediments along the inner curve of the lore-existing meander and proportionate excavation along the outer curve. In this manner the river ultimately takes an extremely round about course, and during floods the running water may cut straight through a meander and may follow a shorter horseshoe or oxbow lakes. Sometimes the major portion of the course of the river is abandoned due to shifting, which is termed as paleo-channel.

Deltas Deltas are low-lying land mass formed at the mouth of a river due to deposition of sediments and are commonly swampy in nature. In the earlier stage of formation of delta, the fine rock waste accumulate at the basement on which delta grows, and they are known as 'bottomset beds'. During later stages large quantity of silt, sand and clay are deposited in the form of layers and are known as forest beds. Thin layers of silt and clay are deposited over the forest beds, which are termed as '*topset beds'*. Thus, the delta structure is made up of three types of beds.

12.10 Landform Mapping in Fluvial Environment: A Case Study

Terrain characterization and landform mapping of a region are prerequisite to conduct soil resource inventory, develop landscape–soil relationship, land degradation mapping and other environmental applications (Reddy et al. 1999, 2002). Landform mapping under fluvial environment of Basltic Terrain of Central India has been carried out. In the study, IRS-P6 LISS-IV (5.8 m) satellite data and SRTM DEM (30 m) digital terrain database have been used in detail landform mapping. Slope is an important consideration in landform analysis and mapping. The slope analysis using SRTM DEM (30 m) of the study area shows that level to nearly level (0–1%) slopes occupy 28.4% of the study area. Major parts of the area are covered under very gently sloping (1–3%), and it accounts for 33.6% of the study area. Gently sloping (3–5%) area is associated with upland areas and accounts for 19.3%, whereas moderate slopes (5–10%) are encountered in 9.3% of the study area. Steep

Table 12.1 Slope classes of the study area

S.No	Class	Area (ha)	% Area
1	Level to nearly level (0–1%)	4313.4	28.4
2	Very gently sloping (1–3%)	5098.4	33.6
3	Gently sloping (3–5%)	2931.9	19.3
4	Moderately sloping (5–10%)	1406.8	9.3
5	Moderately steep sloping (10–15%)	783.9	5.2
6	Steeply sloping (15–25%)	447.7	3.0
7	Very steeply sloping (25–33%)	189.6	1.2
	Total	**15171.8**	**100.0**

(15–25%) and very steep (25–33%) slopes were noticed in 3.0 and 1.2% of the study area, respectively (Table 12.1). Landform analysis was carried out based on the visual interpretation of high-resolution IRS-P6 LISS-IV data with the help of image elements such as shape, tone or colour, pattern, shadow, association and texture in conjunction with DEM. The analysis shows nine distinct landform units namely plateau top, isolated mounds, linear ridges, scarp slopes, undulating uplands, undulating lowlands, alluvial plains, narrow valleys and main valley floor in the study area (Fig. 12.1 and Table 12.2). The land use/land cover of the study area shows that double- and single-cropped area occupy about 35.0 and 20.0 of the area, respectively. Nearly 29.0% of the study area is under deciduous forest cover.

Plateau Top This landform unit occupies the highest position in the study area, and elevation varies ranging from 580 to 662 m above mean sea level (MSL) and covered with an area of 1453.2 ha (9.6%). The general slope is varying between 0–1 and 1–3 per cent. However, on the fringes of this unit, they exceed 5–8%. Rain splash, rillwash and slopewash processes dominate rather than concentrated surface run-off. Sheet wash processes are also observed on the very gently sloping areas. Hence, typical summit areas are devoid of fingertip tributaries. Regolith cover is very thin with numerous core stones of varying dimensions spread throughout this unit. Weathering limited condition is responsible for such a situation.

Isolated Mounds This unit occurs mainly in middle and lower portion of the area. Their elevation is around 560–660 m above MSL and covered with an area of 93.1 ha (0.6%). These mounds are generally restricted, much dissected, denuded and appears bevelled on its fringes. By parallel retreat of slopes due to back wearing and circum-denudation, these mounds might have been denuded and detached from the extensive basaltic plateau. The summits of these mounds are marked by the relative absence of concentrated run-on/run-off. It is observed that rains plash is the dominant geomorphic process followed by sheet wash. Numerous core stones are spread throughout this unit, and they vary in their size and dimension, which indicates the severity of erosion.

