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Geospatial Technologies for Resources Planning and Management

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Chapter 1
Geospatial Technology for Geomorphology Mapping and Its Applications

G. Sreenivasan and C. S. Jha

Abstract Geomorphology, which is the scientific study of landforms, provides us with an understanding of the variety of surface and sub-surface processes that have been active on the earth's surface and have carved the variety of landforms. Geomorphology, along with ancillary information on geology, soil, vegetation, and hydrology have wide range of societal applications in various fields for developmental planning. Satellite-based geospatial technology is being used for the last five decades for carrying out geomorphological mapping and its applications. The synoptic and temporal capability of satellite remote sensing can be effectively used to depict the morphography, morphogenesis, and morphochronology of different landforms. Remote sensing is effective in providing rapid and systematic geomorphological mapping at low cost, enables change detection and mapping of landforms in dynamic landscapes at different scales and for different purposes. The advancements in geospatial technology in terms of high and very high-resolution satellite data both in optical and microwave domains, availability of high-resolution DEMs, and new data-driven techniques and algorithms of remote sensing data analysis have brought newer vistas in landform mapping, geomorphic process analysis, and its applications. Geomorphology is considered an important input for disaster risk reduction and is used widely in hazard zonation for floods and landslides. Geomorphology mapping has applications in the area of geoengineering for site assessment before undertaking any major structures such as dams, and road or railway line alignments. Geomorphological guides are one of the indicator zones for occurrence of minerals and are also useful in oil and gas exploration. They also have an important role in demarcation of hydro-geomorphic units and associated ground water potential zones. It is one of the primary inputs for coastal zone management. Geomorphic anomalies are also being widely used in archaeological and anthropological studies. Currently, imprints of geomorphic processes on any landscape are used for studying the climate change. This chapter discusses role of geospatial technology in geomorphological mapping,

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advanced techniques of mapping, different classification schemas, and some major applications of geomorphology.

Keywords Geomorphology · Landforms · Remote sensing · Classification schema · Geomorphology applications · Disaster risk reduction · Geoengineering · Palaeodrainage · Hydrogeomorphology · Geomorphic anomalies

1.1 Introduction

Earth is a dynamic planet and is continually evolving since geological past. Combination of actions by various agents such as wind, water, ice, etc. modifies the earth's surface. The present-day topography of the earth is carved out by these various processes. Geomorphology is the science dealing with the morphology of the terrain forms, their relief, and the processes that carve these forms on the earth's surface (Gregory and Lewin 2017; Lopatin and Zhirov 2017; Merriam-Webster 2021). The term Geomorphology is derived from the Greek words 'ge' meaning earth, 'morphe' meaning form, and 'logos' meaning discourse or study (Gregory and Goudie, 2011; Gregory and Lewin 2017). Geomorphology focuses on the classification of the different landforms with respect to their shape, origin, evolution, and dynamics. The geomorphic processes are either endogenic (related to tectonic, volcanic, or isostatic) or exogenic (related to external agents like wind, water, ice, etc.) (Hauber et al. 2018).

The understanding of geomorphology of an area is important for several geoengineering and developmental planning applications. This is an important planning input in addition to the information on geology, soils, hydrology, and land use. The application of geomorphology is especially well valued in the areas of disaster risk reduction, mineral exploration, groundwater prospecting, water conservation planning, pedology, land resources development, watershed management, archaeological exploration, coastal zone management, regulation zoning, urban planning, etc. Dynamics of landforms is also an important aspect to be studied. Apart from changes that happen due to endogenic and exogenic factors, changes occurring due to anthropogenic impact and climate change are very significant. Therefore, geomorphology is also an important input for environmental management and the study of environmental changes happening due to global climate change and its impact such as global warming (Slaymaker et al. 2015). Present-day, the study of geomorphology deals not only with mapping the different landforms and studying their genesis in terms of the processes that acted in carving these landforms, but it also deals with studying the present-day processes and landform changes and development of landscapes that impact a large number of environmental issues and their mitigation.

In this chapter, we discuss the utilization of geospatial technology for mapping geomorphology and its advancements and the different classification schemas. Finally, major geospatial applications of the geomorphology are discussed with few case studies.

1.2 Geomorphology Mapping

Geomorphological mapping, in a traditional way, has evolved from field mapping about a century back (Knight et al. 2011). While geomorphology dates back to Ancient Greece period, the early modern geomorphology started evolving at the end of 18th Century (Paul and Montgomery 2020). The 'cycle of erosion' model of broad-scale landscape evolution was developed by William Morris Davis during this time, popularly known as 'Davisian theory', which was later modified by Walther Penck (Oldroyd and Grapes 2008). During this time and further into the 19th Century the European Geomorphologists from Germany, Poland, Switzerland, and France did extensive mapping of geomorphology. Emphasis was given to the geomorphological process in large-scale mapping, whereas morpho-structure was given prominence in mapping carried out on medium to small-scale by countries like Russia (Verstappen, 2011). An empirical system of mapping landforms based on the slopes and flats was brought in by geomorphologists in Britain. In Australia, the Geomorphology mapping was used for resources management, wherein, a landform was considered as the functional unit of a landscape and each unit was dominated by a land area that had a similar genesis and also depicts similar topography, soils, and vegetation pattern. The quantitative and process-based geomorphology started evolving during the middle of the 20th Century, which finally lead toward the contemporary geomorphology dwelling upon the form-process relationship models (Mukhopadhyay 2003).

Though the essence of geomorphological processes is emphasized in geomorphology mapping, the importance of the form, terrain configuration, and the underlying structure is considered important for geomorphological mapping (Verstappen 2011). Thus, landforms are also considered as the distinct cartographic forms which are portrayal of the terrain structure. The inherent advantages of Remote sensing technology giving the synoptic view of the terrain in different wavelength bands, beyond visible, forms an effective tool for studying the terrain forms and their association with the surrounding ecosystem, thus giving an understanding of the processes that have acted. These advantages have led geomorphologists to use this technology in mapping. Morphochronology is another important factor embedded in geomorphology, which brings in the factor of time in the formation of landforms and their dynamics. Remote sensing, by virtue of its repetitive coverage, has an advantage in studying these dynamics of landforms.

A new era of geomorphology mapping thus began with the advent of remote sensing from aerial and space platforms. While the aerial photos have been used in studying terrain forms since the World War II times, the space remote sensing-based geomorphological mapping started during 1970s after the launch of Landsat-1, formerly known as Earth Resources Technology Satellite—ERTS-1 (Napieralski et al. 2013; Srivastav et al. 2021). Subsequent availability of large number of Remote Sensing Satellites both by India and other countries, advancements in the spatial and spectral domains, and also advancements in digital image processing techniques, led to more systematic geomorphological mapping by many countries at different scales.

Scale of mapping has an impact on the way we perceive and describe a landform. Landforms at different scales, will in a way, describe large landforms seen at a smaller scale to small landforms (which are constituents of larger landforms) seen at large scales. For example, a pediment-Inselberg-Complex is a large landform usually mapped at a smaller scale, whereas the Inselbergs which are smaller features can be mapped at a large-scale. Thus, remote sensing satellites, by virtue of providing satellite images at different spatial resolutions, will help us in providing the required technology for carrying out geomorphological mapping using a hierarchical system describing landforms at different levels (GSI and NRSC 2010).

