Annals of Arid Zone 52(3&4): 163-180, 2013

A System of Geomorphological Mapping for Western Rajasthan with Relevance for Agricultural Land Use

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Abstract: A geomorphological map of arid western Rajasthan has been prepared using a recently developed classification system for national mapping in India at 1:50,000 scale. The mapping involved digital interpretation of the false colour composite (FCC) of images of 2005-06 from LISS-III scanner in the Indian Remote Sensing Satellite (IRS), followed by field verification of the mapped units and analysis of sediments from key sites. It resulted in the generation of three-tier mapped information on the origin, processes and landform units, as well as other digital database on landform characteristics. To find out the agricultural use of the landforms, a land use map of the same area for 2005-06 was draped on the derived map of landforms, using GIS. Area statistics for all the maps was generated for each of the four agro-climatic zones in western Rajasthan. The mapping reveal that landforms of aeolian origin cover the maximum area (~79%), which dominantly consist of sand dunes (~50%). Landforms of fluvial origin have been masked over large area by the aeolian features, leaving only 13% area as visible. Croplands occur on all the major landforms, but irrigated croplands occur dominantly on older alluvial plains. Sand dunes and sandy plains are dominantly under un-irrigated croplands, and partly under irrigated croplands, which may increase the risk of sand mobility. These and other results have been discussed in the paper.

Key words: Geomorphology, mapping, agricultural land use, western Rajasthan, ACZ, GIS.

Geomorphology, the scientific study of landforms and processes, is not limited to an understanding of the landscapes of earth and other planets. It has a larger goal of being useful to the societal needs, and thereby to a range of sub-disciplines of geography (both physical and socio-cultural) as well as to various other earth-science disciplines, like pedology, geology, hydrology, plant ecology, etc. One of the ways by which it caters to the needs of the above disciplines and sub-disciplines is through mapping of the observed and interpreted land features at different scales. Recognizing this responsible role, geomorphological research, since its beginning in the early 19th Century, has emphasized on preparation of sketches and maps of the landscapes and landforms as a fundamental means of visualization and analysis of the Earth's surface features (Dykes, 2008). A geomorphological map can act as a preliminary tool for land management and landscape risk management, as well as for providing baseline data to other applied sectors of environmental research such as landscape ecology, forestry, soil science, etc. (Cooke and Doornkamp, 1990; Dramis *et al*., 2011). Despite having such a potentially useful role for different scientific disciplines, no universally acceptable system of mapping is still available, especially because of the vast difference in the landscape properties across the globe, and also because of the vastly different user perceptions and needs.

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A Brief History of the Mapping Concept

Throughout the 19th century and early 20th century, the study of landforms was dominated by a static description of physiography, which involved carefully drawn diagrams, sketches and excellent illustrations of geomorphological processes. For example, while explaining the force of water in the carving of the Grand Canyon, Powell (1875) prepared several sketches and maps of the area. Gilbert (1877) used numerous sketches and maps to explain his idea of dynamic equilibrium in landscape in a study of the Henry Mountains, Utah, while Davis (1899) used maps and diagrams to introduce his concept of 'Geographical Cycle'. Since then geomorphological maps have remained an essential graphical component of the inventories of a landscape, depicting landforms as well as surface and subsurface materials. In the early 20th Century and until

World War II, most geomorphological research focused on visualization of regional landscapes by means of physiographic or landform maps. Block diagrams used to be prepared to show the sketched perspective representation of actual landforms. During the period of World War II great advances were made in the use and interpretation of aerial photographs for terrain analysis but the restricted nature of aerial photographs and tedious procedures for ortho-rectification of the photographs, were major deterrents in their large-scale use. Topographic base maps with height contours and a general layout of the hydrography and infrastructure remained the most sought-after secondary database for mapping purpose, fieldwork (and to some extent field mapping) providing the other major input. Subsequently, quantitative analytical techniques, developed in other sciences, were applied to geomorphic research (Strahler, 1957).

An important component of mapping is the preparation of appropriate symbols and 'legend' (Demek, 1982). Recognizing this, the 18th Congress of the International Geographical Union (IGU) at Rio de Janeiro in 1956 and two years later, the 19th Congress of IGU at Stockholm, asked a Sub-commission 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 Klimed, 1968). The legend, produced in collaboration with many geomorphologists from European countries, was published in 1971 (Bashenina *et al*., 1971) and the Manual in 1972 (Demek *et al*., 1972). Demek *et al*. (1972) suggested that a large-scale geomorphological map could have a scale of 1:10,000 to 1:50,000, and occasionally up to 1:100,000, while UNESCO (Anon., 1976) suggested a scale of 1:5000 to 1:10,000 to qualify a map as 'large-scale'. Ideally, such large-scale maps form the strongest scientific source of geomorphological information, and are the best explanatory presentation of landforms and landscape development (Cooke and Doornkamp, 1990). However, such detailed mapping being data-intensive, there was very little acceptance of the system till the current developments in GIS with extended graphical capabilities, as well as the availability of high-resolution remote sensing data products, including digital elevation data (Lee, 2001; Paron and Claessens, 2011; Smith *et al*., 2011). Even otherwise, the collaborative research efforts of the 1970s for a universal mapping methodology, did not find many followers.

Knowing where a landform is, why it is there, what it is made of and how it has changed is a powerful knowledge for many applied disciplines, especially when in a mapped form. This has made geomorphology a cross-cutting discipline, relevant to many earth science- and society-related disciplines. Accuracy in mapping of several geomorphological variables has vastly improved due to the recent developments in remote sensing and Geographical Information System (GIS). With the advent of digital image processing, GIS, Global Positioning System (GPS), Ground Penetrating Radar (GPR), it is now possible to observe and map the earth's surface and near-surface features in greater details than before and to interpret them for newer information. The higher capabilities of the recent PCs in handling and simultaneous processing of large datasets from diverse satellites and secondary sources, and their ability to accurately represent the derived products in 2D and 3D formats, now offer added flexibility in data collection, data handling and presentation (Bishop *et al*., 2012). Geospatial functionalities like scalable map display, layer visibility control, access to attribute data, coordinate queries, and spatial measurements have helped some geospatial data providers like the United States Geological Survey (USGS; http://Store. usgs,gov) and the Australian Hydrographic Service (AHS; http://www.hydro.gov.au) to publish interactive maps using the GeoPDF format. In spite of these developments, however, a great deal of diversity and disagreement still exists in the procedures and contents of geomorphological maps. As the technologies are evolving fast and the demands of the society are increasing the case for a fixed, universal methodology of mapping is becoming weaker.

In India a major effort was made during 1961-80 by the National Atlas & Thematic Mapping Organisation, Calcutta, to map the physiographic regions, landforms, slopes, relative relief, geology and other related variables at 1:1 M to 1:6 M scale (Anon., 1980). Although useful for understanding the geomorphological features at regional level, the scales were found inadequate for identification of units at local level. For the arid western Rajasthan, a system of landform classification and mapping at 1:50000 scale was developed at Central Arid Zone Research Institute (CAZRI), Jodhpur, that could be easily understood and used by soil scientists, plant ecologists, hydrologists, land use specialists, agricultural scientists, etc. (Ghose *et al*., 1977a; Singh *et al*., 1990). It was based partly on the classification system developed by the Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia, and depended on the interpretation of large-scale aerial photographs, field data, laboratory analysis of sediment samples, and interpretation of large-scale topographical sheets (Christian and Stewart, 1968). A four-tier classification system for terrain mapping at 1:250000 to 1:10000 scales, involving both hierarchical and non-hierarchical concepts of defining landscape assemblages, was proposed by Kar (2011a) for the arid lands of Kachchh. While CAZRI's mapping methodology was developed for an inter-disciplinary research group catering to the needs of agricultural and allied land development activities, the Geological Survey of India (GSI), Western Region, Jaipur, used a different methodology that put more emphasis on hydro-geological applications and exploration of Quaternary deposits.

