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B8: Geomorphological Field Guide Book on THAR DESERT

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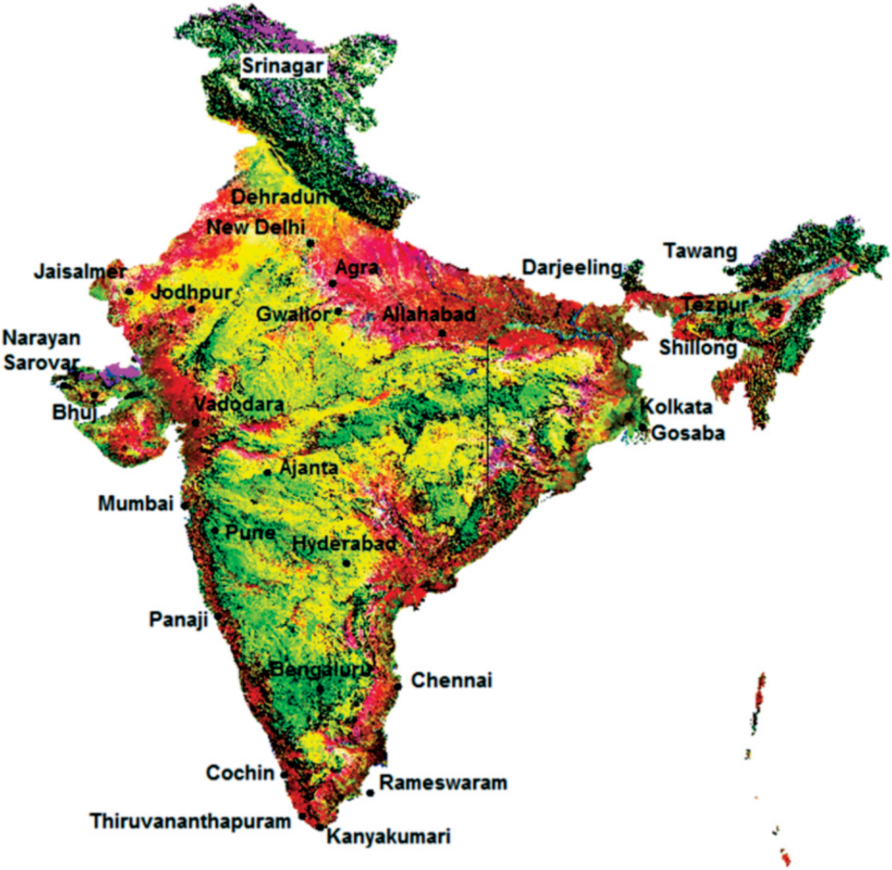

Fig. 1. Image-map of India, showing some places of interest for the 9th International Conference on Geomorphology, 2017 (Map prepared by A. Kar through processing of relevant ETM+ FCC mosaics and SRTM 1km DEM, both sourced from the US Geological Survey site). Boundaries are approximate.

Geomorphological Field Guide Book on Thar Desert (12 November to 16 November, 2017)

Itinerary

Day	Date	Places from - to	Stay
Day 1	12 November 2017	New Delhi to Jodhpur by Flight; Field Visit to Sursagar, Osian, Central Arid Zone Research Institute (CAZRI) Research Farm at Jodhpur	Jodhpur
Day 2	13 Novemver 2017	Jodhpur to Jaisalmer Field visit to Agolai, Balesar, Shetrawa, Dechu, Pokaran, Chandan	Jaisalmer
Day 3	14 November 2017	Jaisalmer to Sam and back Field visit to Damodara, Kuldhara, Kanoi, Sam	Jaisalmer
Day 4	15 November 2017	Jaisalmer to Jodhpur Field visit to Mokal, Bharamsar, Chhatrel, Rupsi, Lodurva	Jodhpur
Day 5	16 November 2017	Jodhpur to New Delhi by Flight	New Delhi

Notes

A. THAR DESERT: AN INTRODUCTION

Thar Desert, spread between the Aravalli Hill ranges in the east and the Indus River in the west, has its maximum area within India, and a smaller area in Pakistan. In India, the desert is spread over the western part of Rajasthan state, and forms a part of the hot arid zones of India that cover an area of 31.7 million hectare (m ha). While the arid western part of Rajasthan state (i.e., Thar Desert) covers an area of 19.6 m ha (61.9% of the total hot arid zone), there are other smaller hot arid areas, especially in the north-western part of Gujarat state (6.22 m ha, 19.6%), southern part of Punjab and Haryana states (2.75 m ha, 8.6%), south-western part of Andhra Pradesh state (6.8%), south-eastern part of Karnataka state (2.7%), and the north-central part of Maharashtra state (0.4%). India also possesses a cold arid zone that lies in the rugged Himalayan terrain within the state of Jammu and Kashmir (7 m ha).

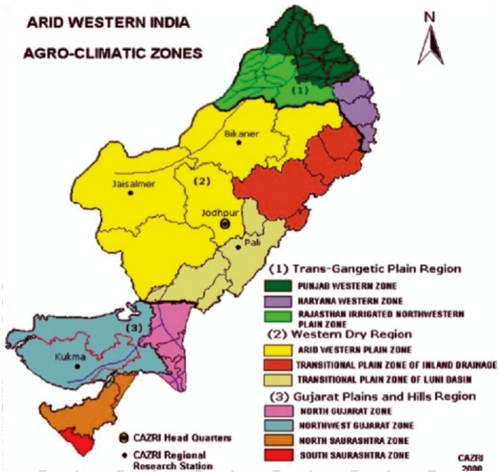

Fig. 2.
Agroclimatic zones in arid western India.

The eastern limit of the arid western Rajasthan is along the calculated moisture availability index (also called the aridity index) of –66.6, which roughly passes through the foothill zone of the degraded, NNE to SSW-trending Aravalli hill ranges. From agricultural viewpoint, arid western Rajasthan can be divided into the following two agro-climatic regions: (a) the Western Dry Region, and (b) the Trans-Gangetic Plain Region, both having some sub-divisions *(Fig. 2)*. Thar Desert lies essentially in the Western Dry Region, and has three subdivisions: (i) the arid western plain zone in the districts of Jaisalmer, Barmer, Bikaner, Churu and Jodhpur, covering 133074 sq. km), (ii) the transitional plain of inland drainage in Nagaur, Sikar and Jhunjhunun districts (31329 sq. km), and (iii) the transitional plain of Luni basin in Pali and Jalor districts (22951 sq. km). In the north, the Rajasthan irrigated north-western plain zone in the districts of Ganganagar and Hanumangarh (20557 sq. km), is largely a transitional plain between the Thar Desert and the arid Punjab-Haryana plains.

Climatic Characteristics

The key characteristic of arid regions is low precipitation compared to high atmospheric water demand. The hot arid region of India is no exception where annual rainfall is 100-500 mm and potential evapotranspiration (atmospheric water demand) is 1400-2000 mm (Goyal et al., 2013). Rainy season is quite distinct in Indian arid zone. The precipitation is mainly received during south-west monsoon season (June-September). The monsoon reaches the Thar Desert by 1st week July and the entire arid zone is covered by mid-July. The withdrawal of monsoon starts from the extreme west in Jaisalmer district by September. Thus, the monsoon season is effectively of 2.5 to 3 months, compared to four months in most parts of India. Only a few active monsoon spells bring rains in this region, resulting in wide inter- and intra-seasonal variations in rainfall amount. The annual rainfall in western Rajasthan, based on 1901-2010 rainfall data, is 291 mm, about 88% being received during the southwest monsoon season. High rainfall variability and coefficient of variation result in frequent droughts in this low-rainfall area (Rao and Roy, 2012). The rainfall deficit and duration of droughts vary from year to year and spatially. Early-season droughts due to late onset, terminal droughts due to early withdrawal and mid-season droughts due to breaks in monsoon are very common. Attri and Tyagi (2010) reported that west Rajasthan faced maximum (34) droughts during 1875-2009. At district or smaller scale, one or other pocket in arid zone faces drought almost every year as the temporal distribution of rainfall is also highly variable during the season. Floods are relatively less common, and are limited in area coverage because of light textured soils. However, flash floods sometimes do occur in small areas due to high intensity rains. There was increasing trend in annual as well as monsoon rainfall in west Rajasthan from 1901 to 2010. Presently there is a distinct rainfall gradient in western Rajasthan from east (500 mm) to west (150 mm). The mean annual rainfall in the districts within agro-climatic sub-zones of western Rajasthan are provided in Table 1.

Table 1. Mean annual rainfall in the 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

Since cloud cover is low during most of the year, solar radiation is abundant. In arid Rajasthan, average annual solar radiation is about 22 MJ m^2 per day. The value ranges from 15-18 MJ m^2 per day in winter and 23-26.5 MJ m^2 per day in summer (Rao and Roy, 2012). Solar radiation in drier districts of Jaisalmer and Barmer is higher (22.3 MJ m^2 per day) than in the northern irrigated belt of Hanumangarh district (20 MJ m^2 per day).