1.3 Role of Geospatial Technology in Geomorphology Mapping

The geospatial technology mainly constitutes of the Remote Sensing, Geographical Information System (GIS), and Global Positioning System (GPS). Remote sensing, which employs electromagnetic radiation (EMR) to acquire information about the earth's surface features from aerial or satellite platforms, mainly works on the principle of interaction of electromagnetic energy with the material on the earth's surface. The spectral response patterns generated from the interaction of EMR with earth's surface aid in the detection, identification, and analysis of earth's surface material.

Geospatial technology has been deeply linked with study of geomorphology since the advent of these technologies during mid-twentieth Century. Since then, these technologies have been extensively used in many geomorphological studies for mapping, analysis, and measurement of the geomorphological forms and processes. With the continual advancements in the geospatial tools and techniques, especially the remote sensing image processing and photogrammetric techniques, and also availability of the Digital Elevation Models (DEMs) from space, the quantification of landforms and detection of geomorphic changes has become possible. In this section, the role of geospatial technology, including the conventional methods, digital techniques, and advanced methods of mapping are discussed.

1.3.1 Conventional Techniques of Photo Interpretation

The use of remote sensing technology for geomorphology mapping initiated with visual interpretation of aerial photographs. Landform mapping from aerial photographs was done using both qualitative interpretation as well as quantitative stereoscopic methods to measure the landforms by 3-D visualization, which was possible by viewing two aerial photos of the terrain from two different vantage points simultaneously. The qualitative interpretation usually required distinguishing and identification of the terrain/relief features, drainage, and cultural features, and knowledge of the geomorphology to analyze the relief features and drainage patterns for interpreting different landform features. Some mapping techniques depended on using other data like topographic maps and identifying and demarcating boundaries of landforms using contour lines for bringing out the actual relief. As aerial photographs are having inherently high spatial resolution, large-scale geomorphic maps features were extracted and depicted in the maps. However, the large spatial resolution is compensated by the small area coverage and thus preparation of local area maps. Bringing aerial photographs onto a georeferenced framework was also a very cumbersome exercise. Therefore, the initial efforts of interpreting aerial photographs for preparing geomorphological maps were limited to local areas and lacked the regional perspective to the geomorphological mapping. Especially, mapping large area features like mountains and large rivers and associated landforms required large number of aerial photographs to be stitched, which was time-consuming and expensive. The aerial photographs also had the limitation of not being able to image the earth's surface in many numbers of spectral bands.

The limitations of the aerial photographs in geomorphological mapping were quickly overcome by the advent of the satellite platforms for remote sensing. The conventional techniques of remote sensing imagery interpretation for mapping geomorphology used hardcopy photos or satellite images, which were printed after applying required photo/image corrections and enhancements. Visual interpretation of images requires keen observation and understanding of the basic elements of photo interpretation, viz., tone, color, texture, pattern, shape, size, shadow, association, location of the feature, and the height or depth and related aspects. These elements of visual interpretation are already well described and understood by remote sensing professionals (Jenson 2007; Asokan et al. 2020). Though for interpreting any feature on a photo or imagery use of all these elements is not possible at all times, a combined use of at least some of these will guide an experienced interpreter to arrive at a fairly correct conclusion about the feature or form. Additionally, for mapping geomorphology through visual interpretation, knowledge of other terrain features such as drainage patterns, the geology of the area, and the climatic environment are important to arrive at the correct understanding of the geomorphic process and interpretation of the landform.

1.3.2 Analysis and Information Extraction from Digital Remote Sensing Data

The development of the advanced computational techniques and image processing algorithms made a revolutionary change in remote sensing techniques as well. Remote sensing progressed from use of hard copy images to processing of digital data. This had advantages for information extraction from remote sensing images by applying corrections to the raw image data for improving the radiometry of the images, geometric correction of the images for tying them precisely to any geographical point on the earth's surface, applying area-specific enhancements to images and generation of mosaics of large areas for preparing seamless databases.

As a part of radiometric corrections, pixel digital value is converted to at-sensor radiance by subtraction of the atmospheric contribution, topographic normalization, and sensor calibration. The calibration of images has an important impact on the information extraction from the images by giving a correct spectral response pattern for proper identification and classification of the earth's surface features and forms (Sreenivasan and Krishna Murthy 2018). Further, it will allow comparison of any feature's continuity from one image to another, especially when we use large number of images taken over different time periods for mapping geomorphology over a large study area. This calibration is also important when we are monitoring geomorphological changes over a long period of time. By doing geometric correction, the systematic and nonsystematic distortions and relief displacement is corrected and will result in adding the map projections and ground coordinate system with a local or global ellipsoid.

The image enhancement is an important step in processing digital remote sensing images before we can start mapping the geomorphology. It improves the quality of the image and information content from the original images and brings out landform information hidden in the data. The most commonly used digital image processing tasks include contrast enhancement, edge enhancement, spatial filtering, band combinations, principal component analysis, and band ratios (Haldar 2018; Sreenivasan and Krishna Murthy 2018). Contrast enhancement expands the gray levels in the original data and brings about better contrast between closely resembling features and the background. For instance, the boundaries between the pediplain and pediments, and the paleochannel features which are difficult to discern in original data will get enhanced after applying contrast stretch to the satellite images, and enable extraction of these features in a more precise way. Spatial filtering and edge enhancement are more commonly used for sharpening the boundaries of features and enhancing linear features like lineaments and structures, which have controlled the formation of the geomorphic forms.

Band combinations are more pertinent when using multi-spectral data involving number of bands and diverse information content being provided by image at each wavelength band. The usually used band combination is standardized and is called False Color Composite (FCC) which has combination of Infrared, Red, and Green image bands given the colors of Red, Green, and Blue in the RGB color model, and has been extensively used for landform identification and mapping (Fig. 1.1). FCC is considered standard as it has been found to give the maximum information of the earth's surface features compared to the natural color composites (Haldar 2018). This is also because the land cover is prominently brought out in the standard FCC. The geomorphology has a significant influence on the land cover pattern of an area and is an important guiding factor in differentiating landforms.