This article discusses the results of a geomorphological mapping in western Rajasthan at 1:50000 scale, using a new methodology that has been applied for national level geomorphological mapping in India (Anon., 2009). The methodology was developed as part of a program taken up by Indian Space Research Organisation (through National Remote Sensing Centre, Hyderabad), along with GSI, and the mapping was carried out by different national institutes of the country. CAZRI carried out mapping in the western part of Rajasthan. For the purpose of this paper we have simplified the classification system and re-ordered some units for practicality and relevance in agricultural land use and allied applications. It is proposed to describe the methodology of mapping, the spatial pattern of landforms derived from the mapping, and an assessment of the related geomorphic processes. An attempt will also be made to find the major agricultural uses of the landforms.

Study Area and its Environment

The mapping was carried out in arid western part of Rajasthan state that includes a major part of the Thar Desert (Fig. 1). Its eastern limit passes roughly through the foothills of the degraded, NNE to SSW-trending, Aravalli hill ranges, while the western limit is along the international border with Pakistan. The Aravalli hill ranges were formed more than 2500 million years ago, and underwent at least three cycles of orogenesis and plantation since the Proterozoic. It is one of the oldest hill ranges in the world (Heron, 1953). The basement in much of the arid plain is made up of granite, rhyolite and the gneissic complex. From Upper Proterozoic period onward sedimentation here took place in several basins, under continental and marine conditions. The identified basins are: (i) Marwar basin, (ii) Lathi basin, (iii) Jaisalmer basin, (iv) Barmer basin, (v) Palana-Ganganagar Shelf, and (vi) Sanchor basin (Sinha Roy *et al*., 1998; Kar, 2011b). Western Rajasthan has a dominantly dry environment, with a mean annual rainfall of about 500 mm along its eastern margin to about 150 mm along the western border (Table 1). Although both fluvial and aeolian processes are present, the dryness and a relatively high wind environment during the summer months have allowed the domination of aeolian processes over the fluvial processes. Studies based on morphological characteristics of landforms, stratigraphy and absolute dating of sediments have revealed that during the late Quaternary period climate oscillated in the region between dry and wet phases, and led to the relative dominance of fluvial and aeolian processes at different times (Ghose *et al*., 1977b; Kar, 1995, 1999; Kar *et al*., 2004).

Studies suggest that most of the landforms in this region are polygenetic in nature, but it is possible to classify them according to the processes that dominated for a fairly long period. Broadly, the landforms are fluvial, aeolion and lacustrine. A very small area in the south comes under fluvio-marine processes, where the northern fringe of Great Rann of Kachchh is a part of the mapped area. Kar (1993a) recognized nine major dune types and twenty-three subtypes in Thar Desert, which

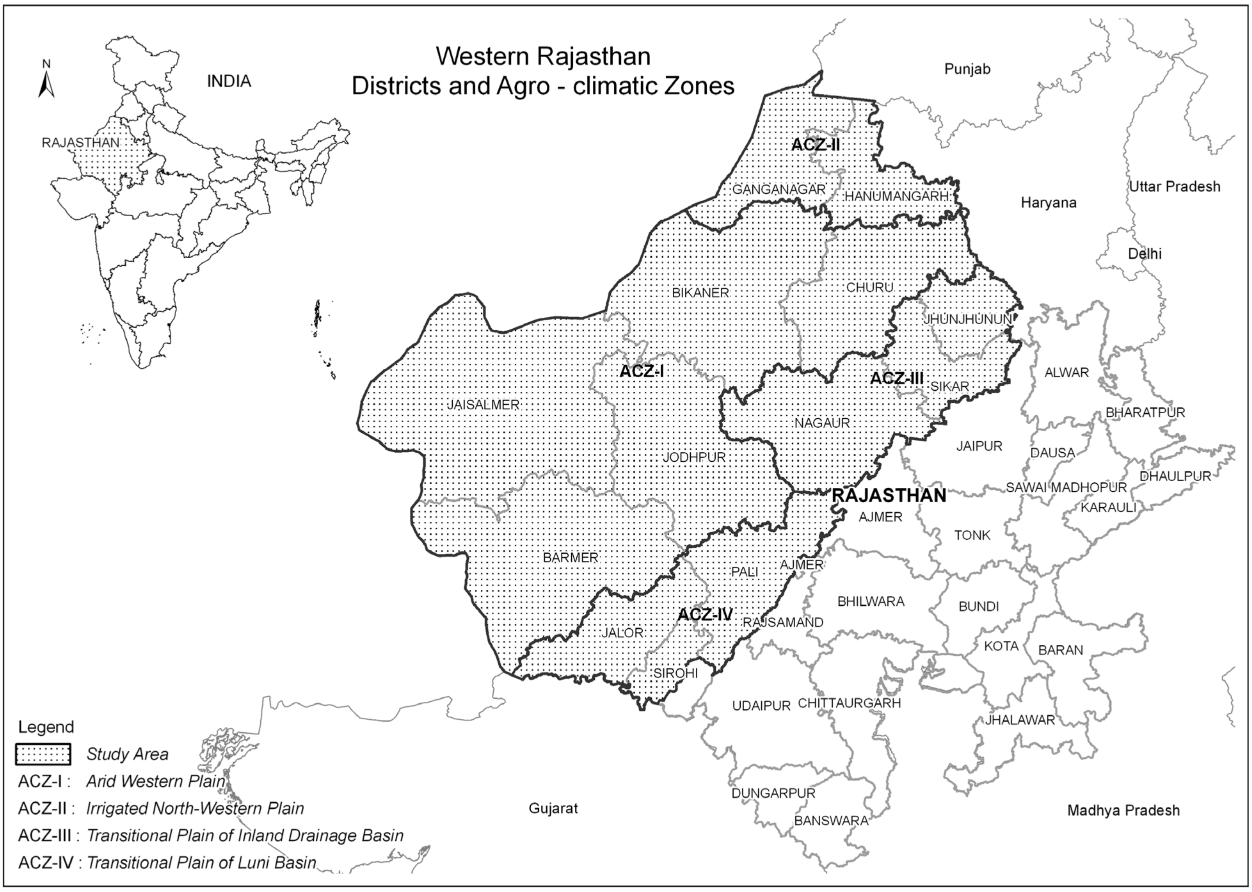

Fig. 1. Study area – western Rajasthan – Major part of the Thar Desert.

can be 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. In Ajmer-Pushkar area, two old phases of dune formation were found at the exposed base of old dunes, which were topped by a layer of modern sand (Goudie *et al.*, 1973; Allchin *et al.*, 1978). Recent studies have identified several other dune building phases within the desert and its margin, dating back to more than 100 ka (kilo annum) before present (Kar *et al.*, 2001; Dhir *et al.*, 2010). Presently there is a distinct rainfall gradient in western Rajasthan from east (500 mm) to west (150 mm), but also distinct variability in the four agro-climatic zones (Table 1). 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, 1993a).