Linear Ridges Linear ridges are sinuous, narrow, highly disintegrated by mechanical weathering processes and are remnants of land reduction process formed due to

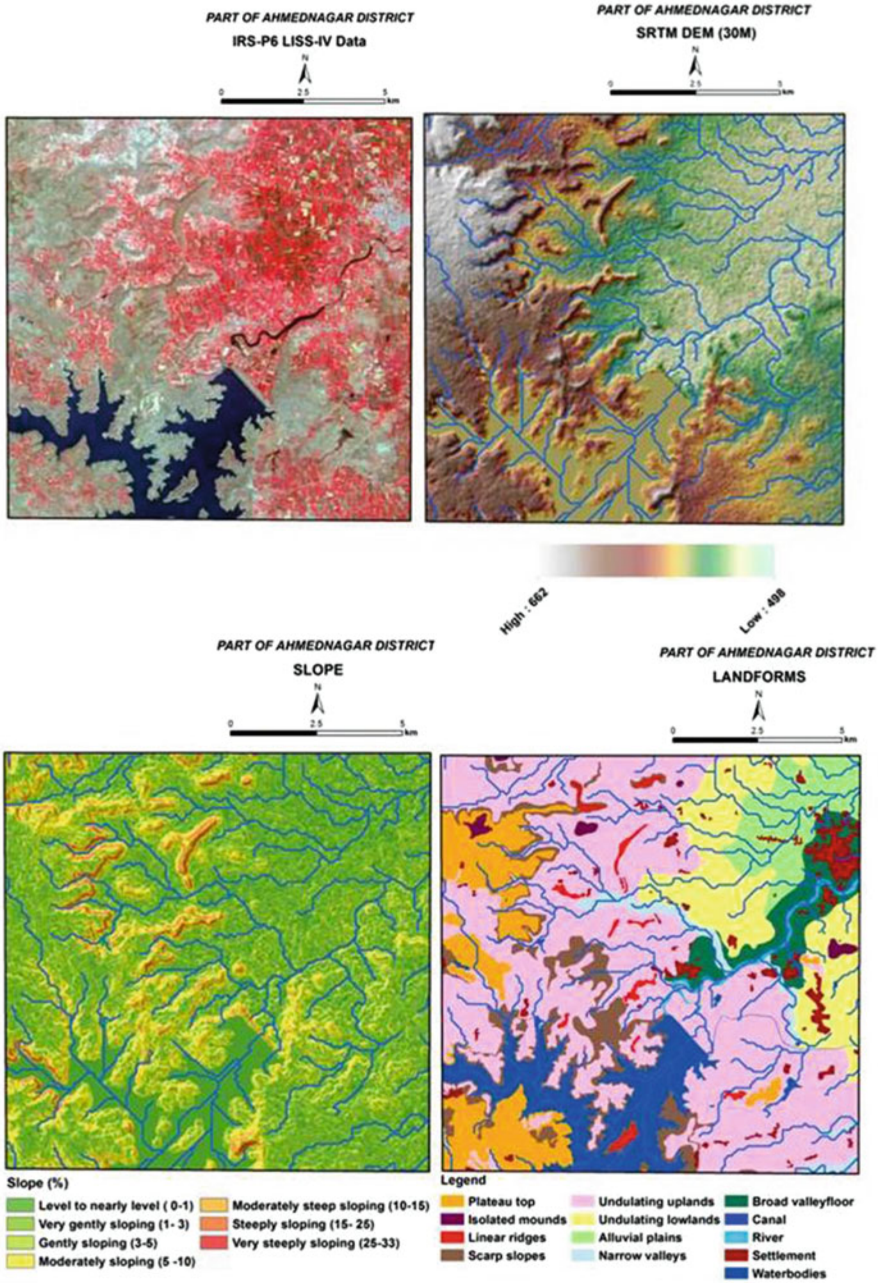

Fig. 12.1 IRS P6 LISS-IV data, SRTM-30 m data, slope and landform maps of part of Ahmednagar district of Maharashtra

Table 12.2 Landform units of the study area

S.No	Class	Area (ha)	% TGA
1	Plateau top (Pt)	1453.2	9.6
2	Isolated mounds (Im)	93.1	0.6
3	Linear ridges (Lr)	147.7	1.0
4	Scarp slopes (Ss)	1212.0	8.0
5	Undulating uplands (Uu)	6787.1	44.7
6	Undulating lowlands (Ul)	1768.4	11.7
7	Alluvial plain	906.5	6.0
8	Narrow valleys (Nv)	299.0	2.0
9	Broad valleyfloor (Bvf)	598.4	3.9
10	River	102.7	0.7
11	Canal	10.4	0.1
12	Settlements	485.6	3.2
13	Water bodies	1310.7	8.6
	Total	**15174.8**	**100.0**

detachment and isolation by various fluvial processes. The drainage pattern is mainly radial around the ridges and at places, basaltic lava flows of different geological periods exposed due to various fluvial processes. This unit covers with an area of 147.7 ha (1.0%).

Scarp Slopes This landform unit occurs as side slopes of plateau-top region of the study area and covered with an area of 1212.0 ha (8.0%). Steep (15–25%) and very steep slopes (25–33%) are predominent and due to this reason, sudden slope drop prevails between the plateau top and undulating uplands. Rigorous slope wash processes dominate due to the presence of the extreme steep slope. Moderate to deep gullies and, at places, proto-gullies are common, which led to extreme erosion throughout this unit. Moreover, increase in gradient also favours the removal of fines and other weathering products very easily; hence, the entire escarpments are strewn with larger corestones and disintegrated piles of basalt pebbles. Continuous incision and removal of weathering products resulted in the formation of hard and nose slopes within the escarpments.