The diurnal, seasonal and annual temperature ranges are high owing to the geographical location, sandy terrain, sparse vegetation and low soil and atmospheric moisture content. During summer, the temperature may rise up to 50°C, while in winter -5.7°C has been recorded. During winter, the mean monthly maximum temperature ranges from 22°C to 29°C, and the mean minimum temperature ranges from 4°C to 14°C. May is the hottest month with mean maximum temperature of 40-42°C. The temperature declines by 3-5°C during monsoon season but again increases slightly during September and October when the monsoon withdraws.

The wind direction is normally southwest during summer and rainy season, and northeast during winter season. The wind speed remains quite low (3-4 km/h) during winter and high (9-12 km/h) during May to July. Strong winds of 15 to 18 km/h are often observed during June when the wind speed may reach 60 to 80 km/h during severe dust storms. Records for the last 40 years of the 20th Century suggest that the wind speed has declined gradually, particularly during the summer months (Kar, 2013). The decline was more pronounced up to the mid-1990s. A recent study (Vautard et al., 2010) found that winds are slowing in northern hemisphere. Such decline in wind speed was attributed mainly to changing patterns of atmospheric circulation, increased vegetation due to afforestation as well as changing landscape management practices and increase in urban density.

Geomorphology

Basement and the Late Quaternary Sedimentation

The Aravalli hill ranges, which form the eastern boundary of the desert over much of its length, 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 out of which 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, 2011).

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., 1977; Kar, 1995, 1999; Kar et al., 2004). Ghose et al. (1979) discovered a very old course of the Saraswati River from the Himalayas, buried under 40-60 m of dune sand in Jaisalmer district and adjoining parts of Cholistan Desert and in Tharparkar area of Pakistan through the dune-infested terrain of Kishangarh, Ghantiyal, Longewala, Shahgarh and Mondhlo. The discovery was made with the help of a set of the earliest, and coarse-resolution, Landsat imagery of the 1970s, aerial photo-interpretation and field survey in selected areas for geomorphological parameters. Kar and Ghose (1984), Kar (1999) revealed several other early courses of the Saraswati-Drishadvati river system from the Himalayas through the desert, and suggested that the thick alluvium in the dune-covered area between the Ghaggar River in the north and the

Luni River in the south was largely contributed by that system in pre-Holocene periods, with smaller contributions from the tributaries from the Aravallis and elsewhere.

Several phases of dune building activities have also been identified from 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).

A multi-disciplinary and multi-institutional study on the aeolian stratigraphy in the desert and its margins revealed that the history of aeolian sedimentation dates back to at least 150 ka. Several aeolian episodes have been dated to around 100-115 ka, 65-75 ka, ~55 ka, 30-25 ka (Kar et al., 2004; Singhvi and Kar, 2004). Wetter phases in between in the east and south resulted in partial leaching of carbonates from the profiles. During the last 20 ka the principal periods of sand accumulation were 14-7 ka, 5-3 ka and around 2 ka. Most of the major sand dunes show a strong phase of aeolian accumulation during the terminal Pleistoscene. This was a period when SW monsoon wind started building up. The beginning of Holocene was marked by increased rainfall that peaked around 6 ka and resulted in large scale landscape stabilization. The present rate of century-scale sand mobility is much higher than the past geological rates (Kar et al., 1998, 2001; Thomas et al., 1999). Summary of research is available in (Kar et al., 2004; Singhvi and Kar, 2004).

Present Landforms

Broadly, the landforms in Thar Desert are fluvial, aeolian and lacustrine. The efficiency of aeolian processes now increases with decreasing rainfall from east to west, as well as with the increasing wind speed in that direction (Kar, 1993a). The Luni River forms the only organised drainage system. Surface water resources are limited due to low and scanty rainfall and poor water-yielding efficiency of sandy terrain. Besides storage tanks, other common systems for surface water are Nadis (village ponds) and Khadins (runoff harvesting systems). Vegetation constitutes to be primary source of life support because of dependency by animal husbandry. The northern desert thorn forest, northern Acacia scrub forest, northern Euphorbia scrub and inland dune scrub are the recognised forest types in this region.

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) recognised nine major dune types and twenty-three subtypes in Thar Desert, which can be grouped under the old dune system and the new dune system (Pandey et al., 1964; Vats et al., 1976; Singh, 1982).

Geomorphological Mapping

During 2012-2015, under a National Level Mapping project of ISRO's (Indian Space Research Organization) NRC (Natural Resources Census) programme and with technical collaboration of GSI (Geological Survey of India, Western Region), CAZRI prepared a geomorphological map of arid western Rajasthan at 1:50,000 scale, using a recently developed classification system. The mapping involved digital interpretation of the false colour composite (FCC) of images of 2005-06 from Indian Remote Sensing Satellite (IRS), LISS-III, followed by field verification of the mapped units and analysis of sediments. The mapping *(Fig. 3)* shows that aeolian landforms are most dominant in the area (~79% of the total area), but actual area covered by sand dunes is about 48%. Based on the origin, six types of landforms have been identified; structural, denudational, fluvial, aeolian, fluvio-marine and anthropogenic (Moharana et al., 2013). A brief description of the result is presented below.

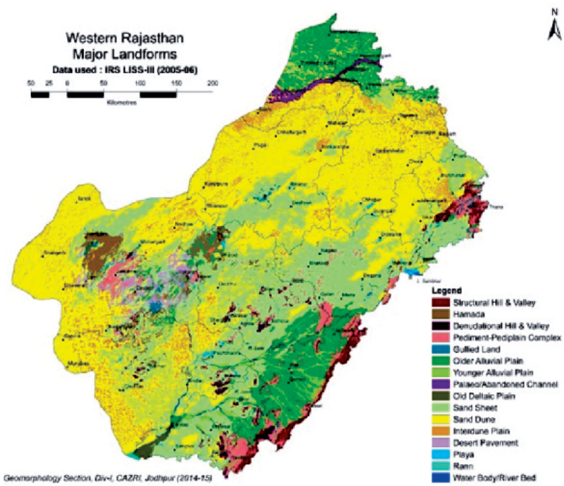

Fig. 3.
Major landforms in western Rajasthan.

Major Landforms

Landforms of structural origin account for only 2.4% area of western Rajasthan, while those of denudational origin occupy 5.1% area. The major forms are hills and valleys, dykes and ridges, pediments and pediplains. However there is marked variations in morphology and origin. In Jaisalmer district, the hills are low and scattered distributed; in contrast, Barmer and Jalor districts have few clusters of inselbergs and domes. Hamadas, the rocky structural plains, occur in Jaisalmer district. Isolated sandstone hills in Jodhpur and Nagaur districts occur as mesas and buttes while those occurring at Agolai, Korna, Gotan, Pundlu, Bilara are of rhyolite and limestone hills.

Fluvial landforms:

The major fluvial landform sequence follows hills and uplands, rocky/gravelly pediments/pavements, buried pediments, flat older alluvial plains, younger alluvial plains and riverbeds.

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 occurrences are between Phalodi and Bap in Jodhpur in a continuous belt at Shekhasar, Ramdevra and Damodara till Sam in Jaisalmer (Moharana and Raja, 2016). 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 (1995, 2014) explained the gravel spread as weathering and erosion of a conglomeratic bed of Jurassic age.

Older alluvial plains are usually characterised 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., 1977). 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. 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. 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). Water from many of the small channels is impounded by the villagers in Nadis (ponds) and Khadins (runoff farming system) for humans and livestock consumption and even for farming activities (in Khadins). The flow path of the channels often gets obliterated in thick sand. Moharana and Kar (2002) simulated the development of drainage network in a gravely and sandy terrain of the desert from available topographic height information, which can help in finding the better sites for runoff conservation.

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. The western margin of the delta appears to be gradually covered under aeolian sand.