Methodology

Classification system for geomorphological mapping

A three-level classification scheme developed by the National Geomorphological and Lineament Mapping Project (Anon., 2009) was used. 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. Some modifications in the scheme were necessitated. A new level-1 unit, 'fluvio-marine' was introduced for the Great Rann area within the mapped region. Landforms were identified from an interpretation of IRS-LISS-III FCC images of 2005-06 for three seasons (Kharif, Rabi and Zaid). Based on the FCC signatures, digital mapping was carried out on a GIS platform at 1:50000 scale. Table 2 provides the scheme used for mapping at 1:50000 scale. For the sake of simplicity in this paper, some of the level-2

Table 1. Mean annual rainfall in districts of western Rajasthan

District	Mean annual rainfall (mm)	Coefficient of variation (%)
Arid Western Plain		
Barmer	266.7	63
Jaisalmer	185.3	65
Bikaner	290.6	47
Jodhpur	368.9	52
Churu	365.7	37
Canal Irrigated North Western Plain		
Ganganagar	255.1	53
Hanumangarh	250.5	56
Transitional Plains of Inland Drainage Basin		
Sikar	467.4	42
Jhunjhunun	402.0	36
Nagaur	327.7	53
Transitional Plains of Luni Drainage Basin		
Pali	426.9	49
Jalor	381.0	52

and level-3 units were merged. For example, the landforms with high, moderate and slight dissection were clubbed together. Sub-divisions within older alluvial plain and younger alluvial plain were mostly deleted.

Landforms in agro-climatic zones and land use units

In order to provide a view of the landforms from an agricultural perspective, the level-3 landform units were first placed on a map of agro-climatic zones (ACZ) in a GIS environment. The districts under each ACZ in the generalized map are given in Table 3. To get a broad view of what major agricultural uses the landforms are put to, a land use map was first prepared from interpretation of IRS LISS-III FCC images of 2010-11, showing the following major units: irrigated crop lands, un-irrigated crop lands, permanent pastures, open rangelands, forests, saline wastes and water bodies/River beds. This 7-unit land use map was then superimposed on the landform map.

Results and Discussion

Mapping of landforms on the basis of origin indicates that about 80% area has aeolian landforms, followed by the fluvial and denudational ones (Table 4). The distribution pattern of the major landforms is shown in

Table 2. Classification system used for mapping

Level-1	Level-2	Level-3
Origin	Process	Landform
Structural	High/ moderate/ slightly dissected hills and valleys	Hills & valleys
		Strike Ridge
		Ridge
		Hogback
		Dyke/Sill ridge
		Dome
Denudational	High/ moderate/ slightly dissected hills and valleys	Hills & valleys
		Residual hill
		Scarp
		Inselberg
		Pediment
		Pediplain
		Valley fill
		Gullied land
Fluvial	Younger alluvial plain	Younger alluvial plains
		Abandoned channel
		Valley Fill
		Gullied land
		Channel bar
	Older alluvial plain	Older alluvial plain
		Palaeochannel
		Abandoned channel
		Cut-off Meander
		Point bar
		Gullied land
	Deltaic plain	Old deltaic plain
Aeolian	Aeolian plain	Sand sheet
		Deflation plain
		Barchan
		Longitudinal dune
		Parabolic dune
		Transverse dune
		Dune complex
		Interdune plain
		Dissected dune complex
		Desert pavement
		Playa
Fluvio-marine	Saline depression	Rann with fan deposit
Anthropogenic	Anthropogenic terrain	Active quarry
		Abandoned quarry
		Mine dump
		Dam and reservoir
		Salt pan

Table 3. Agro-climatic zones of western Rajasthan

Agro-climatic zone (ACZ)	Description	Districts	Total area (sq. km)	Area (%)
ACZ- I	Arid Western Plain	Barmer, Jaisalmer, Bikaner, Jodhpur, Churu	133073	64.01
ACZ-II	Irrigated North-western plain	Ganganagar, Hanumangarh	20557	9.89
ACZ–III	Transitional plains of inland drainage	Jhunjhunun, Nagaur, Sikar	31329	15.07
ACZ–IV	Transitional plains of Luni basin	Jalor, Pali	22951	11.04

Plate. Their area in different districts within the four agro-climatic zones is shown in Tables 5-8.

Summarizing the distribution pattern we find that aeolian landforms cover 90.5% area of ACZ-I, where fluvial and denudational landforms have negligible presence (4.1% and 3.5%, respectively). ACZ-III has also very large area under aeolian landforms (85.2%), and meagre area under denudational, structural and fluvial landforms (6.9%, 3.4% and 3.6%, respectively). Fluvial landforms dominate in ACZ-IV (46.8%), where aeolian landforms cover 30.7% area. Since the zone has a large hilly area, the denudational and structural landforms cover significant area (15.0% and 6.9%, respectively). ACZ-II has also large area under fluvial landforms (44.9%), but aeolian landforms cover the maximum area (54.8%). Landforms of exclusive anthropogenic origin cover insignificant area in all the zones (0.2-0.9%), but other studies have shown that most landforms bear the signatures of considerable anthropogenic alteration (Kar, 2011b, 2014).

Since the sand dunes and interdune plains cover a major part of the region, a separate map shows the major dune types and associated interdune plains (Fig. 2). It reveals that sand dunes of different types cover more than 50% of aeolian landscape in both ACZ-I (54.6%) and ACZ-II (56.4%). Since the dunes are generally closely spaced in ACZ-I, the interdune plains there could be mapped as covering 11.1% area of the aeolian landscape, compared to 25.0% area in ACZ-II, where the dunes are widely spaced. Sand sheets/deflation plains cover 29.5% and 18.6% area of the aeolian landscape in the two zones, respectively. In ACZ-III, separating interdune plains (3.8%) from the dune-covered areas (37.8%) is difficult over large areas due to the complex dune types covering much of the dune landscape. Thick sand sheets/deflation plains cover large areas (57.6%). In ACZ-IV the sand dunes are widely scattered (20.9%), so that the interdune plains (0.7%) are mostly replaced by sand sheets/deflation plains (77.5%). The major characteristics of the landforms and their distribution pattern are described below.