Undulating Uplands This unit occurs immediately below the plateau top and scarp slopes and covered with an area of 6787.4 ha (44.7%). The slope angles are much shallower having concave curvatures. The surface spread of pebbles are much reduced and their dimensions also much diminished. Increased chemical weathering and decomposition is the main reason for the reduced size of the corestone here. Besides overland flow, through-flow also emerges out in this subunit as return flow; hence, this unit is always over saturated. However, during rain storms much of the weathered products are washed downslopes; thus the fills available are all of transitory in nature. Colluviation from the above-occurring units and entrainment of sediments are common features in this unit.

Undulating Lowlands This unit was noticed between 500 and 520 m above MSL and covered with area of this unit is 1768.4 ha (11.7%). This is the zone of obstruction of drainage networks wherein the fourth-order deeper colluvic-alluvial fills. The slope angles are much gentler; hence, this unit is having very gentle undulations and increased area. The weathering front is observed to be much deeper and is more than 150 cm. A few first-order drainages are originating in this subunit, and their lengths are much more when compared with those occurring on the undulating uplands. Another remarkable feature observed in this subunit is the total absence of corestones on the surface as well as on the subsurface horizons. It may be because of the fact that, due to increased chemical weathering, these fragments totally disintegrated, decomposed and assimilated into the colluvic-alluvial fills.

Alluvial Plains Alluvial plains are relatively flat landform and created by the deposition of highlands eroded due to weathering and water flow in study area. The sediment from the hills is transported to the lower plain over a long period of time. It identified on the imageries dark, reddish, moderate to fine texture due to agricultural activities. Alluvial deposits of the area constitute gravel-, sand-, silt- or clay-sized unconsolidated material. This unit covers with an area of 906.5 ha (6.0%).

Narrow Valleys This unit occurs on the lowest portion of the study area with an area of 299.0 ha (2.0%). Because of its narrowness and linear nature, the elevation in this unit is varying upstream ranges from 500 to 580 m above MSL. The well-entrenched nature of this narrow drainage floor is indicative of total integration of drainage network. The valley walls are placed more than 2–3 m deep and show alluvial fills. Vertical accretionary deposits are also available on the hairpin bends indicating lateral shifting of bed material load in the geological past.

Broad Valley Floor This unit is adjacent to a stream or river that stretches from the banks of its channel to the base of the enclosing valley walls and experiences flooding during periods of high discharge. It includes the floodway, which consists of the stream channel and adjacent areas that actively carry flood flows downstream and the flood fringe, which are areas inundated by the flood but which do not experience a strong current. This unit covers with an area of 598.4 ha (3.9%).

12.11 Geomorphological Mapping in Arid (Aeolian) Environment

In regions of comparatively dry climate, the efficiency of the blowing wind becomes most conspicuous in bringing about dust and sandstorms, which badly remove a portion of the mantle. The velocity and direction of wind directly influence earth's surface processes, as there is little vegetation to slow its velocity at ground level and to bind the soil, and the loose, dry sediments are easier to erode. The greater temperature ranges experienced in deserts also generates stronger and more consistent winds. Unlike stream and glacial erosion, wind can only erode fine sediment, but it is not confined to channels, and the erosion affects vast areas. As far as India is concerned, the arid region is spread in 38.7 Mha area out of which 31.7 Mha is under hot arid zone and 7 Mha is under cold arid zone. In India, during 2012–2015, Central Arid Zone Research Institute (CAZRI) prepared geomorphological map of arid western Rajasthan using a classification system developed at 1:50,000 scale in collaboration with ISRO (Indian Space Research Organization) and GSI (Geological Survey of India). The mapping involved digital interpretation of the false colour composite (FCC) of images of 2005–2006 from IRS1D LISS-III, followed by field verification of the mapped units and analysis of sediments. Kar (1993) recognized 9 major dune types and 23 subtypes in Thar Desert and then grouped under the old dune system and the new dune system (Pandey et al. 1964; Vats et al. 1976; Singh 1982). Several phases of dune-building activities have also been identified from the morphological characteristics of dune sediments within the desert and its eastern margin. The efficiency of aeolian processes increases with decreasing rainfall from east to west, as well as with the increasing wind speed in that direction (Kar 1993).