Aeolian landforms:

The aeolian landforms are dominated by sand dunes of various types and morphology, further categorised and mapped as barchan, longitudinal, transverse, parabolic, dune complex and dissected dune complex (where the dune slope has numerous gullies). Sand dunes occur in about 48% area of the region. There are several studies on the occurrence, pattern and types of sand dunes. Kar (1993a) identified and mapped nine major and 21 subgroups of sand dunes in western Rajasthan. Moharana et al. (2013) delineated barchan, longitudinal, transverse, parabolic, 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) *(Fig. 4)* at 1:50,000 scale. Barchans occur 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. The longitudinal dunes 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

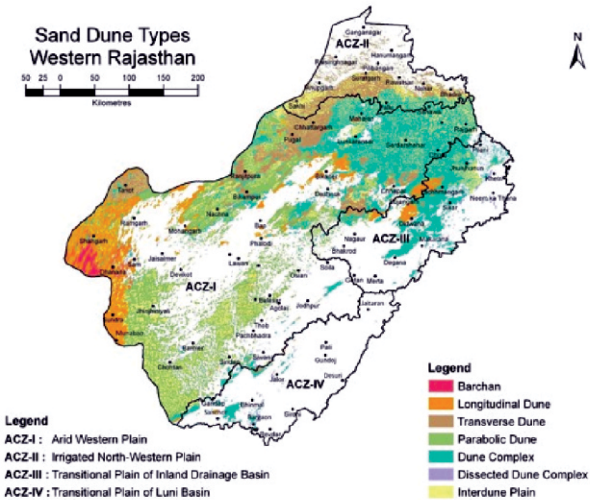

Fig. 4.
Sand dune types in western Rajasthan.

notably near Bikaner, Didwana and Lachhmangarh. The orientation of the dune gradually changes from WSW in the westernmost part to SW in the eastern part. Kar (1987, 1993a) discussed different modes of formation of the linear sand dunes, including formation from streams of barchans and due to vortices along hill margins, etc. Transverse dunes 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 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 (Kar, 1993a). Dune complex, consisting of several dune types, have been mapped in the northern part of the desert, mainly in Churu district in extreme temperature situation. These dunes are 12 m to 20 m high with narrow interdune plains. Dissected dune complex, 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 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 the inland Ranns:

Playas or saline depressions (also called the inland Ranns) occur throughout the region. 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; 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,

2011) also suggested that a long-continued process of sand blasting on softer 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.

Anthropogenic landforms:

Landforms of anthropogenic origin are manifestations of the impact of human activities. Levelling of sand dunes through mechanical methods for cropping has enlarged the area under the plains, mainly in the northern part. Mining of salts and chemicals in salt pans in 118 km2 area, and mining of sandstone, limestone, marble, gypsum, clays and lignite in 176 km2 area, have not only altered the local drainage system in some areas, but have also created large depressions.

Land Degradation in Western Rajasthan

Several studies carried out during the last five decades in western Rajasthan have revealed that the major types of land degradation in the area are wind erosion, water erosion and land salinization. Among these, wind erosion is the most important and widespread. Because of the meagre rainfall, water erosion is localized, and occurs mainly in the eastern part. Salinity/alkalinity of land is partly related to natural causes, but also due to faulty and excess use of water for irrigation. In recent times, water pollution due to industrial effluents and mining activities has also become a major cause of land degradation. Thus, land use has been found to have an important effect on degradation, especially as expansion and intensification of agriculture, overuse of the natural vegetation resources and industry-related activities have led to not only degradation of rangelands and forests, but have also aided wind and water erosion processes and salinity build-up. Results of research on some of the processes are summarised below, followed by a short description of the mapping.

Wind erosivity measurement:

Aeolian activities in the Thar are mostly restricted to summer months as impacts of hot wind blowing from SSW and SW. The NE wind during winter is weak and poor agent for shifting of dunes. The wind strength shows a gradual decline from west to east and the precipitation effectiveness (PE) improves in that direction. Kar (1993a, 1994b) calculated erosion potential of the wind or the erosivity in the form of wind erosion index (WEI) for several meteorological stations of the desert. The annual WEI value was calculated as the sum of the values from March to July. The index values ranged from very low (Index 1-14) to extreme high (index value 480 and above). The analysis and mapping showed that maximum potential wind erosion lies to the SW of Jaisalmer and in adjoining parts of Pakistan, while the lower values occur towards east and north east. WEI calculations for 21st Century on the basis of data from different GCM simulations showed a progressive rise with time (Kar, 2012).

Wind erosion measurements:

Scientists at Central Arid Zone Research Institute carried out studies on the aspects of wind erosion mainly focusing on, (1) satellite based mapping of wind erosion and related desertification in western Rajasthan, (2) field measurements of wind erosion. Mapping based on visual interpretation of the 1:250000 scale FCC of Landsat TM images and ground truth revealed that about 76% area of western Rajasthan was affected by wind erosion (Narain et al., 2000). While 15% area was severe to very severely affected, 36% area was moderately affected and 25% slightly *(Fig. 5)*.

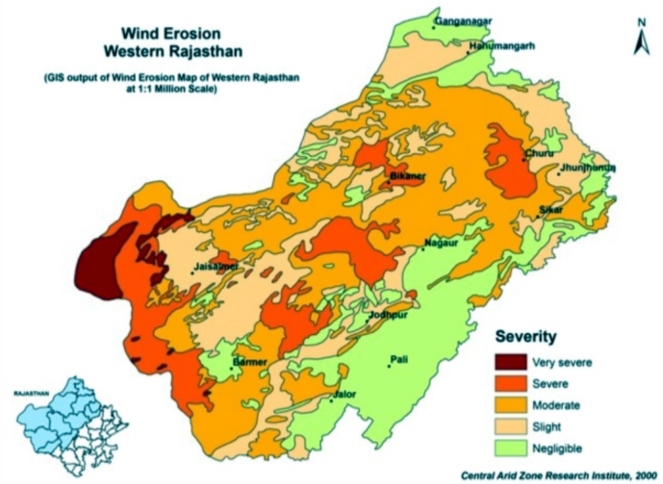

Fig. 5.

Wind erosion in western Rajasthan.

Ramakrishna et al. (1990) measured during a gusty wind the sand transport on a dune crest at Shergarh, situated 100 km away from Jodhpur, as 46 kg/m2/hour. Kar (1994b, 2013) measured the movement of few barchans near Pokaran for 5 years and found a mean mobility rate of 32 m per year. Gupta (1993) found soil loss from a sandy soil much higher than from a loamy sand soil and that clod formation and vegetation were also important factors. At wind speed of 20 km/h the grass cover on a sandy soil at Chandan near Jaisalmer reduced erosion to 76.7 kg/ha/day, while a bare sandy soil at Bikaner lost 273.7 kg/ha/day. Effects of tillage, presence of crop stubbles are also important influencing factors in wind erosion. Excessive tillage before the kharif was found to lower the percentage of clods and thus increase the rates of wind erosion. Measurement during a sandstorm at Bikaner showed more erosion from a bare sandy soil plot (1449 t/ha) than a crop field nearby with a cover of 45 cm high pearl millet stubble (22 t/ha). Fields deep ploughed using tractors lost heavily (mean loss of 2837 t/ha) than soils under 8-12 per cent cover of natural vegetation (472 t/ha; Dhir et al., 1992). Using a CAZRI-developed sand sampler, Santra et al. (2010) reported soil loss during a sand storm in 2004 as 827 kg/ha from an overgrazed site at Jaisalmer and 240 kg/ha from a controlled grazing site at Chandan. They also showed how aeolian mass flux got reduced with height above the surface. Soni et al. (2013) used erosion pins to measure sand loss from different crop fields at Bikaner.

Fluvial process measurements:

CAZRI carried out a detailed field-based measurement of water erosion in a small upland stream catchment on a hill-rocky/gravelly pediment - colluvial plain sequence at Agolai near Jodhpur (9.3 ha, second order ephemeral channel, 1.0 - 1.4 km long and 1.0 - 1.5 m deep), which involved repeated measurement at fixed locations to record channel configuration, water and sediment flow, and other parameters during and after a rainfall event for a number of years. A rough estimate of velocity was made by measuring the time required for a float to travel a fixed distance along the stream at selected cross-sections. To monitor bed load movement along the main channel, key particles >2 mm size were coloured and placed at different locations of the channel. All the particles were grouped under weight groups of >100 g, 51-100 g, and <51 g. For understanding aspects of shape factor and sediment movement, the degree of flattening (flatness index) of each particle was calculated and was measured under three categories: <25, 26-50 and >50. During 2007, two high rainfall events of 42 mm and 52 mm generated measurable runoffs with peak discharge of 20 m3/s (upstream) and 13 m3/s (downstream). These moved the bedload sediments to distances of 43-141 m in the upstream, 6-28 m in the middle reach and 63-95 m in the lower reach. The long and cross profile measurements showed a sequence of alternate deposition and erosion throughout the channel with a marked asymmetry in the form of concavity (scours) and convexity (fills) in the lower reach. Cross profile measurement showed bank cuts (6 cm) and vertical incision (1-2 cm) on the rocky-gravely V shaped valley in the upper reach, incision (4-30 cm) and localized higher deposition (10-12 cm) in the narrow (<1 m) and deep (1.5 m) U shaped valleys in the middle reach and mainly deposition (13 cm) on the wide (1-4 m) and shallow channels (0.1 to 0.2 m) in the lower reach. The rain storms showed more impact on the bed load movement. Analysis of particle weight and distance moved by them indicated, 62.5% particles in the upper reach (av. wt = 214 g), 87% in the middle reach (av. wt = 129.7g) and 26.4% in the lower reach (av. wt = 83.1 g) moved less than 50 m distance. Among the lighter weight group (<50 g) the highest (124.56 m) and the lowest displacement (28.80 m) were recorded at upper and middle reaches, while the maximum displacement (60-70m) of heavier particles (>100 g) occurred in the lower reaches. Similarly, less flat particles (FI 0-25), moved maximum in the lower section and minimum in the middle section. The more flat particles (FI >50) moved maximum distances in the upper reach. In general it was found that particles <50g weight and less flat (FI = <25) experienced the highest displacement (95-106 m).