Table 4. Origin-wise distribution of landforms in western Rajasthan

Origin	Area (sq. km)	Area (%)
Structural	5008	2.37
Denudational	10740	5.09
Fluvial	28005	13.27
Aeolian	167816	78.87
Fluvio-marine	86	0.04
Anthropogenic	754	0.36
Total	211058	100.00

Distribution and Characteristics of Landforms

Landform of structural and denudation origin

Landforms of structural origin account for only 2.4% area of western Rajasthan, while those of denudational origin occupy 5.1% area. The major occurrences are in the forms of hills and valleys, dykes and ridges, as well as pediments and pediplains, mostly in the districts of Jaisalmer, Barmer, Jalor, Pali, Nagaur and Sikar. In Jaisalmer District the hills are low and scattered, mostly between Pokaran and Bhaniyana (mainly rhyolite), Randha and Lakhan (mainly granite) and along the outer margin of the Hamada between Joga-Ramgarh in the north and Sam-Shipal-Rasla line in the southwest (sandstone and limestone). In contrast, Barmer and Jalor Districts have few clusters of high hills in the form of inselberg and dome, especially around Barmer, Chohtan, Dhorimanna, Siwana, Mokalsar, Nakoda, Jalor, Bhadrajun, Jaswantpura and Raniwara, where granite and rhyolite form them. According to Kar (1992) the near-circular arrangement of hills in Siwana-Mokalsar area with basins within is the result of a major volcanic eruption in the area during Pre-Cambrian period, which was followed by blowing away of the upper part of the volcanic cone. Granite hills are numerous in Pali and Sirohi Districts also, where the hill slopes exhibit exfoliation and cavernous weathering features (Kar, 1995). Many of the isolated hills of sandstone in the central and western parts of Jodhpur and Nagaur Districts occur as mesas and buttes (e.g., at Osian, Bhopalgarh, Balesar), while the rhyolite and limestone hills have a craggy outline (e.g., at Agolai, Korna, Gotan, Pundlu, Bilara). The major hilly terrain in western Rajasthan runs along the eastern margin of Sirohi, Pali, Nagaur, Sikar and Jhunjhunun Districts, where the NE-SW trending Aravalli hill ranges with narrow valleys in between are formed mostly of metamorphic rocks. The hill slopes are highly dissected due to higher rainfall as compared to the central and western parts. The lower and middle slopes of many of these hills are covered with obstacle dunes that are also highly dissected. Hamadas, the structural plains, occur in Jaisalmer District, especially between Pokaran and Ramgarh. Dykes and ridges could

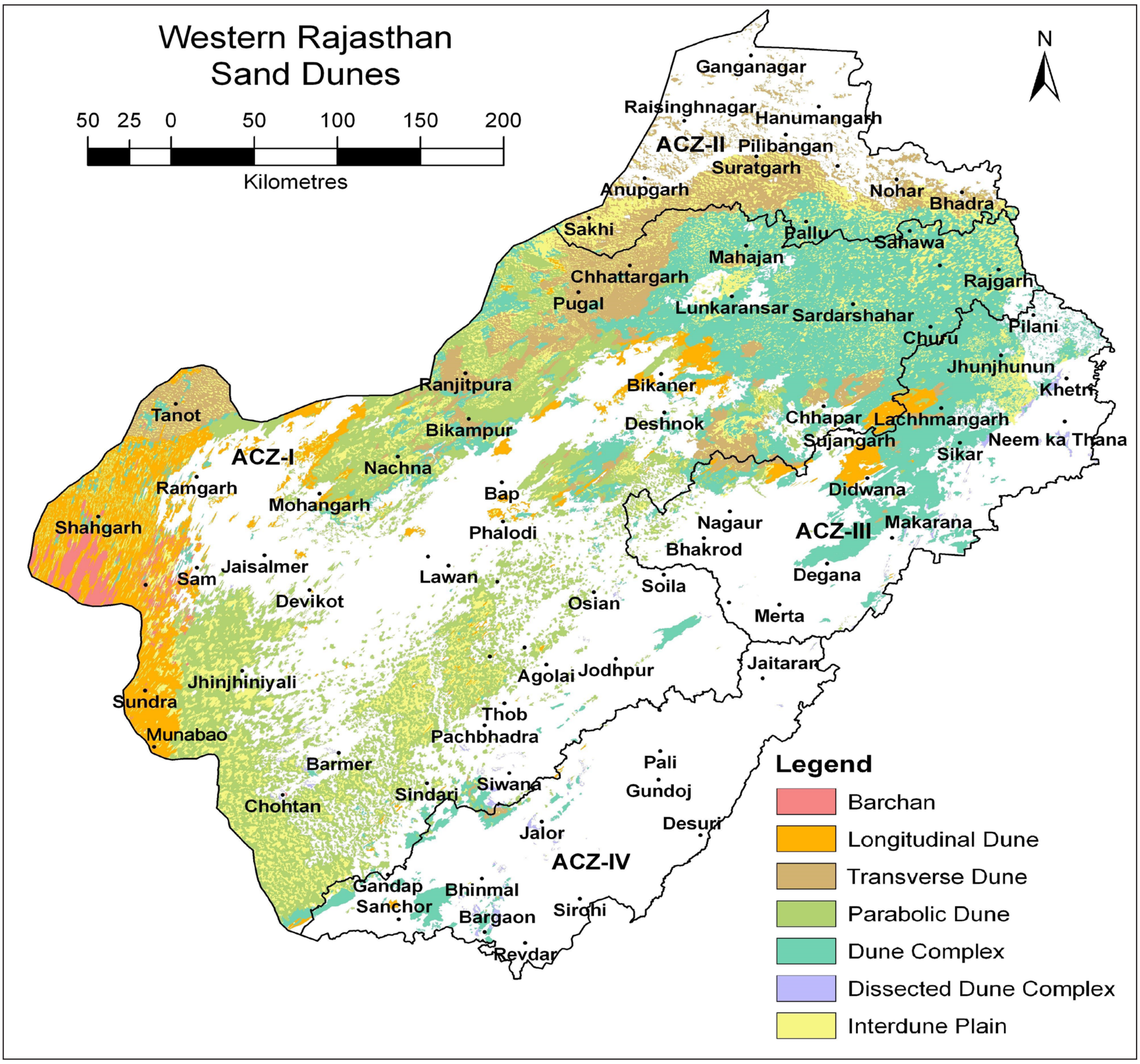

Fig. 2. Major dune types.

Table 5. Landforms in the districts of ACZ-I (area in km²)

Landform	Barmer	Jaisalmer	Bikaner	Churu	Jodhpur
Structural					
Hill and valley	4	0	0	0	0
Dyke and ridge	0	22	0	0	0
Hamada	0	2119	0	0	0
Denudational					
Hill and valley	478	41	0	6	385
Residual hill	63	49	0	1	73
Pediment/pediplain	207	1065	0		890
Pediment-pediplain complex	305	782	3	1	318
Fluvial					
Older alluvial plain	405	1166	2	141	2090
Abandoned/palaeo channel	90	34	5	2	36
Younger alluvial plain	395	0	0	0	315
Gullied land	46	295	108	0	13
River bed	186	0	0	0	94
Aeolian					
Sand sheet	9047	7059	6001	1155	11897
Deflation plain	50	304	0	0	0
Barchan	10	1534	0	0	1
Longitudinal dune	1324	7168	1124	363	267
Transverse dune	49	1877	5286	721	93
Parabolic dune	10273	6213	4396	379	3590
Dune complex	535	1460	6716	11387	803
Dissected dune complex	148	0	0	8	19
Interdune plain	3453	3434	3430	2538	471
Desert pavement	971	3378	42	0	1152
Playa	159	111	3	43	49
Fluvio-marine					
Rann	45	0	0	0	0
Anthropogenic					
Mine/quarry	3	31	48	0	36
Salt pan	19	32	0	0	32
Water body	24	11	8	7	52
Total	28289	38185	27172	16752	22676

be mapped in limited area, especially in the Aravalli tract of Nagaur and Sikar Districts.