12.11.1 Geomorphological Processes in Arid (Aeolian) Environment

In arid environment, deflation, abrasion, attrition, saltation and suspension processes are prominent. *Deflation* (L. deflare = to blow away) can be defined as the process of removal of all loose, light particles from the earth's surface. The process of removal of loose soil or rock particles during storms along the course of the wind has been defined as 'deflation'. Continual deflation of fine material can result in an accumulation of coarser material, which then protects the land from further deflation and a 'gibber plain' (desert pavement) result. Alternatively, 'deflation basins' or 'blowouts' may occur until the water table is reached, where the moist ground and resulting vegetation prevents further erosion. *Abrasion* process is wear and tear of the exposed country rocks (mainly by sand blasting). It is concentrated close to the ground, where most of the material is transported. Close to the ground, objects are smooth and polished, and large rock formations are undercut. Larger rocks have their windward faces flattened and polished and are termed blowing wind which generally causes erosion by three distinct processes deflation. *Attrition* can be defined as that the wind-borne particles traveling is suspension condition collide with one another and causes a further grinding of the particles. *Saltation* is a process of transport of sand grains by wind in a series of leaps along a low, curved trajectory. In case of sand particle transportation, it takes place due to the forward movement of the grains in a series of jumps, and the process is described as '*saltation*'. *Suspension* is a process that being finer in grain size the dust particles are conveniently lifted up in air and continue to move in suspension due to the turbulence present in the air currents.

12.11.1.1 Denudational Landforms in Arid Environment

Due to wind abrasion, the exposed irregular surface of a rock mass is gradually converted into a plane surface, which may be smooth and polished.

Pedestal Rocks Blasts of wind cause more of abrasion near the surface than what is possible in higher horizons. Vertical columns of rocks are more readily worn out towards their lower portions, and as a result 'pedestal rocks*'* are formed.

Desert Pavement The process of deflation leads to the development of 'desert pavement*'* – which are made up of a layer of residual pebbles and cobbles stream upon the surface while the intervening finer particles have been removed.

Yardangs The wind causes the development of 'U' shaped troughs within relatively softer rocks. The ridges left between such successive troughs are known as '*yardangs'*. They are generally small in size and extending from tens of kilometres long and up to 100 m high to small structures a few metres in length.

Ventifacts Ventifacts are pebbles of rock, which have developed some plane surfaces due to wind abrasion. The rock particulars, which travel along with the blowing wind, are commonly more concentrated near the surface than higher up in the atmosphere. These are sometimes mistaken for man-made artefacts. Soft rock strata are more easily eroded, leading to 'honeycombed rocks'.

Reg A surface covering of coarse gravel, pebbles, and/or boulders from which all sand and dust have been removed by wind and water.

Desert Varnish A dark, shiny coating that forms on rock surfaces that are exposed to desert air for a long time, often associated with regs.

Hamada A barren surface of consolidated material, usually consisting of exposed bedrock but sometimes of cemented sedimentary layers.

Inselbergs Isolated hills, known as inselbergs, form in areas of relatively homogeneous, resistant rock. Horizontal strata may form dissected plateaux, mesas and buttes.

Bornhardt A rounded inselberg composed of very resistant rock that stands above the surrounding terrain because of differential erosion and weathering.

Pediments Gently inclined bedrock platform that extends outward from a mountain front, usually in an arid region a residual surface formed by erosion not deposition. Sloping away from the uplands are 'pediments' – thinly and incompletely covered with alluvial material and containing the courses of ephemeral streams. Pediments are bedrock surfaces, rather than alluvial fans, but can superficially resemble them, having a concave surface typical of fluvial landforms. They are thought to be the product of sheet erosion during flash floods, which erode laterally as well as vertically, but the exact way they are formed has not been firmly established.

12.11.1.2 Depositional Landforms in Arid Environment

Dust and sand is deposited if the winds lose their velocity, obstructions create wind shadows, or the particles moving by saltation strike a softer surface and so lose energy. Sediments deposited by wind are called ‘aeolian’ (wind) deposits. Typical deposits include:

Loess Loess are deposits of windblown silt (rather than sand). Loess deposits produce productive farmlands but make a poor foundation material. It has a light, open structure that is relatively strong when dry, but when wetted it tends to settle, crack and become more consolidated.

Dunes Dunes assume a characteristic cross-section with a gently sloping windward side and a steeper downwind side. Generally particles rolled and moved by saltation up the shallower upwind face and then rolled down the sheltered ‘slip face’. Migrating dunes can be a major problem; they migrate over roads, forests, etc. Dunes on beach roads can be a constant problem, with the usual remedy being to try to stabilize the dunes with vegetation. Desert roads are harder to protect due to the harsh climate, which supports little vegetation, especially on dry and shifting dunes.

Barchans The wind-borne particles are dropped down whenever the velocity is reduced to an appreciable extent. The deposits thus formed are either in the form of irregular mounds or have some definite shape. The deposits of sand are commonly described as dunes; they may vary in considerable dimensions. Dunes formed within wind shadow zones are described as shadow dunes. The dunes are found to have a gentle slope along the windward side and a comparatively steep gradient along the leeward side. Dunes, which are more or less crescent-shaped, are commonly described as ‘barchans’.