These spatio-temporal bed load movements presented a view of cascading flow as generally is noticed during desert floods (Moharana and Kar, 2010).

Simulation of a revived drainage system after flood:

Several major floods have occurred in the region during the last four decades, the most notable ones taking place during 1975, 1979, 1983, 1990 and 2006. The 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. The floods 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, 1994a). 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). During that event from17th to 24th August, several stations in the northern part of Barmer district and adjoining part of Jaisalmer district were inundated because of 300-400 mm rainfall *(Fig. 6)*. The catchment areas have a number of dry streams that are partly covered by low sand dunes. It was found that in the flow path of the flood water in the upstream areas, there were many water conservation structures which breached almost simultaneously under the high intensity rainfall, resulting in a huge surge of water through the dry channels. Some abandoned channels were also revived. A GIS and remote sensing based channel simulation of the area revealed the part revival of a major right-bank tributary of the Luni River (Kar et al., 2007b). Earlier it was believed that the Lik River, originating near Pokaran in Jaisalmer was the westernmost right-bank tributary of the Luni, but the 2006 flood revealed a longer right-bank tributary from near Mehreri in Jaisalmer district that carried the waters of Rohili River catchment from Shiv-Kotara area and other streams from the Baisala hills catchment and the Luni hills catchment, to Kawas and beyond. Beyond Kawas, the stream possibly used to meet the Luni to the south of Sindri, but got subsequently dismembered by high sand dunes. The sediments washed down from uplands

Fig. 6.
Flooded interdune plain at Malwa near Barmer in 2006.

contained micaceous clay having 8-15 times higher N (880-3234 kg ha -1), 3-4 times higher P (20-55 kg ha-1) and 2-9 times higher K (270-1249 kg ha-1) than in the underlying soils, making the land much fertile than before (Kar et al., 2007b). Thus, the study indicated that even in a desert, the old and the abandoned stream courses are potential sites for disaster if their passage is obstructed.

Desertification mapping:
Based largely on field- and aerial photo-based mapping, CAZRI first prepared a desertification map of western Rajasthan in 1977 for the UN Conference on Desertification at Nairobi. In the early 1990's, CAZRI carried out a satellite-based mapping at 1:1 M scale, for which 1:250,000 scale FCCs of Landsat-TM images for 1989-1991 were visually interpreted. According to the above mapping, out of 20.875 m ha area mapped, 19.175 m ha (92% of the total mapped area) was degraded, and the rest was free from any degradation. While 33% area was slightly affected, 35% area was moderately affected and 24% severely. Wind erosion constituted the largest area (~ 76% of the total mapped; 25% slightly affected, 35% moderately and 15% severely). Water erosion was mapped in 15% area, while waterlogging and salinity was mapped in 6% area. The institute then suggested a set of field indicators that helped researchers to interpret the levels of land degradation due to wind erosion and other forms of degradation (Singh et al., 1992).

In 2007 CAZRI prepared a desertification status map (DSM) for arid Rajasthan and Gujarat at 1:1 M scale, which formed a part of the country's map on land degradation for the Thematic Programme Network-1(TPN-1) of UN Convention to Combat Desertification *(Fig. 7)*. The mapping revealed that ~76% area of western Rajasthan was affected by wind erosion, encompassing all the major land uses, but mostly under croplands and dunes/sandy areas, while water erosion affected ~2% (mostly in croplands and scrublands), salinization ~2% (mostly in croplands) and vegetation degradation ~3% (especially in scrublands and forests). Mining activities had spoiled only 0.10% area, and degraded rocky areas covered 1% area. About 18% area was severely degraded and 66% slight to moderately, while 16% area is not affected by degradation (Kar et al., 2007a). This national mapping was coordinated by the Space Applications Centre (SAC) of the Indian Space Research Organisation (ISRO), and used a 3-tier classification system for interpreting the images of 2003 to 2004 from AWiFS sensor on board India's IRS-P6 satellite (SAC, 2007). A review of the above desertification researches, including control methods adopted by CAZRI, is provided in Kar et al. (2009).

In 2013-16 CAZRI participated in the DSM Cycle-II project of SAC to map the degradation in Rajasthan state from satellite data for 2011-13, and to find the changes from the earlier mapping with satellite data of 2003-05. The map for 2011-

13 indicated that as per 2011-13 data, 62.90% area of the total geographical area of Rajasthan (34223900 ha) was affected by various process of desertification *(Fig. 8)*. This indicated an overall decrease of degraded area by 99092 ha (from 21625604 ha or 63.13% in 2003-05 to 21526512 ha or 62.90% in 2011-13). Area affected by wind erosion / deposition covered the maximum area: 15332053 ha (44.80%) in 2003-05 and 15197873 ha (44.41%) in 2011-13, indicating a decrease by 0.39% area. Water erosion affected about 2116315 ha (6.97%) in 2011-13 data, indicating an increase by 0.8% area in comparison to 2003-05. Vegetation degradation was assessed in 2606222 ha (7.61% area) in 2011-13, an increase by 0.03% area over 2003-05. Area under salinity/alkalinity declined by 1898 ha (Moharana et al., 2016).

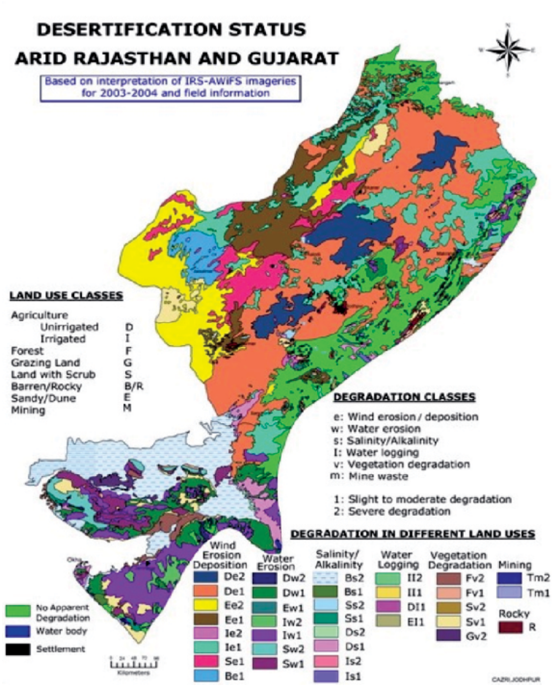

Fig. 7.
Desertification status in arid Rajasthan and Gujarat (2003-04).

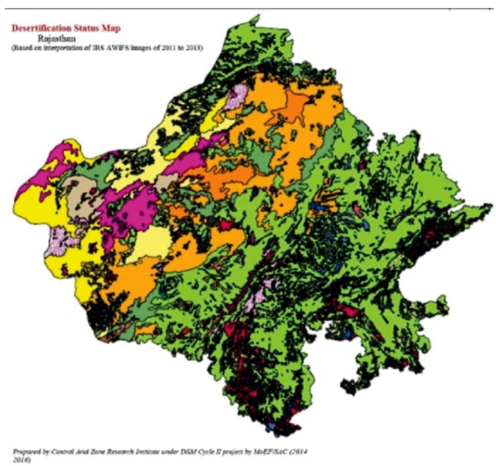

Fig. 8.
Desertification status map of Rajasthan (2011-13).

Socio-economic Conditions

Despite the limitations of an arid environment, Thar Desert in western Rajasthan has a high population density for any desert. According to the 2011 census, human population is 28.15 million, and may reach 41 million by 2031. In case of livestock, the 2012 census shows a total of 30.18 millions (20.5% cattle, 13.0% buffalo, 22.8% sheep, 42.4% goat, 0.9% camel). Both the human and the livestock population are showing an increasing trend in the region. Between 1961 and 2011 census, human population in western Rajasthan has increased by >250%, while between 1956 and 2012 census, the animal population has increased by about 125%. Cattle population has increased by 57.7%, while sheep and goat populations have increased by 44.8% and 26.6%, respectively. The most spectacular increase has, however, been in case of buffalo, which has increased by 412.5%, especially in the irrigated areas. The patterns of human population in different districts of Rajasthan state during 1991, 2001 and 2011 census are shown in (*Fig. 9)*.