However, band combinations with other image bands including Shortwave Infrared (SWIR), have given better information for specific landforms. A good example of this is the mapping of fluvial landforms such as flood plains, meander

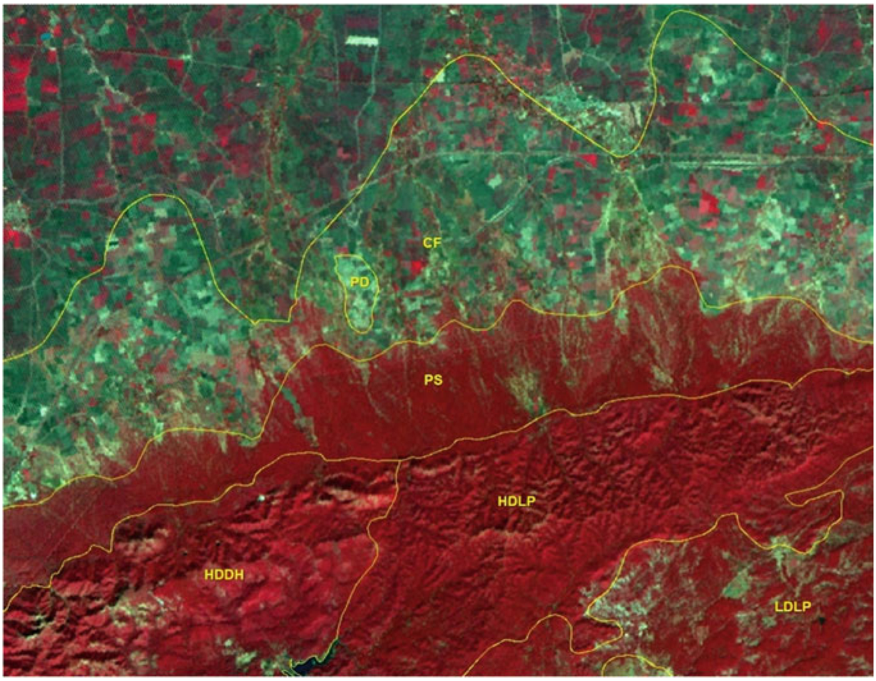

Fig. 1.1 Interpretation of denudational landforms from an area in Hoshangabad district of Madhya Pradesh from a standard False-color composite (FCC) derived from IRS-P6 LISS-III sensor with RGB: IR, R, G. The landform labels are: CF-colluvial fan, PS-piedmont slope, PD-pediment, HDDH-highly dissected denudational hill, HDLP-highly dissected lower plateau, LDLP-low dissected lower plateau

scars, and point bars (Fig. 1.2). The reason for better contrast of the fluvial landforms in the color composite images with SWIR as one of the bands is that these landforms usually contain more moisture than background, and get highlighted by contrastingly darker tones because of extreme absorption in SWIR wavelength in the presence of water content (Tian and Philpot 2015).

Image enhancements such as principal component analysis (PCA), and the color composites generated from the first few principal components (PC) bring out perceptible contrast in landforms, depending on the terrain and geomorphic landscape being mapped. An example of a PCA generated and the color composite of first, second and third PC in RGB for mapping the Quaternary geomorphic units is shown in Fig. 1.3. Good differentiation of alluvial fans formed over the different periods is contrastingly brought out in the images. This helped in detailed mapping of the different alluvial fans formed in the region, and this could further be an important input for morpho-chronological sequencing of the alluvial fans.

The selection of the right season of satellite data is very important in geomorphological mapping as this has a bearing on the interpretability of the landform features. The selection of the right season satellite data is dependent on several factors, like

Fig. 1.2 Use of SWIR band in deriving a color composite highlights the fluvial landforms along the Tawa river in Madhya Pradesh. The color composite is derived using SWIR, IR, and Red bands were given to RGB. The landform labels are: PB-point bar, NL-Natural levee

the target landforms, the topography of area, and the land cover pattern. Though it is a well-accepted practice to use summer season data for interpreting geomorphic features, it may not be always true.

In general, it is observed that certain landforms are better discernable on a particular season data, whereas some landforms get subdued. Some landforms may be better discernable using data of summer season, for e.g., the palaeochannels, whereas some other landforms may be better discernable using winter season data, for e.g., the denudational landforms, as demonstrated by the example shown in Fig. 1.4. Therefore, it is desirable to use multi-temporal satellite images spanning across two or more seasons of the year to derive complimentary information, which may be missing in a single dataset.

After image enhancement, the extraction of geomorphology information is done using various techniques ranging from manual on-screen digitization using the GIS software to semi-automatic and automatic techniques using rule-based classifiers. Though more research is now toward quantitative geomorphology, however, for preparing operational and baseline geomorphological maps for large areas, we still

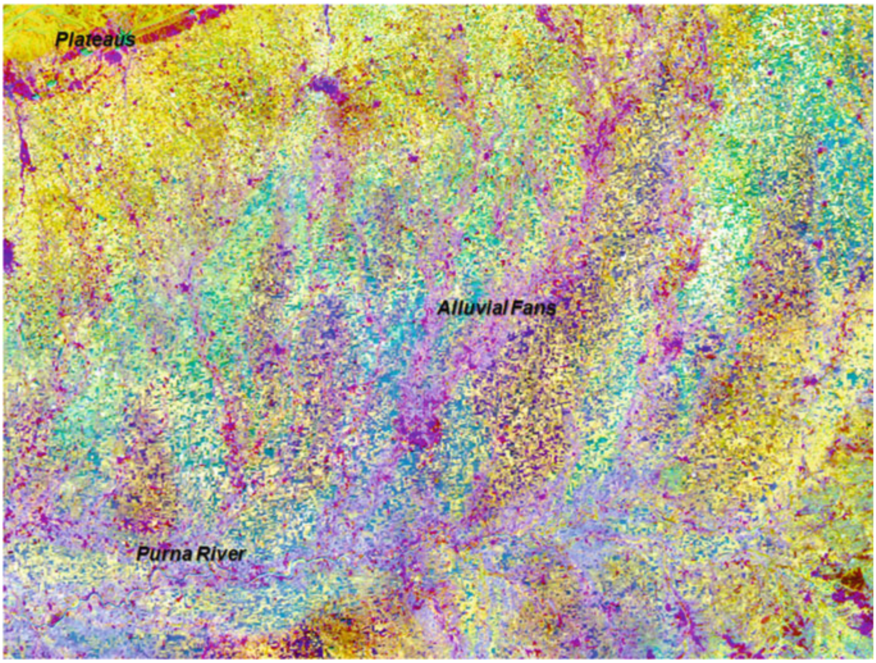

Fig. 1.3 Principal component analysis and the combination of the PC1, PC2, and PC3 in a color composite help in differentiation of alluvial fans formed over the different periods and is an input for morpho-chronological sequencing of the alluvial fans

continue to adopt on-screen interpretation of the landforms from satellite data, considering and integrating additional information derived from other terrain and natural resources datasets (GSI and NRSC 2010; Kumar et al. 2013; GSI 2014; Gnanachandrasamy et al. 2018; Sreenivasan and Krishna Murthy 2018). This process involves loading enhanced satellite images on the computer screens in any GIS package and carrying out digitization using the GIS tools. The interpreter is expected to have knowledge of geomorphology and skills in remote sensing image interpretation. The advantage of this approach is that the professional can use all his experience and intuitive knowledge about the area and modulate the information extraction accordingly.