12.11.2 Geomorphological Mapping in Glacial Environment

Geomorphological mapping in glacial environments is the study and mapping of landforms produced by glacial and fluvioglacial processes in the areas of present glaciers as well as in the areas covered by glaciers in the past. Glacier mapping is to represent the spatial morphology of glacier terrain and geomorphological features. The Himalayan Mountains are characterized by the presence of peaks, which are crowned permanently with snow. These peaks necessarily lie above the snow line, which represents in any region the lowest limit of perpetual snow. The altitude of the snow line varies more or less inversely as the latitude of the place concerned and is to some extent modified by the local climatic conditions and topographic pattern. DEMs are valuable tools for mapping, modelling, analysing and visualizing of various glacio-geomorphic phenomena in glacial environment (Etzelmüller and Sollid 1997; Etzelmüller et al. 2001). DEMs play an important role in the preparation of ortho-images in high mountain terrain (Finsterwalder 1984), in estimating glacier hypsometry (Brocklehurst and Whipple 2004) and in derivative of various terrain parameters such as slope, plan and profile curvature and aspects, which can be further used for geomorphological mapping in glacial environment.

12.11.3 Geomorphological Processes in Glacial Environment

Above the snow line continuous precipitation and accumulation of snow gradually gives rise to a 'snow field'. Periodic additions of snow in course of time increase the thickness of any snow field. At this stage the prevailing moisture and the weight of the overlying snow brings about a conversion of loose snowflakes into small granules of ice. Such granular mass of ice are known as 'neve' or 'firn'. With further addition of snow to the field, neve or firn is gradually transformed into a compact block of ice. In any snow field therefore loose flakes sive by neve or firn followed by compact ice. Snow fields slowly gain in thickness and do not ordinarily cause the ice to move on level grounds. But along the hill slopes, the increasing weight of the growing mass of ice at length is sufficient to make the ice flow or creep downwards. Such bodies of slowly moving ice are called '*glaciers'*. Sometimes a portion of the creeping mass of ice may break off and slide down under gravity forming an '*avalanche'*.

12.11.3.1 Denudational Landforms in Glacial Environment

Typical denudational landforms formed due to ice in glacial environment include:

Quarrying and Frost Wedging Despite their slow movement and limited extent in space, the geomorphological work done by glaciers by no means is less important. Glaciers conveniently erode the highlands, transport the products of erosion and deposit them suitably, thus grading the landmasses lying within their access. Glacial erosion takes place due to 'abrasion', 'quarrying' and 'frost wedging'.

Frost Wedging The glaciers may under favourable conditions cause uprooting of blocks of rocks forming the valley floors, and such excavations are known as 'quarrying' and are most common in regions where the country rocks are very much fractured. The process of breaking down of the country rocks due to alternate melting and freezing of ice within openings in rocks has been described as 'frost wedging', which causes shattering of rocks, thereby rendering them extremely weak and very much susceptible to erosion. The process of abrasion, quarrying and frost wedging operate hand in hand and mould the valley suitably offering a characteristic pattern and profile of its own. Unlike the 'V'-shaped river valleys, the transverse profile of all glaciated valleys is necessarily 'U' shaped.

Cirque Cirques are common occurrence of landform in the glaciated mountain regions and the most recurrent worldwide feature in the glacial landscape. Frost wedging followed by quarrying of the shattered rocks renders the head of the glaciated valleys blunt and steep; they are described as 'cirques', and the process, which leads to their formation, has been defined as 'nivation'. With the growth of adjacent radiating cirques along the adjacent slopes of the mountains, the peaks become narrower and on the long run give rise to a sharp and irregular ridge known as 'arete' or 'combridge'. A pyramid-like peaks with steep slopes are produced due to enlargement of three or more neighbouring cirques in glacial environment.

Roches Mountannes They have smooth rock surfaces on all the sides, which have been produced by glacial abrasion. The boulders and pebbles held firmly within the mobile mass of solid ice rub themselves against the floor of the valley and thus cause its gradual abrasion. During abrasion the boulders and pebbles worn out and in course of time are found to have been polished, striated or grooved. Due to firm grip of ice on them, the boulders and pebbles cannot have any rolling motion and therefore develop polished/grooved faces only. Small mounds on the sides of the valley floors with fine striation on their surface due to glacial abrasion are described as 'roches mountannes'.

Hanging Valley The amount of erosion caused by a glacier is a function of its size, shape, rate of flow and the quantity of rock fragments, which it can utilize in abrading the valley and the nature of the bedrock. No two glaciers are therefore likely to excavate their valleys to the same extent. Thus when a smaller glacier joins a larger one as its tributary, they do not have their valleys meeting at the same level. The valley of the larger glacier is much deeper than that of the smaller tributary. The tributary valley appears to hang above the floor of the main valley occupied by the larger glacier. They are called '*hanging valleys'.*

Fiords At high latitudes, the glaciers often excavate their valleys up to the sea level. These glacial valleys occurring along the coasts and occupied subsequently by the sea itself are known as 'fiords'. Within fiords glaciers come in contact with marine water, and blocks of ice are found to break off from the mass of the glacier. This process of wastage of glacier ice is known as 'calving', and the dislodged blocks of ice float on the sea in the form of icebergs.