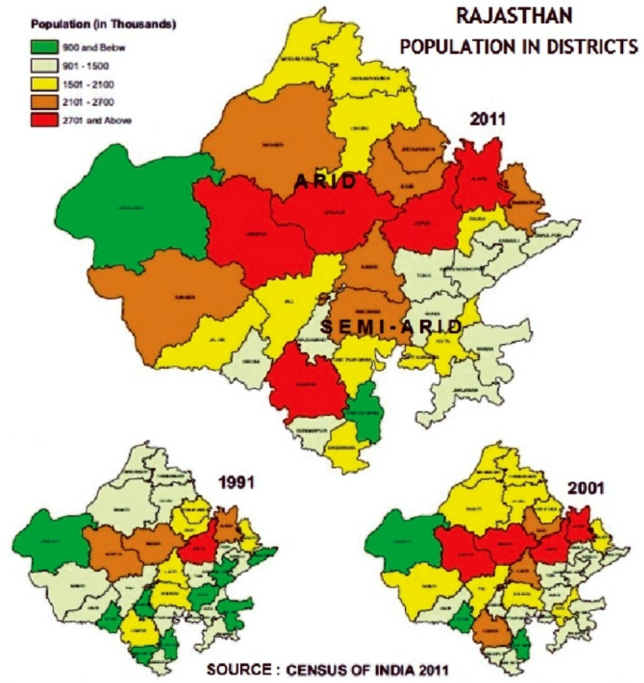

Fig. 9
District-level population in Rajasthan state.

Irrespective of frequent droughts, the region has a dominant agricultural economy. The land use mapping by CAZRI for 2005-06 shows 61.15% area of western Rajasthan under cultivation, which includes 51.19% as net sown area, 9.96% as double cropped area and 12.97% as net irrigated area. Wastelands were mapped in 29.4% area *(Fig. 10)*. When compared with an earlier land use map by CAZRI, prepared in 1982-83, an increase in net irrigated area by 128%, and in double cropped area by 70% is noticed, whereas a decline of culturable waste area by 7.70% took place. An analysis of production and income for the period 2007-08 showed that in the four agro-climatic

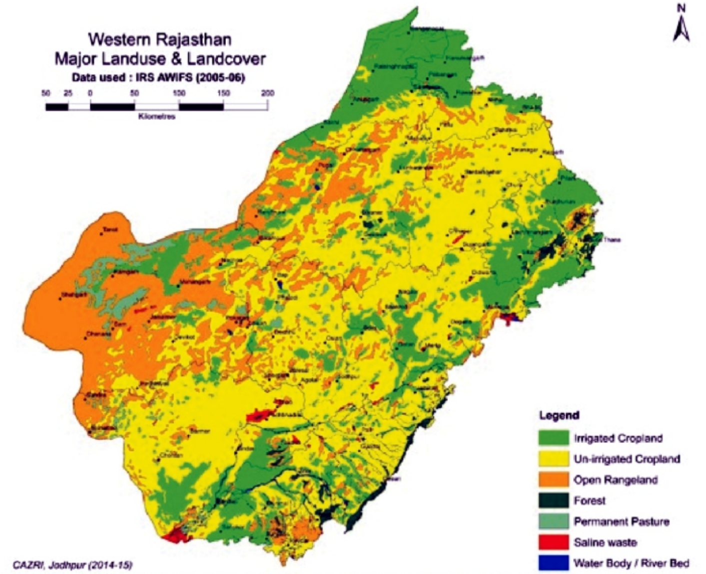

Fig. 10.
Land use and land cover in western Rajasthan (2005-06).

zones of western Rajasthan, income from agricultural sector contributed 26-43% of the total income, the mining 1.6-1.8%, and other sectors like service, business and allied activities contributed 56-73% of the total income (CAZRI Vision 2030). In agricultural sector, income from cropping provided 59-71% of the total agricultural income, while livestock provided 28-42%.

Net sown area in western Rajasthan is showing an increasing trend, mainly at the cost of fallow lands. According to the land use statistics for 2010-11 the net sown area in western Rajasthan was 56.8%, current fallow 4.7% and other fallow lands 5.8%. Forests occupied 3%, pasture 4%, land put to non-agricultural use 5%, and barren uncultivable land 4.8%. The net irrigated area is 13% of the total geographical area.

Pearl millet, grown during the summer monsoon (Kharif season) in about 4.2 million ha (m ha) area, is the major food crop in western Rajasthan, and a staple food of the inhabitants, especially in the rural areas. The region produces 25% of the country's total pearl millet production. Cluster bean, Moth bean, Cowpea and Horse gram are the other major crops grown during the Kharif season. Area under cluster bean is about 2.8 m ha. Moth bean is cultivated in about 1.6 m ha. Sesame, groundnut, castor are also grown in significant area. Since rainfall is highly erratic and drought occurs frequently, Kharif crop production has high inter-annual variation. CAZRI and few agricultural universities have developed several drought-resistant and early-growing crop varieties that help to improve the crop production. Cotton is grown mainly in the northern part. During winter several irrigated crops are grown, which include wheat, mustard, some pulses, chilli and several spices and medicinal plants like coriander, cumin, garlic, isabgol, fennel and fenugreek. These winter crops are essentially the cash crops, and provide good income to the farmers. Gram is also grown, but mostly in conserved moisture.

Important horticulture crops of the region are Ber (Ziziphus mauritiana), pomegranate, Aonla (Emblica officinalis) and Bael (Aegle marmelos). Date palm is also grown with some success. Medicinal plants like Aloe vera, Sonamukhi are also grown. Areas surrounding the major towns and cities grow vegetables in limited areas. Broadly, the region has now surplus production of cereals and pulses but production of oilseeds, fruits and vegetables still lag behind. The overall progress of agriculture is the result of improvement in agro-technologies, infrastructure development and irrigation water availability in the form of groundwater wells, IGNP Canal and Narmada Canal. However, few problems of waterlogging and soil salinity due to faulty irrigation need proper management.

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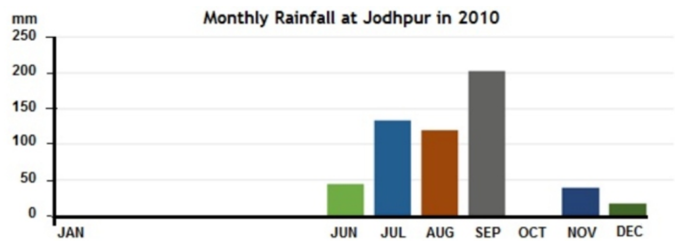

Fig. 11.
Monthly rainfall at Jodhpur in 2010.

B. DESCRIPTION OF THE FIELD SITES

Day 1: 12/11/2017
New Delhi to Jodhpur by Flight
Visit to CAZRI and Mehrangarh Fort
Stay at Jodhpur.

The first day of the visit will be spent on visiting the office and research facilities of Central Arid Zone Research Institute (CAZRI) Institute at Jodhpur, followed by a visit to Mehrangarh Fort to have a bird's eye view of Jodhpur city and the terrain around it. Jodhpur, popularly known as the "Sun City", is the second largest city in Rajasthan, having a population of 1.14 million (2011 census). Being located in the desert proper the city experiences extremes of weather. The peak summer temperature during May often crosses 47°C, the mean maximum being 41.2°C, but the highest recorded so far is 48.9°C. The minimum temperature is recorded in January, when the mean minimum value is 9.6°C, while the lowest recorded is -2.2°C. The mean annual rainfall in the city is 359 mm, received 20 days, but with a coefficient of variation of 46%. The highest rainfall received in any year was 815 mm, while the minimum received was 91 mm. About 90% of the annual total is received during the summer monsoon months of June to September (*Fig. 11*). The highest one-day rainfall received was 157 mm on 31 July 1990.

Stop 1: CAZRI Research Facilities and Farm at Jodhpur

The headquarters of Central Arid Zone Research Institute (CAZRI) is located in the southern part of the Jodhpur city, where it has its main research farm and experimental laboratories. The Institute had a humble beginning in 1952 as a Desert Afforestation Research Station. In the early 1950s there was strong apprehension among the academicians and policy makers in India that the Thar Desert was spreading towards the wetter east at an alarming rate, and that it might engulf large fertile areas of present day Punjab, Haryana, Delhi, western part of Utter Pradesh and the eastern part of Rajasthan. The climate of the period was marked by low rainfall, high wind speed and high frequency of droughts. The Government of India, therefore, established a Desert Afforestation Research Station at Jodhpur in 1952, mainly to focus on sand dune stabilization and shelterbelt plantations, so as to check wind erosion. In 1957, the Station was reorganized as Desert Afforestation and Soil Conservation Station. On October 1, 1959 Government of India, on the advice of Dr. C.S. Christian, a UNESCO expert from CSIRO, Australia, reorganised the Station into a major centre for arid zone research, called the Central Arid Zone Research Institute. While proposing the Institute, the guiding principles were spelt out as study of fundamental aspects of the problems and development of principles of control measures. More focus was laid on a holistic approach that recognizes the fragility of the arid landscape and strength of the region in mixed agriculture, consisting of both crops and livestock. In other words, the Institute was created for research addressing the environmental and livelihood-based issues of the region, with emphasis on conservation agriculture. This was one of the first International Institutes of its kind funded by UNESCO under its programme of International Studies on Arid Zones. On April 1, 1966 CAZRI was brought under the administrative control of Indian Council of Agricultural Research *(Fig. 12)*.

Fig. 12.
Central Arid Zone Research Institute's main building at Jodhpur.