Additional ancillary information including geology, geological structures, terrain, slope, drainage, and land use and cover in the form of GIS layers is usually overlaid for analysis and improvising the geomorphology mapping. Use of any supplementary data, such as geophysical data, will provide additional information on surface and sub-surface form, composition, and structure and will help in better deciphering the landforms and processes. Use of advanced techniques like object-based image analysis and machine learning-based classifiers are also being attempted. A broad process flow for preparation of geomorphological maps is given in Fig. 1.5. Description of advanced methods of geomorphology mapping is given in the further sections.

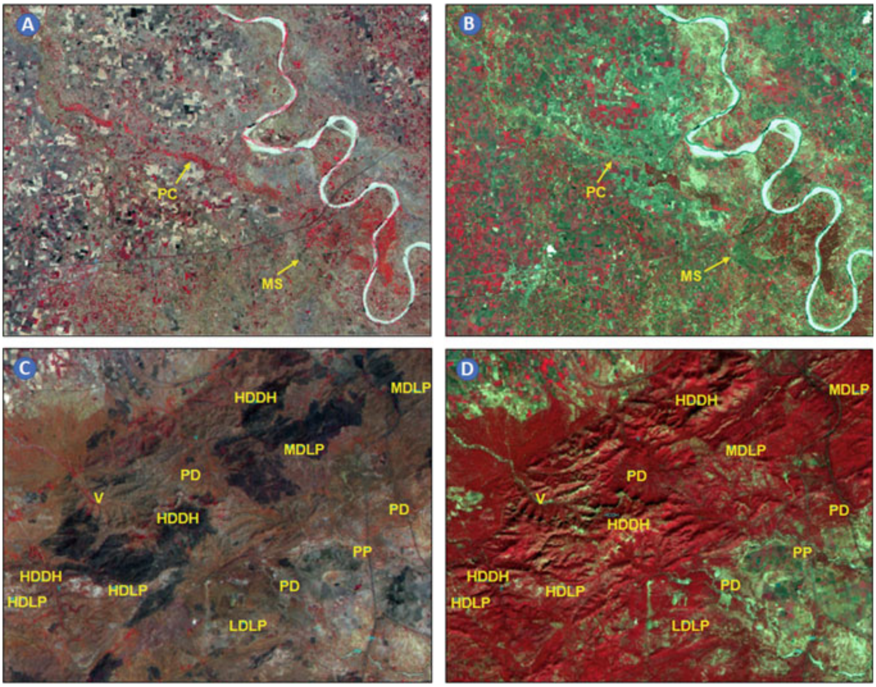

Fig. 1.4 Influence of time-period of satellite data on the interpretability of the landforms. The palaeochannel (PC) is seen very conspicuously in the satellite image of IRS Resourcesat LISS-III sensor of April month (A), whereas it is not interpretable in the satellite data of the same sensor acquired in December month (B). The meander scar (MS) is better interpreted in data acquired in December (B) than in the April (A). Similarly, the denudational landforms viz., highly dissected denudational hills (HDDH), highly dissected lower plateaus (HDLP), moderately dissected lower plateau (MDLP), low dissected lower plateau (LDLP), valley (V), pediment (PD), and pediplain (PP) are not interpretable from the satellite image of IRS Resourcesat LISS-III sensor of April month (C), whereas these landforms and the details like dissection pattern are very clearly visible in the satellite data acquired in December month (D)

1.3.2.1 Optical Remote Sensing

The remote sensing in optical region includes satellite data imaged in the visible and infrared regions, including SWIR and Thermal Infrared (TIR) wavelength regions. Presently, optical remote sensing data is available from a number of satellites and sensors, with varied spectral and spatial capabilities suitable for mapping geomorphology. The selection of the type of satellite/sensor data for mapping geomorphology can be made based on the type of terrain and features being mapped and the required scale of mapping. Satellite images having spatial resolutions from ~1 to ~188 m have been extensively used for mapping geomorphology at various scales of mapping ranging from 1:2 Million scales to 1:10,000 scale. For regional-scale geomorphological map preparation low spatial resolution data from ~188 to ~70 m

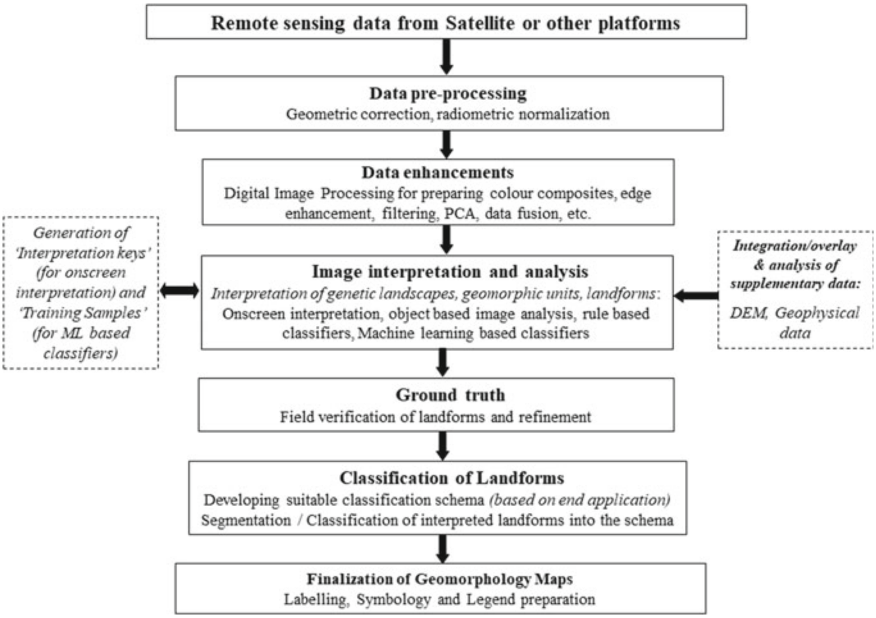

Fig. 1.5 Process flow for preparation of geomorphological maps using integrated geospatial technology

is ideal, and for preparing moderate scale maps satellite data with ~23 to ~10 m is useful, whereas satellite data of ~6 to ~1 m is ideal for detailed landform mapping for a small area for the purposes of micro-level developmental planning (Sreenivasan and Krishna Murthy 2018).

Indian Remote Sensing Satellite (IRS) provides Earth Observation remote sensing data at different spatial, spectral, and temporal resolutions with spectral dimensions covering entire EMR in the Optical region with a series of satellites starting from IRS-1A to the recent Resourcesat-2A and Cartosat series of satellite (Jaiswal and Bhatawdekar 2018) (Table 1.1). These satellite sensors provide images with spatial resolutions ranging from 1 km to better than 1 m, and radiometric resolution ranging from 7 to 12 bits. With flexible imaging capabilities, these data have been extensively used for geomorphology mapping at regional level to village level for detailed landform mapping. Additionally, a number of satellite sensors from other space-faring nations of the world are available for geomorphological mapping, providing remote sensing data at varied spatial and temporal resolutions (Table 1.1).