Pediments have been identified at the base of hills over the rocky/gravelly surfaces. These have a gentle 1-3% slope, and are often covered by thin sand sheet. The pediplains are essentially the pediments variously covered by heterogeneous sediments that are mostly sourced locally. The major occurrences of the above two units above sand sheet have been mapped in the districts of Jaisalmer (e.g. around Mokal, Kinoi, Chhatrel and Fatehgarh), Barmer (Shiv, Baishala, Jasai), Jodhpur (Agolai, Osian, Kankani, Bhopalgarh, Borunda), Nagaur (Bhakrod, Harsor, Khimsar), Sikar (Patan, Nim ka Thana), Pali (Bali, Desuri, Sojat, Jadan), and

Table 6. Landforms in the districts of ACZ-II (area in km²)

Landform	Ganganagar	Hanumangarh
Fluvial		
Older alluvial plain	4738	3279
Abandoned/palaeo channel	858	363
Aeolian		
Sand sheet	841	1248
Deflation plain	6	0
Transverse dune	3173	1511
Dune complex	112	1560
Interdune plain	1546	1269
Playa	3	0
Anthropogenic		
Mine/quarry	6	0
Water body	34	9
Total	11317	9239

Sirohi (Anadra, Revdar). Sandstone, limestone, granite, rhyolite and metamorphic rocks like quartzite, slate and phyllite form these units. The parent rock has a high influence on the debris characteristics on the pediment and on piedmont angle, which is more pronounced on sandstone and least on rhyolite (Kar *et al*., 1977; Kar, 1984). At many places the pediments occur extensively without any hills nearby, especially in the south-eastern part, which has been explained by Kar (1995) as the result of a long-continued process of pedimentation and coalescing of pediments.

Landforms of fluvial origin

Exposed fluvial landforms cover 13.3% area of western Rajasthan, especially in the northern part of Ganganagar and Hanumangarh Districts, where these are associated with the Ghaggar River basin, and in the districts of Nagar, Jodhpur, Pali, Jalor and Sirohi, where these are associated with the Luni River and its tributaries. The maximum area of these landforms is in Pali District (30.3%), followed by Ganganagar (20.0%) and Hanumangarh (13.0%) Districts. Older alluvial plains, not covered under thick aeolian sand, occupy about 9.7% area. These are usually characterized by layers of fluvial and aeolian sediments and by zones of illuviated soft nodular carbonates (kankar) or gypsum at 30 -300 cm depth within the alluvium (Ghose, 1964; Ghose *et al*., 1977b).

Table 7. Landforms in the districts of ACZ-III (area in km²)

Landform	Jhunjhunun	Sikar	Nagaur
Structural			
Hill and valley	388	519	129
Dyke and ridge	12	5	3
Denudational			
Hill and valley	3	0	6
Residual hill	15	9	4
Pediment/pediplain	252	377	918
Pediment-pediplain complex	136	320	114
Fluvial			
Older alluvial plain	26	89	422
Abandoned/palaeo channel	0	14	1
Younger alluvial plain	70	31	108
Gullied land	55	226	77
River bed	0	9	0
Aeolian			
Sand sheet	1742	2720	10923
Longitudinal dune	1	259	648
Transverse dune	0	135	266
Parabolic dune	0	56	554
Dune complex	2265	2679	2974
Dissected dune complex	81	95	69
Interdune plain	816	99	102
Desert pavement	0	0	81
Playa	0	11	127
Fluvio-marine			
Rann	0	0	0
Anthropogenic			
Mine/quarry	1	0	48
Salt pan	0	0	36
Water body	37	42	120
Total	5900	7695	17730

The exposed area of the older alluvial plains is much smaller than the actual extent of the older alluvium in the region. In the north, the dry valley of the Ghaggar River was identified long ago as the course of the Saraswati River, while the course of its tributary valley, the Chautang, was identified as that of the Drishadvati River, both originating from the Himalayas (Oldham, 1893). Studies based on satellite remote sensing

Table 8. Landforms in the districts of ACZ-IV (area in km²)

Landform	Pali	Jalor	Sirohi
Structural			
Hill & valley	1373	0	435
Denudational			
Hill & valley	231	269	307
Residual hill	70	32	20
Pediment/pediplain	1238	114	475
Pediment-pediplain complex	248	161	754
Fluvial			
Older alluvial plain	6577	884	660
Abandoned/palaeo channel	6	9	0
Younger alluvial plain	1814	1384	265
Gullied land	4	3	15
Old deltaic plain	0	152	0
River bed	90	288	63
Aeolian			
Sand sheet	389	5541	269
Longitudinal dune	3	40	0
Transverse dune	0	49	0
Parabolic dune	3	120	0
Dune complex	0	1176	24
Dissected dune complex	7	166	84
Interdune plain	0	57	0
Desert pavement	0	11	1
Playa	3	56	0
Fluvio-marine			
Rann	0	41	0
Anthropogenic			
Mine/quarry	0	0	1
Water body	0	46	69
Total	12057	10599	3440

and field data by Ghose *et al*. (1979) and Kar and Ghose (1984) revealed several former courses of the above two rivers through the desert, which contributed the thick alluvium in parts of Churu, Nagaur, Bikaner, Jaisalmer and Jodhpur. Kar (1999) suggested that the flow regimes of those palaeochannels depended largely on the contribution of the Sutlej, while climate change and neotectonic movements played crucial roles in the shifting of the courses, burial of the channels under aeolian sand and their ultimate demise. Presently the dry valley of the Saraswati through Tibbi, Hanumangarh, Pilibangan, Suratgarh and Anupgarh, and that of the Drishadvati through Bhadra, Nohar, Rawatsar and up to Suratgarh, provide the best agricultural lands in the northern part of western Rajasthan. Using geophysical methods, Kar and Shukla (2000) defined a palaeo-valley of the River between Ramgarh and Tanot in the western part of Jaisalmer District and located the groundwater aquifer in it. Subsequent studies have confirmed the above findings (Radhakrishnan and Merh, 1999; Mitra and Bhadu, 2012). The Luni River system was sometimes a tributary to this Himalayan River system. Ghose (1964, 1965) first mapped the palaeochannels in the Luni drainage basin from aerial photographs, which encouraged several other studies in mapping of the palaeochannels and abandoned channels in the region. Kar (1994) showed that the shifting pattern of many streams in the Luni drainage basin was related to lineaments in the area, while the process of major shifting was triggered by exceptional rainfall events. The major palaeochannels and abandoned channels in the present map cover 1420 km² area (0.7%).

Younger alluvial plains cover only 2.1% area of western Rajasthan, but have very high relevance for agricultural uses, as these are well endowed with shallow groundwater and silt. The plains occur in narrow zones along the 462.5 km long Luni River and its major tributaries like the Jawai, the Lilri, the Guhiya, the Sukri, the Bandi, the Mithri, the Khari and the Sagi in the districts of Nagaur, Jodhpur, Pali, Jalor, Sirohi and Barmer. A small strip is also noticed along the Kantli River in Jhunjhunun District. All these streams originate from the Aravalli hill ranges, are ephemeral and flow only during the monsoon season. Because of the meagre and uncertain rainfall, water flows along the full length of the channels only during high-rainfall years, and that too for a few hours to days. The thick sandy plains, in which the channels have been formed, absorb much of the water during each flow, while the sandy banks encourage more widening of the beds than deepening. The stream beds exhibit an alternate sequence of erosional features and depositional lobes all along their courses. Even the small upland channels exhibit such alternate sequence of scour and fill (Moharana and Kar, 2010).