At present, CAZRI has five Regional Research Stations (RRSs) at Bikaner, Jaisalmer and Pali in Rajasthan, at Kukma-Bhuj in Gujarat and at Leh in Jammu and Kashmir. The RRS at Leh was established in August, 2012 to address the agricultural problems of cold arid region. CAZRI also has three agricultural technology centres, or the Krishi Vigyan Kendras (KVKs), located at Jodhpur, Pali and Kukma-Bhuj. The institute also manages five experimental field areas for range management studies, and hosts an All India Network Project on Vertebrate Pest Management that has many sub-centres in agricultural institutes and universities across the country. At present the mandates of the institute are: (a) basic and applied research on sustainable farming systems in the arid ecosystem, (b) repository of information on the state of natural resources and desertification processes, (c) livestock-based farming systems and range management practices for the chronically drought-affected areas, and (d) generating and transferring location-specific technologies.

Since its inception, CAZRI has been following an integrated resources management approach. It has carried out landmark research on subjects like: assessment, monitoring and management of natural resources of the Indian arid zone; development of integrated farming systems; improvement of crops, grasses, shrubs, trees and fruits; livestock production and management; use of alternate energy resources, etc. The institute has evolved strategies for combating drought and desertification. It has developed several need-based and cost-effective technologies like shelterbelt plantation, wind erosion control, sand dune stabilization, watershed development, rehabilitation of wastelands, arid land farming systems, alternate land use strategies, range management, pest management, post-harvest technologies and value addition of crops and livestock products, development of farm implements

Fig. 13.
An improved variety of Ber during the fruiting season.

Fig. 14.
A demonstration of some fruits developed by CAZRI.

useful for the dry sandy terrain, etc. Several solar energy devices like solar cooker, solar water heater, animal feed solar cooker, solar dryers, solar candle making device, PV duster, PV winnower, PV based water pumping system for irrigation, etc., have also been developed. CAZRI's improved varieties of Ber *(Fig. 13)* provides the desert farmers a cost-effective means to combat severe droughts when most crops fail to survive, as the plant requires less water than the crop plants and need less maintenance, while the farmers can reap the harvest of its nutritious fruits, fodder from its leaves and fuel wood from its branches. These and other horticultural products have become very popular in India and abroad *(Fig. 14)*. Its pearl millet varieties have also proved to be wonder crops as these can withstand early and mid-season droughts, and are quick-growing with adequate grain and fodder

Fig. 15.
CZP 9806,
an improved variety of pearl millet from CAZRI.

production *(Fig. 15)*. CAZRI's aloe-based research has produced some popular health and food products. Many of the silvo-pastoral, agronomic, horticultural and other plant-based experiments, with emphasis on dryland farming technologies, are conducted at the institute's Research Farm at Jodhpur. Farmers and other stakeholders from the region are invited regularly to demonstration of results during the cropping season, when they are also guided about the methodologies, post-harvest technologies, etc. The institute remains in direct contact with the farmers through its extension wing and three KVKs. An Agricultural Technology Information Centre (ATIC) caters to the needs of the farming community and others interested in the technologies and produce of CAZRI. The institute also works in close liaison with several national and international institutes and stakeholders working for the development of arid agro-ecosystem. CAZRI takes pride in developing since inception 52 research areas for silvopasture, where it conducted elaborate grazing studies and demonstrated the benefits of range management, as also the methodologies for sand dune stabilization, shelterbelt plantation, etc. After developing the research areas CAZRI handed them over to the Government of Rajasthan, except the five experimental areas mentioned above.

Stop 2: Mehrangarh Fort

Mehrangarh Fort is one of the tallest and imposing forts in India *(Fig. 16)*. Built in 1460 by Rao Jodha on a rhyolite hillock, the fort is situated 410 feet (125 m) above the city and is enclosed by imposing thick walls. Inside the fort there are several palatial buildings known for their intricate carvings and expansive courtyards. A winding road leads to and from the city below. There are seven gates of the fort, which include Jay Pol (meaning victory gate), built by Maharaja Man Singh to commemorate his victories over Jaipur and Bikaner armies, and Fateh Pol (also meaning victory gate), which was built by Maharaja Ajit Singh to mark the defeat of the Mughals. The palm imprints on these gates still receive much tourist attention. The fort was constructed when the ancient palace at Mandore, the capital of Marwar State for a long time, was to be shifted due to frequent attacks by

Fig. 16.
Mehranagarh Fort at Jodhpur.

the enemies. Mandore is located about 7 km to the north of the fort, and is now a tourist destination for its beautiful garden, and the cenotaphs erected in memory of the several kings of Marwar.
The museum in the Mehrangarh fort is one of the well-stocked museums in Rajasthan. In one section of the museum there is a selection of old royal palanquins, including the elaborate domed gilt Mahadol palanquin, which was won in a battle from the Governor of Gujarat in 1730. The museum exhibits the rich heritage of the then-ruling Rathore clan in the form of arms, costumes, paintings and decorated rooms.

Day 2: 13/11/2017
Jodhpur to Agolai, Balesar, Shetrawa, Dechu, Pokaran, Chandan and Jaisalmer
Stay at Jaisalmer.

Jaisalmer is located about 300 km west of Jodhpur, and the route is through a variety of sandy and rocky-gravelly terrain, with spectacular views of the parabolic sand dunes, the playas, the pediments and pavements, as well as sandy undulating plains. The rainfall decreases gradually westward from Jodhpur. Balesar, at a distance of about 65 km from Jodhpur receives an annual rainfall of ~285 mm, while Pokaran, about 165 km from Jodhpur receives 203 mm, and Jaisalmer, 300 km west of Jodhpur, receives 195 mm. Further west, Sam, about 50 km from Jaisalmer, receives 180 mm. As the rainfall decreases, so does the rainy days. This change is reflected in a gradual decline in plant cover westward, as well as an increase in aeolian features. Topographically, we shall move towards a lower elevation which varies from about 230 m at Jodhpur to 225 m at Jaisalmer.

Landforms will be both rocky and sandy, with a distinct nodular carbonate horizon at some depth. Radiocarbon dating of the $CaCo3$ nodules near Jodhpur has suggested its formation between 40k and 20k BP. This phase was followed by a major dry phase when much of the present day dunes were formed. Another major wet phase arrived during 10k to 3.8k B.P which prevailed upon to stabilize the bigger dunes. So terrain at Jodhpur will have low hillocks (rhyolite and sandstone), followed by low denuded rhyolite hillocks at Agolai, sandstone (rocky uplands) and sand dunes at Balesar (sandstone mining area), Shetrawa, Dechu. The saline depressions will appear amidst the sandy terrain at Khara Bhagotiya, Lawan and Pokaran. From here, the terrain will be almost flat and some extensive desert pavements will be the major feature. It will be a different rocky /gravelly pavement surface between Chandan and Jaisalmer where tone will see occurrence of rounded and surrounded gravels. This may suggest a marine connection to this region in the distant past. Intermixed with rocky plains, there will be scattered patches of sandy plains, low dunes till Jaisalmer.

Stop 1: Agolai Hills and Pediments

Agolai is a small town about 40 km west of Jodhpur, having hill - rocky/gravelly pediment - colluvial plain sequence on rhyolite *(Fig. 17)*. A narrow shallow belt of palaeochannel can be seen as one approaches the town towards Jaisalmer. Dominantly because of rainfed situation, people of this region has adopted to conserving the meagre rainfall of few days in the ponds which they call the "nadi". Runoff from the low rhyolite hillocks are collected in the nadi within no time (10 to 20 minutes) and the channels (~1 m deep and <1 m wide) dries off faster. However, people cultivate both deep (alluvial plains) and shallow gravel lands for major rainfed crops. It is interesting to see the water conservation structures as well as a shallow khadin at the distal end.

Fig. 17.
Hill-pediment on rhyolite at Agolai.

Stop 2: Balesar Sandstone Mines

At Balesar, the Jodhpur Sandstone is being quarried from the late 1970's for use as building material *(Fig. 18)*. The expansion of the quarries and dumping of rubbles on the adjacent plots have spoilt some marginal agricultural lands *(Fig. 19)*. Adjacent to such mine areas one can see 20-45m high sand dunes and large interdune plains *(Fig. 20)*. Almost all the high sand dunes are in parabolic form, occurring either as isolated parabolic or in chains of coalesced parabolic dunes. Weak segregation of CaCO3 within the dunes leads to formation of minor kanker nodules; silt and clay percentage varies from 2 to 6 percent only. In spite of natural stability the higher dunes are subjected to excessive pressure of cultivation, grazing and other form of exploitation. Result is high reactivation of the dunes, formation of mobile barchanoids along their slopes (Fig. 21).

Fig. 18.
Sandstone mine at Balesar.