Arêtes and Horns The mechanical disintegration of rocks in glacial environment results in the development of certain peculiar forms like arête, which is a knife-edged, sharp and narrow crest of a glaciated mountain. The slender shape of an arête commonly occurs due to removal of most of the material from in between two cirques, due to their advanced growth. Their sharp edges are attributed to wedging by frost action. A horn is a pyramidal multifaceted projection formed in the glacial mountainous region.

12.11.3.2 Depositional Landforms in Glacial Environment

Glacial Drift The materials undergoing glacial transport and all deposits of glacial origin constitute what is known as 'glacial drift'.

Till Unsorted heaps of glacial deposits made up of an assemblage of rock fragments and particles of widely varying dimensions are known as *till*.

Deglaciated Valleys The deglaciated valleys are formed due to the retreat of a glacier from its maximum extent. Cross profile of well-developed deglaciated valley appears in U shape, and side walls are considerably steep, approaching vertical in place, and the valley floor is broad and flat. Widening and deepening deglaciated valleys depend upon the ability of the glacier to erode valley walls and cut into the rock of its bed and lithology of its bedrocks. The valley floors are filled with reworked outwash sediments and marked by a series of rock basins.

Lateral Moraines Lateral moraines are formed as the linear ridges produced from the dumping of till with allied outwash deposits in the trough between the glaciers and valley sides in the glacial environment. They are one of the commonest depositional features in glacial environment. During their downhill journey, valley glaciers always deposit some rock debris in the form of ridges along their lateral margins and known as *lateral moraines*.

Medial Moraines When two valley glaciers meet and together form a large one, they commonly give rise to a medial moraine, which results due to coalescene of two lateral moraines.

Terminal Moraines A major part of the glacial drift, however, accumulates at the terminus of the glacier in the form of ridges known as terminal or end moraines. Terminal moraines are the ridge of till that marks the maximum limit of glacier advance. A well-developed terminal moraine indicates the past climate features that the ice remained inactive for a considerable period of time. The series of terminal moraines indicates the recession of the glacier and are called as recessional moraines. These are basically crescent-shaped glacial landforms with the convex side extending down the valley and appear as arcuate ridge.

12.11.4 Glacio-fluvial Landforms in Glacial Environment

Drumlins In regions where the deposit is made up mainly of clayey materials, it occurs in the form of a series of smooth mounds known as drumlins, which appears like plain and more or less elliptical with their long axes lying parallel to the direction of flow of the pre-existing glacier.

Outwash Plains The terminal moraines are readily worked upon by the melt water and gives rise to stratified glacio-fluvial deposits. Stratified deposits formed by melt water and occurring further down the valley beyond the end moraine are known as outwash plain.

Kettles Outwash plains usually contain a number of circular or elongated depressions known as ‘kettles’, which are formed due to enclosure of blocks of ice within glacial drifts, which subsequently melt in course of time.

Kame Terraces Glaciated valleys often contain well-defined terraces of glacio-fluvial origin known as kame terraces. Kame is an isolated hill mound of stratified drift deposited in an opening within or between ice blocks or in a moulin. If the opening was between ice and a valley wall, the resulting form is called a kame terrace.

Eskars Stratified glacio-fluvial deposits occurring in the form of meandering ridges are called esker. Eskar is a sinuous or meandering ridge of stratified sand and gravel commonly with very well-rounded pebbles and cobbles. Eskars form in open channels on glaciers and in tunnels within or beneath them. They often appear as sinuous ridges with lengths up to several kilometres and heights of tens of metres.

Verves Glacio-fluvial deposits in the form of very thin laminated layers occurring on the nearly lakes are called verves, which are indicators of the advance and retreat of glaciers.

Debris/Talus Cones The deglaciated areas generally marked with several debris/talus cones. These talus cones are formed by several glacio-fluvial processes, which include avalanches, mass wasting, hill slope evolution, etc. The loose debris formed due to glacial deposition provides the soft target for the movement of the large boulders during these processes.

Glacio-fluvial Deltas Glacio-fluvial deltas are landforms formed due to transported sand and gravel material by glacial meltwater and deposited in standing water. Subsequent to deglaciation, the landforms have been separated from the original body of water either by land uplift or lake-level lowering.

12.11.5 Geomorphological Processes in Karst Environment

Karst is 'terrain with distinctive hydrology and landforms arising from a combination of high rock solubility and well-developed secondary porosity' (Ford and Williams 1989). Karst as a type of landscape found on carbonate rocks (limestone, dolomite, marble) or evaporites (gypsum, anhydrite, rock salt) is characterized by a suite of landforms comprising springs, dolines, caves, collapsed sinkholes and carbonate depositional landforms (Gunn 2004; Ford and Williams 2007). Solution becomes a process of both weathering and erosion, wherein the weathered products are removed from the surface and carried away in solution. Temperature, precipitation, biologic activity and amount and seasonality of run-off are all climatic factors that affect the intensity of karst processes. Application of remote sensing and GIS improves the generation of geomorphological maps and helps to monitor and mitigate karst geohazards (De Carvalho Jr et al. 2014; Pardo-Igúzquiza et al. 2013). The fusing of different satellite datasets at different resolutions and analysis in GIS is proven to provide better results in karst morphological studies and landform mapping in karst environment (Siart et al. 2009).