Some of the ephemeral channels originating from the isolated hills in the desert try to meet the Luni River, but can hardly flow their total length (e.g., Jojari River from near Jodhpur, Lik River from near Pokaran). Such streams, therefore, get partly buried under aeolian sand and sand dunes, as has been the case with the Lik River (Kar, 1988). Occasional high-intensity rainfall for 2-3 days during the rainy season of July-September sometimes revives these channels, which create flood and problems for human habitation and infrastructures. Usually such rainfall events are area-specific, linked to the passage of a deep depression during the monsoon, and do not necessarily cover the whole region. For example, a very high rainfall event in 1979 in parts of Jodhpur, Pali and Jalor Districts led to very high flood-related damages in the central part of Luni basin, but Nagaur District experienced moderate drought, and so the upper reaches of the Luni River experienced very little flow. In comparison, the high rainfall events of 1975 and 1990 were more widespread in the Luni basin area, causing large flow along all the streams and revival of some palaeochannels (Kar, 1994). Another widespread flood-causing rainfall event in the southern part of the desert took place in 2006 when a partially buried drainage system of the Rohilli River in Barmer District got rejuvenated after about 8 decades, and created havoc in Shiv – Kawas area (Kar *et al*., 2007). Such events also lead to rill and gully development on the uplands, the obstacle dunes and the stream banks. Moharana and Kar (2002) successfully simulated the development of such drainage network in gravely and sandy terrain of the desert from available topographic height information. Gullied lands along the margins of the uplands and in alluvial plains cover 841 km^2 area (0.4%), mostly in Jaisalmer, Bikaner and Sikar Districts, but also in Pali, Jalor and Sirohi Districts.

A small delta of the Luni River has been mapped downstream of Gandap, which is south of the river's confluence with the Jawai River. The delta is about 20 km wide, in which the Luni bifurcates into several streamlets before meeting the Great Rann of Kachchh. Although the delta formation is now almost defunct, the deep alluvium between Gandap and the margin of the Great Rann of Kachchh suggests that the delta-building process was active during some previous wetter climatic phases. Its total area is now 153 km^2. The western margin of the delta appears to be gradually covered under aeolian sand.

Landforms of aeolian origin

Aeolian landforms cover 78.9% area of western Rajasthan, and have been classified into sand sheets, deflation plains, sand dunes, interdune plains, desert pavements and playas (inland Ranns). Sand sheets and deflation plains (28.1%) have been mapped in the areas where sandy plains occur outside the dune-covered areas. Their major occurrences are in Jodhpur, Nagaur, Barmer, Jaisalmer, Bikaner and Jalor Districts. Aeolian sand thickness generally varies from 1 m to 3 m, the thickness increasing nearer the dune fields. Sand streaks in the form of shrub-coppice dunes and fence-line dunes are numerous in these plains.

Sand dunes, excluding the sandy plains, have been mapped in about 48% area of western Rajasthan (60.2% of aeolian landscape) and have been mapped as barchan, longitudinal, transverse, and parabolic. Two more types, the dune complex (in areas where the form is a result of complex wind pattern) and dissected dune complex (where the dune slope has numerous gullies), have also been mapped (Fig. 2). Barchans (1545 km^2) have been mapped mostly to the west and south-west of Jaisalmer, especially between Shahgarh and Dhanana, where they are mostly 15 to 40 m high, coalesced, and occur in long chains within the longitudinal dune field. Kar (1987, 1990a) classified these dunes as megabarchanoids, and explained their formation mechanism. Small barchans (1-5 m high) occur in many parts of the desert, but beyond the western part of Jaisalmer and Barmer Districts these seldom occur in clusters. Since these dunes move much faster than the other dunes mentioned above, their mapping is difficult. The longitudinal dunes (11197 km^2) occur dominantly to the west and south-west of Jaisalmer, where Kar (1987) identified small feathers along the flank of these dunes and inverted Y junctions. Smaller occurrences have been mapped notably near Bikaner, Didwana and Lachhmangarh. The orientation of the dune gradually changes from WSW in the western-most part to SW in the eastern part. Kar (1987, 1993a) discussed different modes of

Table 9. Major land uses in the landforms (area in km²)

Landform	Irrigated cropland	Unirrigated cropland	Open rangeland	Permanent pasture	Forest	Saline waste
ACZ-I						
Hill and valley	6	43	44	1	6	0
Hamada/desert pavement	2	38	50	10	0	0
Pediment/pediplain	9	36	52	1	0	1
Gullied land	0	23	75	2	0	0
Older alluvial plain	17	60	18	3	0	2
Younger alluvial plain	35	61	1	3	0	0
Old deltaic plain	27	59	9	1	0	5
Sand sheet	13	65	16	5	0	1
Sand dune	7	50	38	4	0	0
Interdune plain	15	51	31	3	0	0
Playa	0	1	19	2	0	79
Mine/quarry	3	43	54	0	0	0
ACZ-II						
Older alluvial plain	96	2	1	0	0	0
Sand sheet	64	31	4	1	0	0
Sand dune	24	65	11	0	0	0
Interdune plain	31	56	13	0	0	0
Mine/quarry	89	11	0	0	0	0
ACZ-III						
Hill and valley	17	34	16	0	33	0
Hamada/desert pavement	17	74	4	5	0	0
Pediment/pediplain	31	42	24	2	0	1
Gullied land	22	47	23	0	8	0
Older alluvial plain	43	49	2	3	3	0
Younger alluvial plain	60	39	0	0	1	0
Old deltaic plain	69	31	0	0	0	0
Sand sheet	44	49	4	2	0	0
Sand dune	35	61	3	0	1	0
Interdune plain	60	39	1	1	0	0
Playa	2	0	2	3	5	89
Mine/quarry	0	66	34	0	0	0
ACZ-IV						
Hill and valley	4	40	18	0	38	0
Hamada/desert pavement	0	15	53	0	32	0
Pediment/pediplain	10	57	25	1	6	0
Gullied land	47	38	15	0	0	0
Older alluvial plain	18	77	3	0	1	0
Younger alluvial plain	22	71	3	0	1	0
Old deltaic plain	7	44	1	22	0	26
Sand sheet	41	51	5	3	0	0
Sand dune	39	36	19	4	2	0
Interdune plain	11	29	37	23	0	0
Playa	0	0	17	15	0	68
Mine/quarry	13	49	33	0	6	0

formation of the dunes, including formation from stream of barchans and due to vortices along hill margins, etc. Transverse dunes (13162 km^2) have been mapped mainly to the west of Bikaner, NW of Jaisalmer, and in parts of Ganganagar and Hanumangarh Districts. The dunes generally occur in 1-5 km long chains with narrow interdune plains in between. In Bikampur-Karanpur area, the dunes are 20-40 m high, but those in the east are mostly 8-15 m high. Parabolic dunes (25585 km^2), with two arms in the upwind direction and a curved nose downwind, constitute the major dune type in Thar Desert. Their major occurrences are in Barmer, Jaisalmer, Jodhpur and Bikaner Districts. The dunes usually occur in chains of 4 to 8, or more. In the west, their arms are 5-8 km long, which gradually shorten eastward to about 1 km or less. Dune complex (31691 km^2), consisting of several dune types, have been mapped in the northern part of the desert, especially in the north-eastern part, where the dunes are so closely spaced and differently oriented that it was difficult to delineate them individually. These dunes are 12 m to 20 m high with narrow interdune plains. Dissected dune complex (677 km^2), which usually include the major obstacle dunes along the hill slopes and some parabolic and other dunes along the wetter eastern margin of the desert, are most numerous along the foothills of the Aravalli hills, the Siwana hills and the isolated hills in the sand-covered areas. The runoff from the rocky slopes run through the dunes, forming rills and gullies. The mappable interdune plains cover 8.2% area, and are mostly flat sandy or sandy undulating. The major occurrences have been mapped in Barmer, Jaisalmer, Bikaner, Churu, Ganganagar and Hanumangarh Districts.