The spectral variability from visible, near-infrared to shortwave infrared has been fully exploited for different types of landforms detection. The selection of spectral bands for geomorphological mapping depends on the morphogenetic regime that is being mapped. Though usually the Green and Red wavelengths in the visible region, and the near-infrared wavelengths in infrared region of the EMR are suitable to map landforms sculpted due to most processes, certain wavelength bands are useful

Table 1.1 Optical remote sensing satellites-sensors available for geomorphology studies

Satellites	Sensor	Spatial resolution (in meters)	Revisit time (days)	Scales of geomorphology mapping
RESOURCESAT-1/2, IRS-1C/IRS-1D	LISS-III	23.5	5	1:50,000
RESOURCESAT-1/2	LISS-IV	5.8	5	1:25,000–1:15,000
RESOURCESAT-1/2	AWiFS	56	5	1:250,000
CARTOSAT-3	MX	1.12	–	1:5000–1:3000
CARTOSAT-2C, D, E, F	HRMX	~2.0	4	1:10,000–1:5000
CARTOSAT-1	PAN	2.5	5	1:10,000–1:5000
LANDSAT-9	OLI-2	30	16	1:50,000
LANDSAT-9	TIRS-2	100		1:500,000–1:250,000
LANDSAT-8	OLI-1	100	16	1:250,000
LANDSAT-8	TIRS-1	30	16	1:250,000
SENTINEL-3	OLCI	300	2–4	1:500,000–1:10,00,000
SENTINEL-2A/2B	MSI	10–20	5	1:50,000–1:20,000
SPOT-7	PAN	1.5	1–5	1:10,000–1:3000
SPOT-7	MS	6.0	1–5	1:25,000–1:12,000
PLANET LAB SKYSAT-C	MS	0.5	5	1:5000–1:2000
PLEIADES NEO-3/4	MS	1.2	Daily	1:5000–1:3000
PLEIADES 1A/1B	MS	2.0	Daily	1:8000–1:4000
KOMPSAT-3A	MS	2.2	1.4	1:10,000–1:5000
KOMPSAT-3	MS	2.8	1.4	1:15,000–1:10,000
WORLDVIEW-4/3	MS	1.24	<1	1:10,000–1:3000
WORLDVIEW-4/3	SWIR	3.70	<1	1:20,000–1:10,000
RAPID EYE	MS	6.5	1–5.5	
TERRA-ASTER	VNIR	15	16	1:50,000–1:25,000
TERRA-ASTER	SWIR	30	16	1:50,000
TERRA-ASTER	TIR	90	16	1:250,000
CBERS-4	MUXCam	20	26	1:50,000
CBERS-4	IRS	40	26	1:250,000–1:50,000
CBERS-4	WFI	64	5	1:250,000–1:150,000
SUPER VIEW-1	MS	2.0	2	1:8000–1:4000
QUICKBIRD	MS	2.62	1–3.5	1:10,000–1:5000
GEOEYE-1	MS	1.84	3	1:10,000–1:4000
GAOFEN-2	MS	3.2	5	1:20,000–1:10,000

(continued)

Table 1.1 (continued)

Satellites	Sensor	Spatial resolution (in meters)	Revisit time (days)	Scales of geomorphology mapping
TRIPLESAT	MS	3.2	Daily	1:20,000–1:10,000
IRS-1C/IRS-1D	PAN	5.8	5	1:25,000–1:12,000
LANDSAT-7	ETM + (V, NIR)	30	16	1:100,000–1:50,000
LANDSAT-7	ETM + (TIR)	60	16	1:250,000–1:150,000
IKONOS	MS	3.28	3–5	1:20,000–1:10,000
SPOT-5	MS-NIR/SWIR	10 (NIR)/20 (SWIR)	2–3	1:25,000–1:15,000
LANDSAT-4 & 5	TM (V, NIR)	30	16	1:100,000–1:50,000
LANDSAT-4 & 5	TM (TIR)	120	16	1:500,000–1:250,000
IRS-1A/IRS-1B	LISS-I	72.5	22	1:250,000–1:150,000
IRS-1A/IRS-1B	LISS-II	36.25	22	1:100,000–1:50,000
LANDSAT-1,2,3,4,5	MSS	60	18	1:250,000–1:150,000

for landforms formed due to specific agents and processes. For instance, shortwave infrared and mid-infrared in a combination with other bands are more suitable for mapping fluvial landforms, whereas, the thermal infrared may be of specific aid in mapping active volcanic landforms.

The temporal nature of satellite remote sensing is exploited in studying the dynamics of geomorphic processes and the resultant landforms. Each satellite sensor has a specific revisit period. As a virtue of this capability, the same site is imaged after a fixed time-period. Presently satellites are available with temporal resolution ranging from 1 to 22 days (Jaiswal and Bhatawdekar 2018). This enables monitoring of any change that is happening on the earth's surface. The time scale of change for different landforms vary, and range from tens and hundreds of years for denudational and depositional landforms to just few days for landforms formed due to endogenic processes like volcanism, diastrophism, and the events caused by their impacts like earthquakes, landslides, and change in river courses, and the natural disasters like floods and cyclones.

1.3.2.2 Radar Remote Sensing

The microwave region of the EMR provides additional advantages for remote sensing of geomorphology. Active sensors like Synthetic Aperture Radar (SAR) are more widely used for geomorphological mapping due to their high spatial resolution compared to the passive microwave sensors.

Apart from the general advantages of all-weather imaging, which is beneficial for all-natural resources applications, geomorphological studies especially benefit from the side-looking geometry of the Synthetic Aperture Radar (SAR) sensors and also the sub-surface penetration capability of the SAR signals. The sensitiveness of radar backscatter signal to surface roughness, slope and relief, and moisture (dielectric constant) also are advantageous to geomorphologists in studying landforms, as these inherent properties of radar indirectly give information on the terrain structure and physical properties of surface material. These significantly indicate the type of processes the terrain has undergone in the past that led to the sculpting of the present landforms. The relief and slope, which are very important to perceive and label a landform are not directly sensed from the optical satellite images, whereas in the SAR images the side-looking geometry brings in the shadow effect, due to which the relative differences in relief and slope of the terrain gets clearly highlighted. Therefore, many times SAR data fused with optical data may be more useful in bringing out better contrast of geomorphic forms, than using only optical data of the same area (Fig. 1.6).

The sub-surface penetration capability of the radar is a function of frequency of the radar signal. The larger wavelength bands like L-band (15–30 cm) and P-band (30–100 cm) have better penetration to shallow depth-dependent on the dryness of the sub-stratum. Several active microwave remote sensing satellites are presently available like RISAT series from India, ALOS from Japan, ENVISAT and Sentinel-1 from European Union, Radarsat from Canada, Terra-SAR, and TanDEM-X from Germany, and KOMPSAT-5 from South Korea. Except ALOS all other satellites are C-Band or X-band SAR. Even though the penetration capability of C-band SAR is limited, still it has been used for geomorphology mapping as a standalone as well as complementary dataset along with the optical remote sensing data. SAR has been more advantageously exploited in geomorphology for mapping the shallow buried features such as paleochannels of lost river systems (Gupta et al. 2011). The penetration capability of SAR helps as well in mapping shallow buried pediments, and relict valleys in arid terrains (Fig. 1.7).