Solution Pits On exposed rock (bare karst, pavement karst), horizontal surfaces develop shallow solution pits (rain pits, makatea). On surfaces inclined a few degrees from the horizon, sheet run-off produces flat solution facets (solution bevels). Solution runnels (Rinnenkarren) are branching channels in networks first formed under soil cover but, having formed, are perpetuated by run-off on bare rock surfaces.

Dolines The fundamental geomorphic component of karst topography is the doline, or limestone sink. Whether due to joint control (the most common cause), differential solubility or random events such as cave collapse, localized areas of karst terrain are lowered more rapidly than the surrounding area and form closed depressions. They range in size from shallow soil depressions a few metres in diameter and a metre deep to major landforms several kilometres in diameter and hundreds of metres in depth.

Uvalas A genetic progression can be visualized in which dolines progressively abstract surface run-off into groundwater circulation and leave networks of dry valleys as relict surface forms. The term uvala was given to a compound doline, or a chain of intersecting dolines. A karst window is similar, in that an unroofed segment of an underground stream channel becomes a surface valley in the window and passes underground again downstream.

Poljes The karst topography is on carbonate rocks that are folded and faulted, often in proximity to insoluble rocks. Structural control becomes a major factor of landscape evolution. Large blind valleys or karst valleys, enclosed by either soluble or insoluble rocks, usually elongated along tectonic axes, are called poljes.

Stalactites Stalactites develop downwards and grow from dripping walls and ceilings. The basic form is a straw stalactite.

Stalagmites It grows from the floor, their exact form (columnar or conical) depending upon drip rates, water hardness and the cave atmosphere.

12.11.6 Geomorphological Mapping in Coastal Environment

Coastal geomorphology by definition is the study of the morphological development and evolution of the coasts as it acts under the influence of waves, winds, currents and sea level changes. Bhaskara Rao and Vaidyanadhan (1975) studied the coastal features between Pudimadaka and Visakhapatnam of east coast of India. Waves are one of the most significant forces in shaping the coastline. There are two main types of wave – constructive waves and destructive waves.

Constructive waves are low-energy waves that tend to arrive at the coast at a rate of less than 8 waves per minute. Constructive waves are small in height. They have a strong swash and a weak backwash. This means that constructive waves tend to deposit material and build up a beach.

Destructive waves have much higher energy and tend to arrive at the coast at a rate of more than 8 per minute. They are much larger in height than constructive waves, often having been caused by strong winds and a large fetch. Destructive waves have a weak swash but a strong backwash so they erode the beach by pulling sand and shingle down the beach as water returns to the sea. This means that less beach is left to absorb wave energy.

12.11.6.1 Geomorphological Processes of Coastal Environment

Hydraulic action occurs when waves striking a cliff face compress air in cracks on the cliff face. This exerts pressure on the surrounding rock and can progressively splinter and remove pieces. Over time, the cracks can grow, sometimes forming a cave. The splinters fall to the seabed where they are subjected to further wave action. *Attrition* occurs when waves cause loose pieces of rock debris (scree) to collide with each other, grinding and chipping each other, progressively becoming smaller, smoother and rounder. Scree also collides with the base of the cliff face, chipping small pieces of rock from the cliff, or has a corrasion (abrasion) effect, similar to sandpapering. *Corrasion* (abrasion) occurs when waves break on cliff faces and slowly erode it. As the sea pounds cliff faces, it also uses the scree from other wave actions to batter and break off pieces of rock from higher up the cliff face which can be used for this same wave action and attrition. *Corrosion* is nothing but solution/ chemical weathering occurs when the sea's pH (anything below pH 7.0) corrodes rocks on a cliff face. Limestone cliff faces, which have a high pH, are particularly affected in this way. Wave action also increases the rate of reaction by removing the reacted material.

12.11.6.2 Denudational Landforms in Coastal Environment

Erosional coasts typically exhibit high relief and rugged topography. The different types of coastal erosional landforms are discussed below.

Sea Cliffs The most widespread landforms of erosional coasts are sea cliffs. These very steep to vertical bedrock cliffs range from only a few metres high to hundreds of metres above sea level. Cliffs that extend to the shoreline commonly have a notch cut into them where waves have battered the bedrock surface.

Wave-Cut Platforms At the base of most cliffs along a rocky coast, one finds a flat surface at about the mid-tide elevation. This is a benchlike feature called a wave-cut platform, or wave-cut bench. It is a gently sloping surface produced by wave erosion and extends outward into the sea from the base of a sea cliff. These platforms occur at some height above MSL and formed a result of constant wave action on the rocky cliffs of the head land.