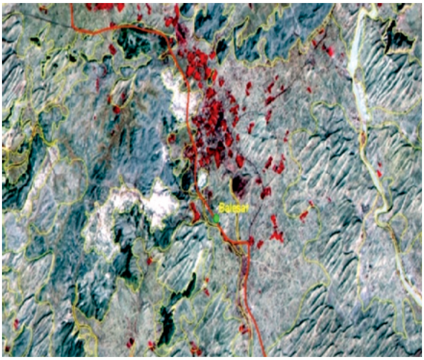

Fig. 19.
IRS-L3 FCC image of the Balesar sandstone mines and surrounding landscape.

Fig. 20.
Google Earth image of parabolic dunes and interdune plains near Balesar.

Stop 3: Shetrawa Parabolic Dune - Stabilization

Shetrawa is a small town 36 km away from Balesar, and has a dominantly sandy landscape with rock outcrops and scattered desert trees *(Fig. 22, 23)*. The sand dunes (parabolic type) are well vegetated, 20-30 m high and exhibit sand reactivated slopes and crest, situated on the left side of the NH 114. Attempt is on to check sand mobility from the dune fields using stabilization techniques like checker board pattern or parallel strips of locally available shrubs *(Fig. 24).*

Fig. 21.
Field photograph of parabolic dune near Balesar.

Stop 4: Dechu Parabolic Dunes – Land use

Dechu is located 20 km away from Shetrawa on the Jaisalmer road. This is a major sandy upland area indicating much of the aeolian activity in the past. Dunes are 20-30 m high and possess well developed flanks *(Fig. 25)*. Looking at the aspect of wind erosion activity and sand accumulation on the nearby highways, most of the sand dunes surrounding Dechu village area especially in the north, are under process of stabilization through tree plantation *(Fig. 26)*.

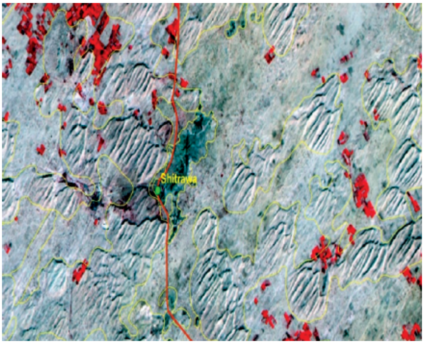

Fig. 22.
IRS-L3 FCC of
dune landscape around Shetrawa.

Fig. 23.
Google Earth view of stabilized
and other sand dunes near Shetrawa.

Fig. 24.
Field view of a sand dune at Shetrawa.

Fig. 25.
Field view of a sand dune at Dechu.

Fig. 26.
Sand dune stabilization through plantation near Dechu.

Stop 5: Lawan and Pokaran Playas

Distance between Lawan and Pokaran is 16 km. Geographically it has both rocky and saline landscape at an average elevation of 233m. The rocky tract is interspersed by number of playas or saline depressions, locally called ranns, with steep bounding rocky slopes, near Dediya, Lawan *(Fig. 27, 28)* and Pokaran *(Fig. 29, 30)*. All these ranns were formerly connected through a stream. Soils are saline and so is the ground water. The pH is 7.6 at surface to 7.4 at 40-60 cm. Ec is 22.9-14.5 dS m-1. Other major landforms are: isolated hills, pediment, pediplain complex, hamada (high level rocky structural plains), gravelly pavements and barchans. Most numerous natural vegetation are Z. numularia, Caparis decidua, salvadoraoleoides. Lasiurus sindicus is the most dominant grass of the region, highly nutritive, therefore has high fodder value.

Fig. 27.
Saline playa at Lawan.

Fig. 28.
Google Earth view of the playa at Lawan.

Fig. 29.
Saline playa at Pokaran.

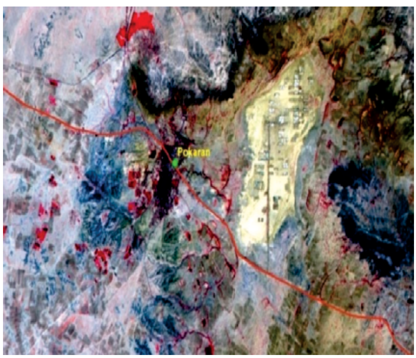

Fig.30.
Satellite view of Pokaran playa and surroundings.

Stop 6: CAZRI Research Farm at Chandan

This is a village between Lathi and Jaisalmer, located about 20 km away from Lathi. This area can be best described as a barren sandy landscape which is suitable for rangeland development *(Fig. 31, 32)*. The terrain is sculptured into rocky / gravelly plains, sand sheets and uplands in the form of linear and barchan dunes with complex formations. CAZRI has one of its research farms (under the Regional Research Station, Jaisalmer) that addresses the regional issues of grasslands / rangelands and crops under pressurized systems for this region *(Fig. 33)*.

Fig. 31.
Google Earth view of sandy plain having barchans at Chandan.

Fig. 32.
Degraded grassland at Chandan.

Fig. 33.
Lasiurus sindicus grass grown by CAZRI at Chandan.

Stop 7: Bhojka Gravel Pavement

On route from Chandan to Jaislamer, one can see a different terrain with moderate uplands and depressions. Bhojka and Basanpir are two of the intermediate villages, within 15 km distance on the highway. The pebbles and cobbles are typical form of Bhojka gravels and are of research interest as origin of these sediments are said to have fluvial connection *(Fig. 34)*. Soils are sandy at the surface and either sandy or loamy sand in subsoil, underlain at variable depth by weakly developed or moderately developed lime concretionary zone, or weathered rock or gravels/pebbles. The environment is similar to Chandan. Besides, this is the place of occurrences of extensive desert pavements, the surface having greater assemblage of rounded pebbles, cobbles and few haematitic gravels *(Fig. 35)*. Such type of sediments can be linked to possible fluvial action during a wetter climate in this region.

Fig. 34.
Gravel pavement at Bhojka.

Fig. 35.
Rounded to sub-rounded pebbles at Bhojka.

Day 3: 14/11/2017
Jaisalmer to Damodara, Kuldhara, Sam and back
Stay at Jaisalmer.

Jaislamer district is spread over 38401 sq. km area in the heart of Thar Desert in India, and is one of the largest districts whose area will be almost equal to one of the states, Kerala. There is no perennial river in the district, but few ephemeral and buried channels do exist. The underground water level is very low. The climate is extremely hot during summer with maximum temperature reaching up to 49.2 degree Celsius and extremely cold during winter with minimum temperature of 1 degree Celsius. Mean annual rainfall is 195 mm *(Fig. 36)*. The terrain within a radius of about 40 km is stony and rocky. The area is barren, undulating with a number of landforms of aeolian, tectonic, lacustrine, fluvial origin with great variability. The traverse from Jaisalmer to Sam (about 45 km on the highway) will be a low undulating terrain (234 m at Jaisalmer to 179 m at Sam) with more of rocky plains with scattered appearances of low sand dunes. The hamada, cuesta, rock weathering and erosional features will be of interest to the geomorphologists. Finally, the rocky terrain will be cut short by an extensively formed sandy landscape at Sam (a linear dune field with barchanic bedforms)

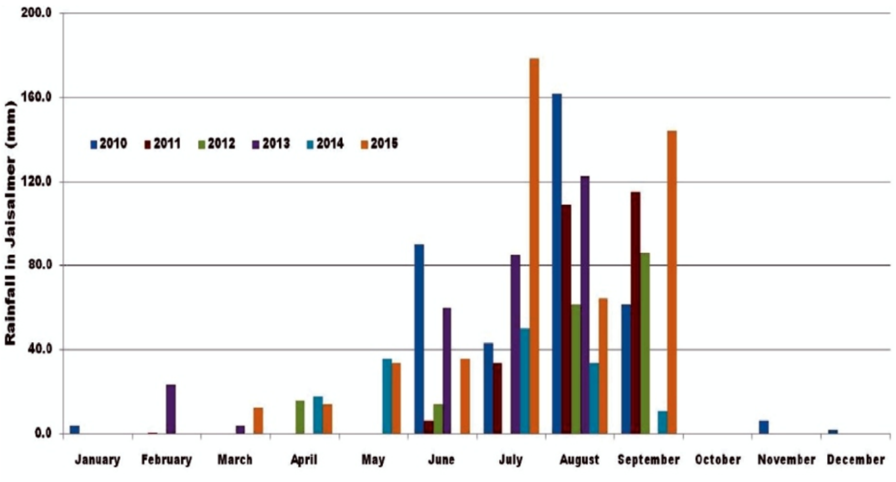

Fig. 36.
Rainfall at Jaisalmer.

Stop 1: Jaisalmer Hamada

Jaisalmer region is also known as both rocky and sandy desert. While you are at Jaisalmer city, a rocky terrain comprising rocky plains, hamadas and desert pavement are in the immediate surroundings (Fig. 37). As one leaves Jaisalmer city towards Lodurva, one encounters first a steep escarpment and then climbs to the top of the rocky structural plains called Hamada on Jaisalmer Limestone (Fig. 38).