1.3.2.3 Digital Elevation Models

The terrain topographical information is important requirement for mapping geomorphology. In the initial days of the geomorphological mapping using satellite data, topographical information available from topographic contour maps was used as a reference dataset. Interpretation of remote sensing images for geomorphological classification is usually descriptive, while quantitative measurements, usually called morphometry, were added through field surveys. But with the development of the Digital Elevation Models (DEMs) and availability of GIS Spatial Analyst tools, DEMs are being directly used for analysis of terrain morphometric conditions, which directly benefits the geomorphic form and process study.

The first Digital Elevation Models (DEM), generated using the topographical maps derived through survey techniques, were available during 1970s. The first satellite-derived digital elevation data was available by the year 2000 with the availability of Shuttle Radar Topography Mission (SRTM) DEM. Presently there are various types of DEM's available from space platforms (Mudd 2020) developed

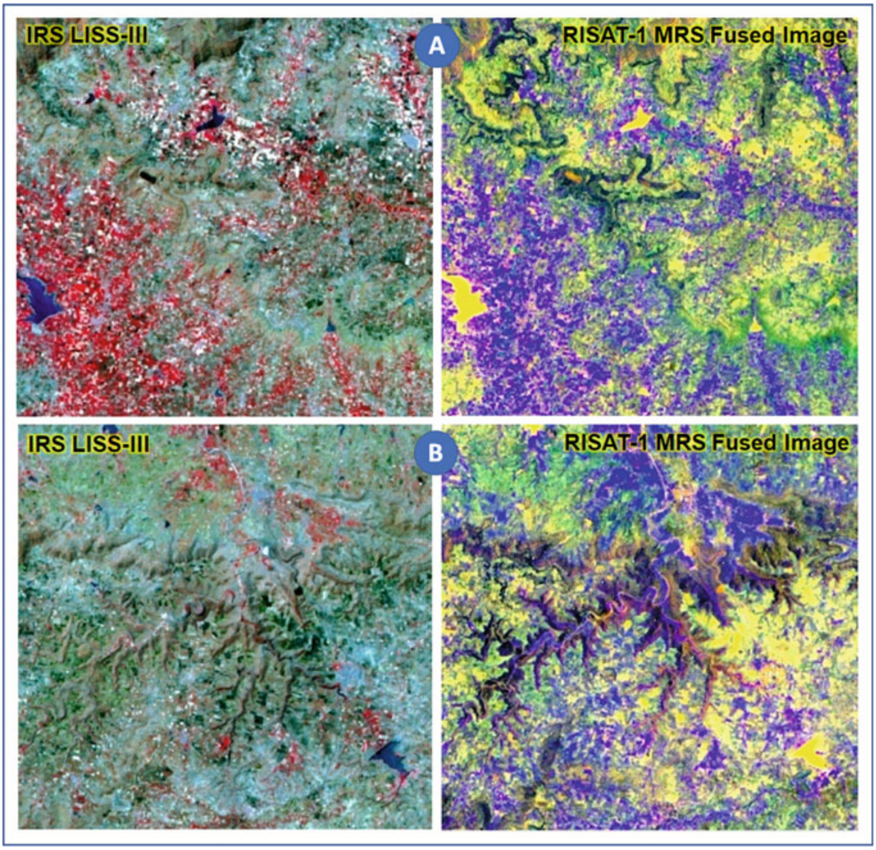

Fig. 1.6 Comparison of the landform interpretation from optical and microwave SAR satellite data. (A) The plateaus, plateaus margins, and scarps are better seen in the RISAT-1 MRS SAR data fused with multi-spectral optical data than the optical data alone from IRS LISS-III sensor. (B) The dissection pattern in the plateaus is more clearly highlighted in the RISAT-1 MRS fused microwave SAR data than in the IRS LISS-III image

through either optical stereoscopic data through photogrammetric techniques or through radar data through interferometric techniques. CartoDEM of 10 m resolution from ISRO, ASTER DEM of 30 m resolution jointly by Japan and USA, ALOS World 3D (AW3D and AW3D30) of 5 and 30 m resolution from JAXA, TanDEM-X of 12 m resolution from DLR Germany, MERIT DEM which is a combination of SRTM and AW3D30 of 30 m resolution are a few global DEMs useful for geomorphological studies (Mudd 2020).

The basic information used from the DEM in mapping landforms are the derivatives of DEM, viz., slope, aspect, and curvature. These are used for analyzing the morphometric conditions and dividing the land into discrete surface forms for quantitative depiction of land topography, which led to the development of the field

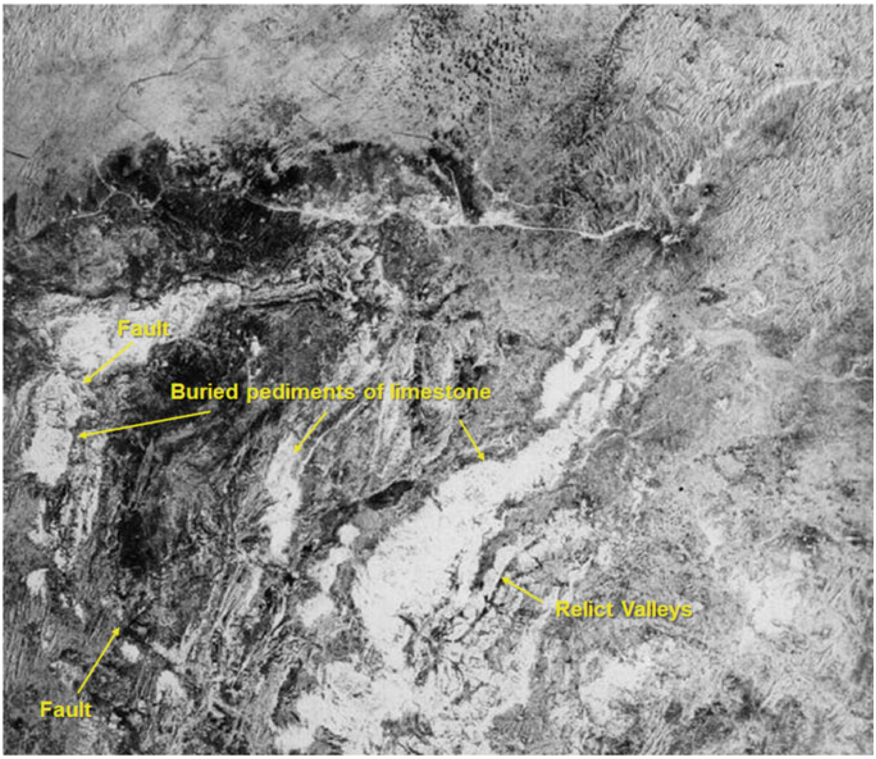

Fig. 1.7 Sub-surface penetration capability of SAR helps in bringing out shallow buried landforms. Here the buried pediments and sub-surface relict valleys in arid Thar Desert region are brought out conspicuously in the ALOS PALSAR L-band SAR data due to the penetration capability of the SAR

of geomorphometry (Napieralski et al. 2013). The landform morphometry data is mainly used for quantitative analysis of size and shape of the landforms, which helps in delimitation of the landscapes at higher level formed under a specific process, for example, the large fluvial landscapes, into smaller homogeneous land features which are then grouped together into landforms (Evans 2012).