Playas or saline depressions (also called the "inland Ranns") occur in both sandy and rocky terrains. The notable playas in the dominantly sandy terrain are Sambhar, Didwana, Tal Chhapar, Pachpadra, Thob, Bap and Lunkaransar, while those in rocky terrain are Lawan, Pokaran, Dediya, Mitha Rann, Kanodwala Rann and Kharariwala Rann. The Sambhar Lake along the eastern margin of the desert is the largest, followed by those at Bap and Pachpadra. Most playa surfaces remain dry almost throughout the year, and get flooded during the monsoon period when a centripetal drainage system brings water and sediments from the surrounding catchment areas. The sediment profile consists of alternate layers of silt, clay and sand, as well as gypsum at places (Singh *et al.*, 1974; Rai, 1990; Deotare *et al.*, 2004). Aggarwal (1957) first postulated a riverine connection for the Pachpadra and Didwana lakes, while Ghose (1964) suggested that salt deposition took place at the confluence of streams, especially at Pachpadra and Thob. Kar (1990b, 1993b) suggested that a process of deflation in the wake of high hills, dune formation along the hill margins and trapping of ephemeral channels in the deflation hollows led to the formation of many playas in eastern Thar. Kar (1993b, 2011b) also suggested that a long-continued process of sand blasting on limestone beds formed the playa basins in Jaisalmer-Mohangarh area, while neotectonism might have played a major role in the formation of Sambhar Lake and some small playas in the Luni basin.

Desert pavements, covering 3.3% area, occur mainly along a discontinuous belt from Shiv to Bikaner through Sankra, Bhojka, Bap and Kolayat in the districts of Barmer, Jaisalmer, Jodhpur and Bikaner. Other notable small occurrences are found between Ramgarh and Mohangarh in Jaisalmer District and Jayal-Kathoti area in Nagaur District. The pavement surfaces are strewn with gravels and pebbles in a matrix of sand, silt and clay, which were interpreted by Bakliwal and Grover (1988) as remnants of the Saraswati palaeochannels. The pavements have a broadly convex outline, with rills and gullies along their margins (Kar, 2011b).

Landforms of fluvio-marine origin

The northern tip of the Great Rann of Kachchh, which occurs in the southernmost part of western Rajasthan, is of fluvio-marine origin. While the Great Rann itself is a remnant of the receding Arabian Sea (Kar, 2011a), the Luni River system supplied considerable fluvial deposits on the Rann surface in its northern part.

Landforms of anthropogenic origin

Human activities are gradually becoming a major factor of landform modification in western Rajasthan, especially through exploitation of the land resources. One of the major changes

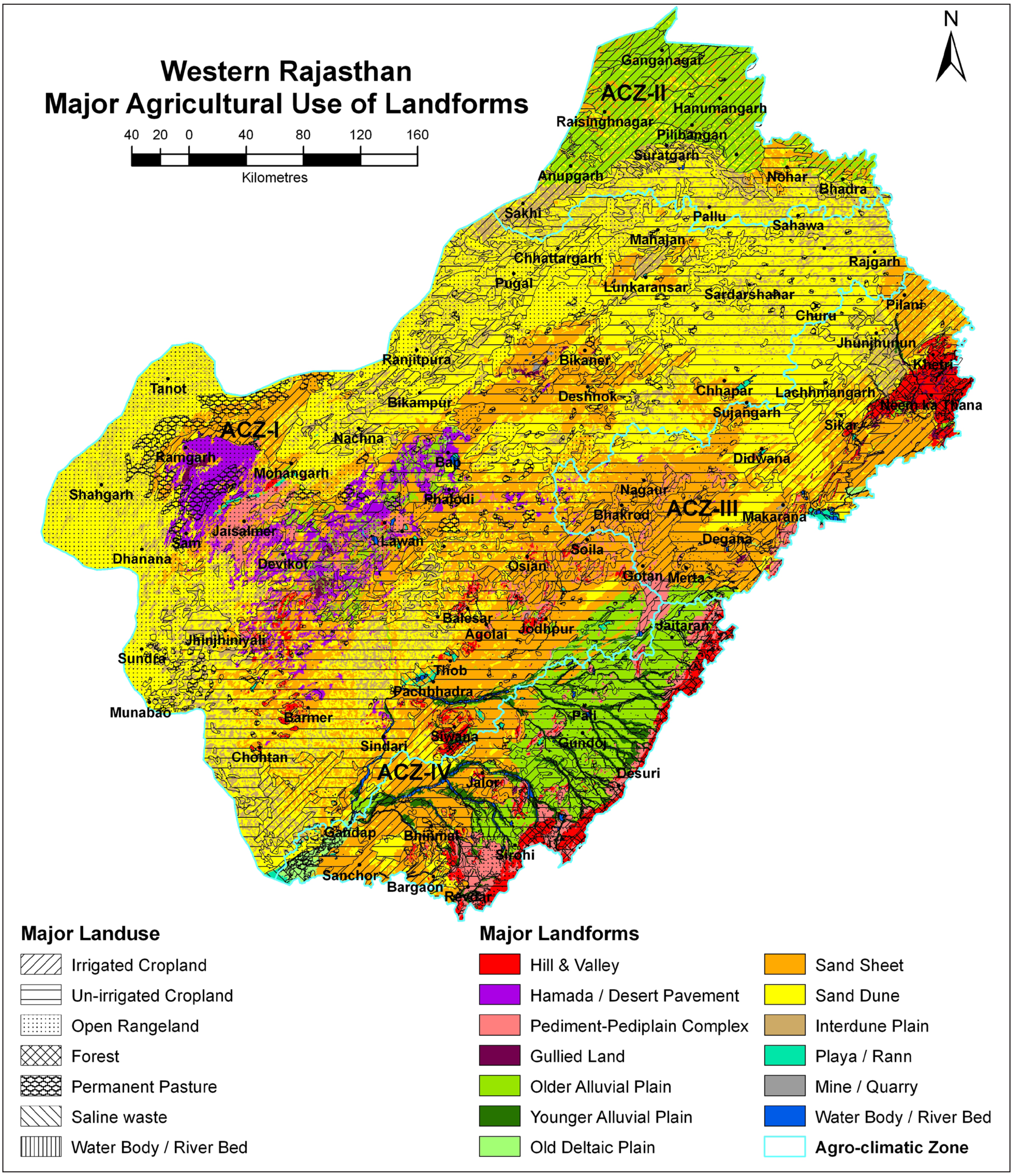

Fig. 3. Major land use of the landforms.