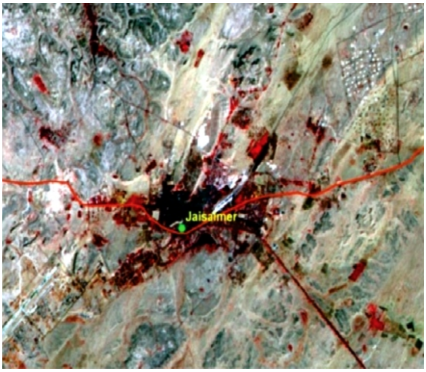

Fig. 37.
Satellite view of Jaisalmer town and its surrounding.

Fig. 38.
Hamada with wind mills at Badabag near Jaisalmer.

Stop 2: Damodara Hill slopes and pediment

The site, about 30 km to the west of Jaisalmer on the Sam route, is an assemblage low rocky upland having pediments and rocky plains *(Fig. 39)*. One can also find some well-developed khadins nearby, once one descends the gentle slope of the hamada to the colluvial plain. Also surfaces and rock features show different stages of weathering and erosion.

Fig. 39.
Rocky landscape near Damodara

Stop 3: Kuldhara, Ancient Settlement

About 15 km west of Jaisalmer lies the ruins of a village which was called Kuldhara. The village was established in 1291 A.D., by the Paliwal Brahmins. The first sight of Kuldhara village, more a town actually, sends one's imagination running to the time it may have been inhabited *(Fig. 40)*. A well-planned settlement, the straight and wide streets ran in grids with houses opening into them. All design elements kept both aesthetics and utility in mind. A kind of a garage opened into the streets to park carts in. Temples, step wells and other structures were all signs of sound development over the centuries.

Fig. 40.
Kuldhara, a deserted and ruined ancient village.

Stop 4: Kanoi Sandy Plain

Kanoi is located 5 km further west on the Sam route after Damodara, and sand starts accumulating before we reach the Sam desert area. The terrain is dominantly rocky with low uplands, weathered morphology with occasional sand deposits *(Fig. 41)*.

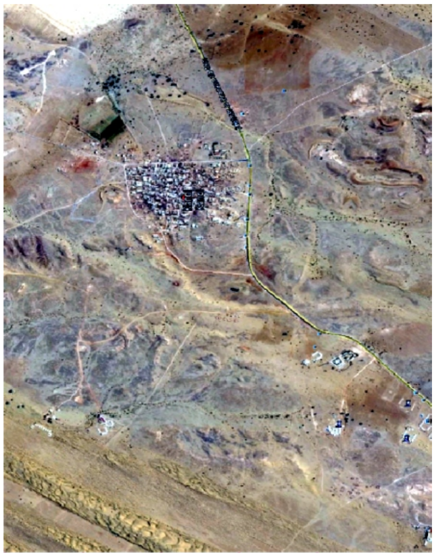

Fig. 41.
Google Earth view of sandy plain at Kanoi.

Stop 5: Sam Linear Dunes

Sam is a tourist place of national importance, about 45 km to the west of Jaisalmer. Because of its aeolian environment and peculiar dune fields, it is one of the must-see sites of Jaisalmer. The region receives annual rainfall of 180 mm and with rocky terrain and almost devoid of any vegetation, this is an ideal place for sand movement, deposition and dune formation *(Fig. 42)*. The major dune systems are longitudinal type. Because of extreme arid situation, dunes become highly reactivated under slightest biotic pressure and start advancing as chains of barchanoids either atop the old forms or in newer areas . During 1978, Government of Rajasthan undertook a programme of stabilization of a part of one longitudinal dune at Sam with technical expertise of CAZRI. The mulching was done with locally available shrubs and grasses. A part of sand dune is left barren and has beautiful chains of barchanoids. This part has become tourist attraction and is known as the Sunset point of Sam. This is also the most mobile part of the dune engulfing newer areas each year.

Fig. 42.
Barchan dunes at Sam.

Day 4: 15/11/2017
Jaisalmer to Baramsar, Mokal, Chhatrel, Rupsi, Lodurva, and to Jodhppur
Stay at Jodhpur.

Broadly the area between Jaisalmer, Mokal, Rupsi and Lodurva is dominantly rocky-gravelly, while the area towards Sam is dominantly sandy. The rocky limestone Hamada surface around Jaisalmer has many wind erosion features, as sand blasting on the softer limestone has cut through the rock *(Fig. 43)*. Down the slope of the Hamada, the low-lying areas or depressions are utilized for runoff farming for winter crops under conserved moisture.

Fig. 43.
Wind erosion feature on limestone Hamada at Jaisalmer.

Stop 1: Baramsar Khadin on Pediment
On way to Mokal, which is about 30 km away from Jaisalmer, Baramsar is a small village located amidst a rocky terrain. The significant features are the number of water conservation structures, locally called Khadin, on the rocky pediment land. The structures represent people's wisdom of conserving water received through rills and narrow but shallow channels emerging from nearly low rocky uplands *(Fig. 44).*

Fig. 44.
Google Earth view of Baramsar Khadin and MithaRann.

Stop 2: Mitha Rann (Playa)

This is a saline playa not suitable for cultivation, but often its margins are used for grazing. These ranns are partly oriented in the dominant SW wind, although a dry valley in the rocky terrain also links these depressions. Kar (1995) thought that strong wind erosion along zones of weakness in the softer limestone terrain and possible groundwater-related weathering could be associated with such rann formation at this place.

Stop 3: Mokal Cuesta and Pediment

Mokal is at a distance of 30km from Jaisalmer town. It is situated in the fringe of dunes and rocky uplands with some dry channels. The rocky landscape is dotted with hamada, rocky/gravelly pediments and pavements *(Fig. 45)*. Interesting features include various rock weathering patterns and erosions due to wind erosion strength in the region.

Fig. 45.
The cuesta with escarpment at Mokal.

Stop 4: Chhatrel Desert Weathering

Chatrail is another rocky upland with hamada nearby. Major landforms are few rock outcrops with dominance of desert pavement. The dry course of some channels are also of interest. One can observe various forms of physical and chemical weathering *(Fig. 46, 47)*.

Fig. 46.
Box weathering near Chhatrel.

Fig. 47.
Honeycomb weathering near Chhatrel.

Stop 5: Rupsi Khadin Cultivation

Khadin is a local system of rainwater conservation, and it preserves the soil moisture in the land to be utilized for agriculture, mainly during winter. Runoff harvested in low-lying areas from the surrounding rocky catchments for practicing agriculture has great significance in this rocky area. In some cases the runoff water is diverted through small channels to farm lands in lower reaches. Bunds constructed across the slope and farm lands lying between the ridges of the catchment are normally inundated with water during monsoon period, but on drying the rabi crops are sown. During drought years, such fields are put under kharif crops. About 84 khadins have now been constructed by the Irrigation Department, Government of Rajasthan. The catchment areas of these khadins vary from 2.5 to 51.0 sq. km, with storage capacity ranging from 0.028 to 2.33 mcm. Some of them are privately owned khadins, constructed by cultivators on their farms. This practice of water harvesting on farmland is thus gaining popularity in the district. One such big khadin is at Rupsi *(Fig. 48, 49)*. According to historical records, the Paliwal clan who resided here in the 15-16th century A.D, developed and perfected this technique.

Fig. 48.
Field view of Rupsi Khadin.

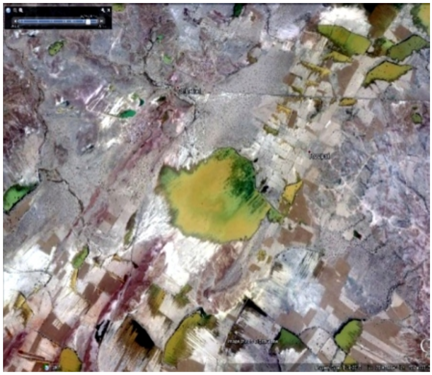

Fig. 49.
Google Earth view of Roopsi Khadin.

Stop 6: Ludarva Temple Architecture

Loduruva, the ancient capital of Jaisalmer, is located along the left bank of a gravelly ephemeral stream named the Kankni Nala. Although in ruins, the site has an old, richly-carved and decorated Jain temple, which has been renovated for its historical and religious importance. The temple shows the skill of local craftsmen in the use of available stones in making architectural beauties *(Fig. 50)*.

Fig. 50.
Jain temple at Lodurva.

Day 5: 16/11/2017
Jodhpur to New Delhi by Flight
Stay at New Delhi.

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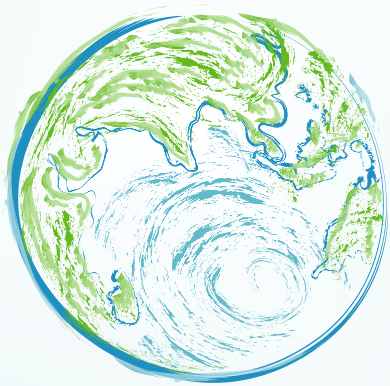

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