Morphometric analysis of landforms using high-resolution DEMs is more applied aspect, than simply mapping the landforms, and has practical applications in several other areas. Geomorphometry of glacial cirque, for instance, could provide indications on the paleoenvironment and paleoclimate during the glaciation period during which the cirque has developed (Barr and Spagnolo 2015), and also be useful for hydrological modeling and natural hazard management (Mudd 2020). DEM is also utilized in geomorphological mapping as a DTM model for visualization of the terrain in 3D perspective for better assessment of the morphology of the landforms (Fig. 1.8), which would help in visualizing the landforms in 3D perspective, that will

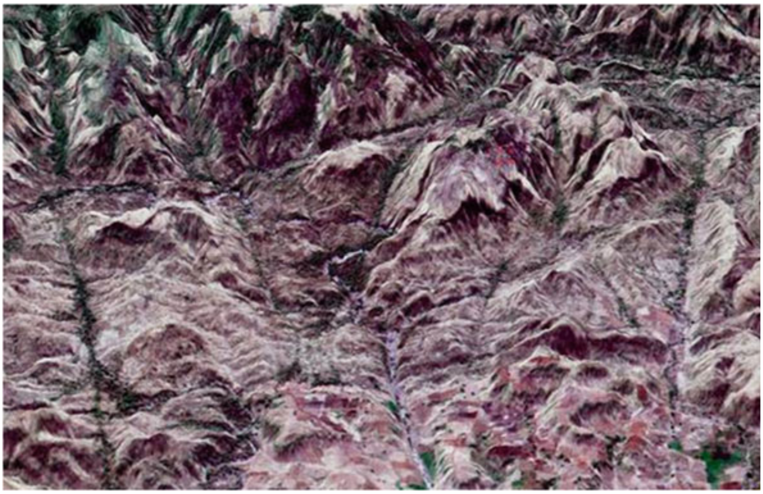

Fig. 1.8 Digital terrain model of an area in Amravati district, Maharashtra. The geomorphic forms, viz., the plateaus and constituent mesas and buttes, along with the structural controls, are better highlighted in the DTM

help in better identification of landforms and preparing geomorphology maps with better thematic accuracy.

1.3.3 Advanced Methods of Geomorphology Mapping

Geomorphology mapping from remote sensing has always been a challenging task. The visual interpretation of satellite images by referring to large number of other ancillary information layers on terrain characteristics, hydrology, land cover, vegetation, soils, geology, structures, etc. has been cumbersome and highly time-consuming job. It also involves an element of subjectivity, which depends on the knowledge and skill of the professional who is carrying out the mapping. Another aspect that needs consideration is that the landform boundaries are not discrete, but are mostly transitional, this is more so for landforms in plains than in mountainous terrain (Eisank et al. 2010; Napieralski et al. 2013). These challenges and limitations are now being overcome with the advancements in remote sensing technology and image analysis techniques. These include availability of very high-resolution image datasets and DEMs from satellite, UAV platform, and LiDAR technology; and image analysis techniques such as object-based classifiers, machine learning algorithms, and data-driven approaches for semi-automatic and automatic mapping of geomorphology.

With the availability of different resolution DEMs, more efforts are presently seen to exploit the terrain segmentation using object-based classifiers. The terrain factors are optimized using other parameters like texture metrics which go as input to rule-based classifiers or decision tree classifiers (Na et al. 2021). The LiDAR is the other technology that is being used for tectonic geomorphological analysis and specifically geomorphometry of micro-geomorphic units. Specifically, the DTM that is generated from LiDAR and other optical and radar remote sensing datasets are useful in precisely limiting the boundaries of geomorphic units (Bufalini et al. 2021), which otherwise are arbitrary if they are drawn from mere remote sensing image interpretation in the optical or microwave domains.

Another comprehensive tool for geomorphological applications that provides hyper-scale three-dimensional (3D) landform models is the structure from motion (SfM) photogrammetry, which is an amalgamation of techniques from photogrammetry and computer vision (Eltner and Sofia 2020). SfM provides very high-resolution topographic dataset with high temporal frequency and accuracies comparable to airborne laser scanners, and thus gives detailed topographic characterization of the surface to the extent of distinguishing micro-geomorphic forms such as granite tors (Kasprzak et al. 2018; Eltner and Sofia 2020). The very high-resolution images from satellite and UAV platforms, high-resolution DEMs from LiDAR, optical and radar data, and SfM technologies separately or in combination are useful for automatic detection and morphological analysis of many other micro-geomorphic forms and processes, for instance, gully formation, their evolution, and monitoring for estimation of their sediment budget and susceptibility mapping (Arabameri et al. 2020; Niculiță et al. 2020), quantifying landform changes (Chirico et al. 2021), mapping coastal landforms and their dynamics (Medjkane et al. 2018; Taddia et al. 2019; Yulianto et al. 2019; Singh et al. 2020b), mapping glacial geomorphology (Benjamin et al. 2018). In the fluvial geomorphology domain, the Airborne Laser Topo Bathymetry (ALTB) has emerged as a new tool for high-resolution mapping of the 3D channel geometry, and erosion and sedimentation mapping, though ALTB is still not an operational remote sensing technique for regular geomorphological analysis (Laguea and Feldmann 2020).

Scale of landforms is an important parameter in selecting the appropriate datasets and classification approaches, which would bring in better accuracies in the final classified maps. Wavelet decomposition techniques such as Discrete wavelet transform (DWT) method are applied on DEMs for discretizing the terrain texture and further classifying the landforms using machine learning-based classifiers like Random Forest (Xu et al. 2021). These automatic landform classification techniques are able to bring in more accurate landform classification giving appropriate consideration to the scale of the landforms.

Recently, data-driven algorithms such as Direct Sampling and Random Forest (RF) are successfully utilized for semi-automatic regional-scale geomorphological mapping, especially for mountainous areas (Giaccone et al. 2021), where elevation and relief are important factors in defining the landform morphology. In addition to RF, other Machine Learning (ML) algorithms such as Support Vector Machines (SVM), Logistic Regression (LR) and Boosted Regression Trees (BRT), genetic algorithm (GA), extreme gradient boosting machine (XGBoost), and ensemble of ML algorithms are utilized for different applied aspects of geomorphology, for instance, landslide and debris flow susceptibility modeling (Pham et al. 2018; Kavzoglu et al

2019; Sahin et al. 2020; Xiong et al. 2020), and mapping gully erosion susceptibility (Arabameri et al. 2021).