Sea Stacks Erosion along rocky coasts occurs at various rates and is dependent both on the rock type and on the wave energy at a particular site. A sea stack is a small isolated usually steep-sided rocky mass or island near cliffy shore often detached from the head land by wave erosion assisted by sub-aerial weathering and are remnants of retreated sea cliff (Bloom 2003). These are erosional remnants on the horizontal wave-cut surface called sea stacks, and they provide a spectacular type of coastal landform.

Sea Caves It is a cavity or opening in the base of a sea cliff excavated by wave action along the weak zones in an easily weather-able rock (Bloom 2003). This is formed as a result of scooping of rock material by constant attack of waves on rocks.

Natural Bridge Another spectacular type of erosional landform of coastal environment is the natural bridge or sea arch, which forms as the result of different rates of erosion typically due to the varied resistance of bedrock (Bloom 2003). These archways may have an arcuate or rectangular shape, with the opening extending below water level. The height of an arch can be up to tens of metres above sea level. Most natural arches form as a narrow ridge, walled by cliffs. They become narrower from erosion, with a softer rock stratum under the cliff-forming stratum that is gradually eroding out until the rock shelters, thus formed and meet underneath the ridge.

12.11.6.3 Depositional Landforms in Coastal Environment

Depositional coasts may experience erosion at certain times and places due to such factors as storms, depletion of sediment supply, and rising sea level. The latter is a continuing problem as the mean annual temperature of the earth rises and the ice caps melt. Nevertheless, the overall, long-range tendency along these coasts is that of sediment deposition. Depositional coasts can be described in terms of three primary large-scale types: (1) deltas, (2) barrier island/estuarine systems and (3) strand plain coasts. The latter two have numerous features in common. The important depositional geomorphological features in coastal environment are discussed below.

Deltas An accumulation of sediment at the mouth of a river extending beyond the trend of the adjacent coast is called a delta. Deltas vary greatly in both size and shape, but they all require that more sediment is deposited at the river mouth than can be carried away by coastal processes. A delta also requires a shallow site for accumulation – namely, a gently sloping continental shelf.

Barrier Island/Estuarine Systems Many depositional coasts display a complex of environments and landforms that typically occur together. Irregular coasts have numerous embayments, many of which are fed by streams. Such embayments are called estuaries, and they receive much sediment due to run-off from an adjacent coastal plain. These barrier islands are typically separated from the mainland and may have lagoons, which are long, narrow, coastal bodies of water situated between the barrier and the mainland.

Strand Plain Coasts Some wave-dominated coasts do not contain estuaries and have no barrier island system. These coasts, however, do have beaches and dunes and may even have coastal marshes. The term strand plain has been applied to coasts of this sort.

Coastal Sand Dunes There are several specific landforms representative of coastal environments that are common and associated with deltas, barrier island/estuarine systems and strand plain coasts. Especially prominent among these are beaches and dunes. They are the primary landforms on barrier islands, strand plain coasts, and many deltas, particularly the wave-dominated variety.

Beaches A consideration of the beach must also include the seaward adjacent nearshore environment because the two are intimately related. The nearshore environment extends from the outer limit of the longshore bars that are usually present to the low-tide line. In areas where longshore bars are absent, it can be regarded as coincident with the surf zone. The beach extends from the low-tide line to the distinct change in slope and/or material landward of the unvegetated and active zone of sediment accumulation. It may consist of sand, gravel or even mud, though sand is the most common beach material. The thickness of the individual layers of beaches varies from a few cm to a few mm.

Coastal Dunes Immediately landward of the beach are commonly found large, linear accumulations of sand known as dunes. They form as the wind carries sediment from the beach in a landward direction and deposits it wherever an obstruction hinders further transport. Sediment supply is the key limiting factor in dune development and is the primary reason why some coastal dunes are quite small whereas others have large dunes. As per the classification of Smith (1954), dunes are transverse, crescent-shaped and parabolic in nature.

12.12 Conclusions

Geomorphological mapping and analysis of various processes in fluvial, arid, glacial, karst and coastal environments plays an important role in understanding various earth surface processes, landscape evolution, geochronology, structural characteristics, natural resources inventory and mapping and natural hazards. It involves the partitioning of the terrain into conceptual spatial units/entities based upon criteria that include morphology, genesis, composition and structure, chronology, environmental system associations and their spatial topological relationships of landforms. The data representation, collection, analysis, modelling and presentation of results in geomorphological mapping depend on the spatial and temporal scale adopted. Integration of multidisciplinary information from the field, remotely sensed data, digital elevation models, GIS and GPS improve the accuracy in geomorphological mapping. Recent advances in remote sensing, GIS and modelling capabilities of surface processes revolutionized the field of geomorphological mapping. The synoptic view provided by satellite remote sensing and digital analysis techniques in conjunction with DEMs offers technologically the appropriate approach to map distinct geomorphic units in different environments.

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