in natural landscape has been flattening of sand dunes for cropping, mainly in the northern part. Mapping of such areas requires an overlay of the recent satellite images on old topographical maps or aerial photographs, but this was beyond the scope of the project, and has not been attempted. Among other activities, mining of salts and chemicals in salt pans have been mapped in 118 km^2 area, especially at Sambhar, Nawa, Kuchaman, Didwana and Tal Chhapar in Nagaur District, Bap, Kaparda and Dedia in Jodhpur District, Pachpadra, Thob and Samooja in Barmer District, and Lunkaransar in Bikaner District. Because of this activity, a part of the otherwise dry playas remain under water throughout the year. The playa margins become hummocky due to the salt mounds. Mining of sandstone, limestone, marble, gypsum, clays, lignite, etc., have also been mapped (176 km^2), which have not only altered the local drainage system in some areas, but have also created large depressions. The major areas of such mining are mainly near Makrana, Parbatsar, Bhadwasi, Degana, Kasnau (Nagaur District), Gotan, Jodhpur, Balesar, Shergarh, Mathaniya (Jodhpur District), Kapurdi, Kawas, Akli (Barmer District), Sanu, Mohangarh (Jaisalmer District), Kolayat, Jamsar and Chhatargarh (Bikaner District). A number of dams and reservoirs have been constructed in parts of Pali and Jodhpur Districts, creating semi-permanent water bodies (460 km^2). The water inflow depends on the amount of monsoon rainfall during a particular year. Apart from the above modifications, introduction of canal irrigation in Ganganagar, Hanumangarh, Bikaner and Jaisalmer Districts and groundwater irrigation over large parts of the desert are fast changing the sandy landscape. We discuss below the current major uses of the landforms for different agriculture-related purposes.

Major Agricultural Uses of the Landforms

Western Rajasthan is dominated by agricultural land uses. According to land revenue records, the net sown area during 2005-06 covered 51.2% of the total area. Net irrigated area covered 13.0% area, but the area sown more than once covered 10.0% area. Fallow lands, both current and old together, constituted 15.6% area. Permanent pastures, culturable wastes and unculturable land, which form majority of the grazing lands, covered 26.4% area, while notified forest area covered 2.2%, and land used for non-agricultural uses covered 4.6% area (Ram, 2009). With current fallows and old fallows added to the net sown area, the area under crop lands was 66.8%, which included the net irrigated area. Mapping of the land uses for 2005-06 at 1:250000 scale (based on interpretation of AWiFS FCC) suggested that the un-irrigated crop lands were spread over 51.0% area, while irrigated crop lands covered 21.2% area, thus putting the cropland area at 72.2% of the total. Pasture lands and open grazing lands together covered 25.8% area. The difference in area from the revenue data was within 10%, which may be considered tolerable. The saline wastes and the water bodies/River beds covered 0.6% and 0.2% area, respectively. Actual forest area could be marked in 1.2% area.

Despite the difference in scale of mapping for geomorphology (1:50000) and land use (1:250000), and the difference in spectral resolution of the imagery used for the two mappings (23 m for geomorphological mapping; 70 m for land use mapping), an attempt was made to find out the broad land use pattern in different landforms. For this, the different land use units in the map for 2005-06 were re-grouped into the following major uses: irrigated croplands, un-irrigated croplands, permanent pastures, open rangelands, forests and saline wastes. The landforms were also re-grouped into thirteen major units. The derived map (**Fig. 3**) shows that the hill and valley unit in the eastern part is predominantly under un-irrigated croplands (39%), followed by forests (28%) and open rangelands (24%), while the Hamada topography and desert pavements in the west are dominated by open rangelands (49%) and un-irrigated cropland (38%). Pediments and pediplains are also dominated by un-irrigated croplands (46%) and open rangelands (37%). The alluvial plains are dominated by irrigated and un-irrigated croplands. The older alluvial plains are dominated by irrigated croplands (52%), where the un-irrigated croplands occupy lesser area (41%), but the younger alluvial plains and deltaic plains are more under un-irrigated croplands (69% and 46%, respectively). The sandy plains are dominated by un-irrigated croplands (sand sheets 58%; interdune plains 51%), where the second-ranking land use is either irrigated cropland (sand sheet 26%), or open rangelands (26%). Surprisingly, sand dunes are also dominated by un-irrigated croplands now (52%), and not by open rangelands (32%). Even irrigated croplands have encroached upon the sand dunes (tube well irrigation), covering the unit's 12% area. This is especially true in parts of Hanumangarh, Jhunjhunun, Churu, Sikar, Bikaner, Jodhpur Districts. In the canal-irrigated areas, there has been large scale levelling of sand dunes for irrigating the fields, especially in the districts of Ganganagar, Hanumangarh, Bikaner and Jaisalmer. A similar situation is expected to occur in the Narmada Canal command area within Barmer and Jalor Districts. Such uses of the sand dunes and sandy plains are increasing the risk of wind erosion in the region. Table 9 show the per cent area covered by different land uses in the major landforms of the four ACZs.

Conclusions

The geomorphological map prepared at 1:50000 scale from satellite image interpretation in a GIS environment provides a more accurate spatial distribution pattern of the landforms mapped than was available earlier. The classification system is hierarchical, and helps us to extract information at three different levels: origin, dominant processes and landform typology. The derived map shows that aeolian landforms are most dominant in the area (~79% of the total area), but that the actual area covered by sand dunes is about 48%. The sandy plains and interdune plains cover another 36% area. In large parts the aeolian bedforms have masked the fluvial landforms whose exposed areas now cover about 13% of the total area. The rocky/gravely terrain, as well as the hills and valleys cover about 7% area. Within the four ACZs, the maximum coverage of aeolian landforms is in ACZ-I (91% of the zone), followed by ACZ-III (85%), while the maximum coverage of fluvial landforms is in ACZ-III (85% of the zone), followed by ACZ-II (45%). Although the anthropogenic landforms have been identified in less than 1% area, field observations show that human impacts on the landforms are very widespread, especially in the sandy terrain and in the irrigated areas, where many sand dunes have been flattened for irrigated cropping.

An association with the land use map shows that croplands have come up in all the major landforms, and cover more than 40% area of major landform units. Un-irrigated croplands occupy the maximum area of the alluvial plains and the sandy terrain, but irrigated croplands cover maximum area of older alluvial plains only. The use of culturable wastelands like slopes of sand dunes or sandy waste for agriculture has brought more area under cultivated category. Open rangelands and permanent pastures occur mainly in the rocky terrain. Since the aeolian bedforms have high mobility, the anthropogenic impacts on landscape is increasing fast, and effects of global warming are expected to enhance the rates of the processes (Kar, 2012; Goyal *et al*., 2013), the database on geomorphology created for the year 2005-06 can be updated at decadal scale or more to find out the location and direction of change in the landforms.

Acknowledgements

Authors are grateful to Dr M.M. Roy, Director, CAZRI and Dr. C.B. Pandey, Head, Division-I, CAZRI for providing facilities, RRSC-W, Jodhpur, NRSC, Hyderabad and GSI (Western Region) for the NGLM project under which the mapping works and database were created.

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Printed in December 2014