Advancement in geospatial technology has also brought in new tools and methods for studying dynamics of landforms and monitoring landforms changes. The changes in landforms due to geomorphic processes may be very minor in scale most of the time, and therefore it had always been a challenge to detect and analyze these minor changes. The capability to measure and monitor surface topographical changes at different spatial and temporal scales has improved with the availability of advanced geospatial techniques such as Differential Interferometric Synthetic Aperture Radar (DInSAR), LiDAR and its elevation products, Differential Global Positioning System (DGPS), and UAV photogrammetry and SfM (Gutiérrez and Soldati 2018; Abdelkareem et al. 2020; Fedele et al. 2021). These techniques have been successfully used for geomorphic dynamics of volcanic fumaroles (Fedele et al. 2021), desert landforms (Abdelkareem et al. 2020), and coastal geomorphology (Medjkane et al. 2018; Godfrey et al. 2020).

The present trend is combining multi-source datasets including remote sensing images from satellite and UAV platforms, data from geophysical surveys such as Electrical Resistivity Tomography (ERT) and DEMs, through geospatial modeling and ensemble of Artificial Intelligence (AI) and Machine Learning (ML) algorithms for achieving mapping, monitoring and modeling of geomorphological landforms and processes (Metelka et al. 2018; Kasprzak et al. 2019; Chirico et al. 2021).

Though these advancements in geospatial technology have leapfrogged geomorphology mapping into more of an analytical and quantitative science, it is important to note that the traditional satellite image interpretation still remains the fundamental technique, due to the fact that geomorphology requires more intricate unraveling of the local details considering the connections with contiguous geomorphic ecosystems, for building a holistic form-structure-process relationship in a regional perspective, especially so for undertaking operational programs.

1.4 Classification Schemas

Development of geomorphological mapping in different countries followed systems of categorizing landforms considering mainly parameters such as morphology, morpho-structure morphogenesis, and morphochronology. The simplest form of landform classification used the morphology, which considered the form or shape of the landforms, and was based on descriptive morpho-graphic features. With the development of the modern concepts of geomorphology, the emphasis on including process or genesis of the landforms in detailed geomorphological maps took a place in the classification systems, whereas the morpho-structure was considered at the highest level of the classification in the small-scale geomorphology maps (Verstappen 2011).

The initial efforts of standardization of geomorphological maps were put by International Geographical Union (IGU) Commission on Geomorphological Survey and Mapping and detailed geomorphological mapping and legend for the International Geomorphological Map for medium scale geomorphological maps were published by a joint consortium of Italy, Poland, Russia, Italy, Germany, Canada, Netherlands, Switzerland, and Britain (Hayden 1986). These standards had emphasized the morpho-structure at the highest level as the basis of the geomorphological classification.

Later on, several geomorphological classification systems evolved. Some geomorphology classification systems were developed for addressing specific geomorphic landscapes, for instance, geomorphic classification for "fluvial geomorphic landscapes" specifically targeting the rivers and streams (Kondolf et al. 2016; Horacio et al. 2017); "standardized geomorphic classification for seafloors" (Goes et al. 2019; Sowers et al. 2020), classification of wetlands (Grenfell et al. 2019). While some other geomorphic classifications systems were developed aiming specific applications, for instance, characterizing forest ecological map units, groundwater prospects identification, landslide hazard zonation, river system management, digital soil mapping, to name a few. One such geomorphic classification was developed during 1995–1998 by the USDA Forest Service. The main purpose of this classification system was to link the ecological unit as well as the aquatic units with the "National Hierarchical Framework" of USDA (United States Forest Service 1998). This classification system considered four components, viz., "Geomorphic Process, Landform, Morphometry and Geomorphic Generation". Another geomorphologic classification system has been developed aimed at "geopedologic mapping" and "digital soil mapping". In this classification system, the "geoforms" are hierarchically structured into six nested levels, giving emphasis to structure of the landscape and morphogenic agents (Zinck 2016).

In India, few attempts have been made to bring out a regional classification system addressing all the aspects of the landform evolution initially by Geological Survey of India (GSI) and later by ISRO (GSI and NRSC, 2010; GSI 2014; Srivastav et al. 2021). The geomorphological mapping carried out by ISRO under the Integrated Mission for Sustainable development (IMSD) during 1992–1996 adopted the hydrogeomorphic-based classification approach (NRSA 1995). The mapping schema lay prominence on identification of landform units with end utility of the maps for groundwater exploration. The legend of these maps depicted structure and lithology apart from the geomorphic units and landforms. The schema was based on the origin of the landforms and the processes were arranged in chronological sequence. This classification schema was further modified under the National Natural Resources Information System (NRIS) program initiated by ISRO during 1998 (Shah and Thakkar 2008). This program developed a geomorphological classification schema that put geomorphic units at the first level, landform at the second, and form based on morpho-structure at the third level. The system is conceptualized in a way to regroup the landform classes at different levels for easy upscaling or generalization.

Another effort for developing a national-level geomorphic classification was made under the Rajiv Gandhi National Drinking Water Mission, which was for the specific application of applying geomorphology for groundwater prospect zones mapping. This classification system categorized the landforms into 116 types considering morphology, weathering, erosion, and dissection (Das et al. 2021). The classification system considered the broad physiography at the first level categorizing the landscape into hills, plateaus, piedmont zones, plains, and valleys. At the second level, the geomorphic unit is considered which is segmentation of the units at first level based on the form, structure, and process, for example, plains at the first level are segmented into eolian plains, flood plains, alluvial plains, etc. At the third level, the units are further categorized into landforms considering the amount of weathering or deposition, or dissection.

A national classification system was developed by GSI, specifically, targeting the Quaternary Geology and Geomorphology of the entire country (GSI and NRSC 2010). The mapping addressed all major river basins of the country. The classification schema was genetic in nature and had geomorphic units and landform units at first and second levels.

Though several geomorphological classification systems in the country partly tried to include the process and genesis of landforms in the schema, however, the first national-level genetic classification system for geomorphological mapping in India was prepared by Geological Survey of India (GSI), the national nodal agency which carries out geological mapping in India, for preparing the geomorphological maps of India on 1:2 M scale. Later, the National Natural Resources Management System (NNRMS) of ISRO under the Standing Committee on Geology and Mineral Resources (NNRMS SCG), discussed the importance of a common standardized national-level genetic geomorphological classification system, and an inter-agency working group of national-level organizations involved in geological and geomorphological studies was constituted to finalize a comprehensive genetic geomorphological classification schema covering all geological provinces of the country (Srivastav et al. 2021). During 2009, the 14th NNRMS SCG meeting of ISRO and 44th Central Geological Planning Board (CGPB) meeting of GSI approved the proposal of national-level geomorphological mapping at 1:50,000 scale using the newly developed comprehensive genetic hierarchical system of landform classification (GSI and NRSC 2010). The genetic aspect is addressed at the first level of this classification system, the broad morphology (geomorphic form) is addressed at the second level and the landform is addressed at the third level. This classification system has categorized the landforms into 11 genetic classes at the highest level and comprises 417 landforms at the lowest level (NRSC 2012a; Singh et al. 2015).

The significant aspect of most of these classification schemas is that they follow a hierarchical system, with broad level to detailed level of landforms representation, thus providing the flexibility to collapse classes at the lower levels to higher levels for regionalization of the geomorphology maps.