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Wind Erosion and its Control in Arid North-West India

J. Venkateswarlu[1] and Amal Kar
Central Arid Zone Research Institute, Jodhpur 342 003, India

Abstract : Wind erosion is a major problem in the arid sandy tract of north-west India, especially in west Rajasthan. To understand the spatial pattern of wind erosion in the region, wind erosivity and erodibility of the terrain have been worked out, which suggest a westward increase in the erosivity with decreasing rainfall and increasing wind velocity. The pattern of erodibility cuts across this gradient. Currently man is the most important agent for acceleration of aeolian process, although the nature of sand reactivation is dependent more on the pattern of erosivity. Many of the problems can be tackled through effective technology intervention like vegetative propagation in the sandy terrain, plantation of dunes, etc., for which the Central Arid Zone Research Institute, Jodhpur has the required expertise. Mechanical methods of control are not very popular, but have their appeal in specific areas. For the success of any technology intervention, however, people's participation will be necessary.

Key words : Wind erosivity, erodibility, assessment, control measures.

Wind erosion is a serious problem in the arid west Rajasthan which forms a part of the Thar or the Great Indian Sand Desert, along with the adjoining sandy arid areas of Punjab, Haryana and Gujarat states (Fig. 1). The region is characterised by low and erratic monsoon rainfall, moderate to high wind velocity during the dry summer months when temperature is also very high, and a dominantly sandy soil in most of its area. Additionally, the present vegetation cover is poor as compared with the situation in the other climatic zones in the country. Thus, the climatic, edaphic and biotic factors culminate in soil erosion through wind action, leading to the attendant problems.

According to the data compiled recently by the Ministry of Agriculture, Government of India, 10.46 million ha of land in India is affected by wind erosion. Out of this total, Rajasthan accounts for 93.8% (9.81 million ha), followed by Haryana (5.1%). Land degradation due to wind erosion has also been reported from Andhra Pradesh (0.4%), Tamil Nadu (0.3%) and Punjab (0.3%). The compiled data do not provide any separate figure for wind erosion in Gujarat, but the area affected by water and wind erosions together is 6.14 million ha. In the arid west Rajasthan, which is most affected by wind erosion, 142,771 sq. km area (68.39% of the total area of the region) is affected by wind erosion alone. The severity classes have been identified for this region as given in Table 1.

Wind erosion leads to the blowing away of the finer soil particles from the ploughed fields, leaving behind the coarser fragments on the surface. At the sites where deposition takes place, the medium to coarse grained sand veneers the surface, thus burying the productive soil. In both the cases, the near-surface sediments become relatively unproductive. Another serious agriculture-related threat of wind erosion is the injury

1. 26-SBI Colony, Gandhi Nagar, Hyderabad 500 080, India

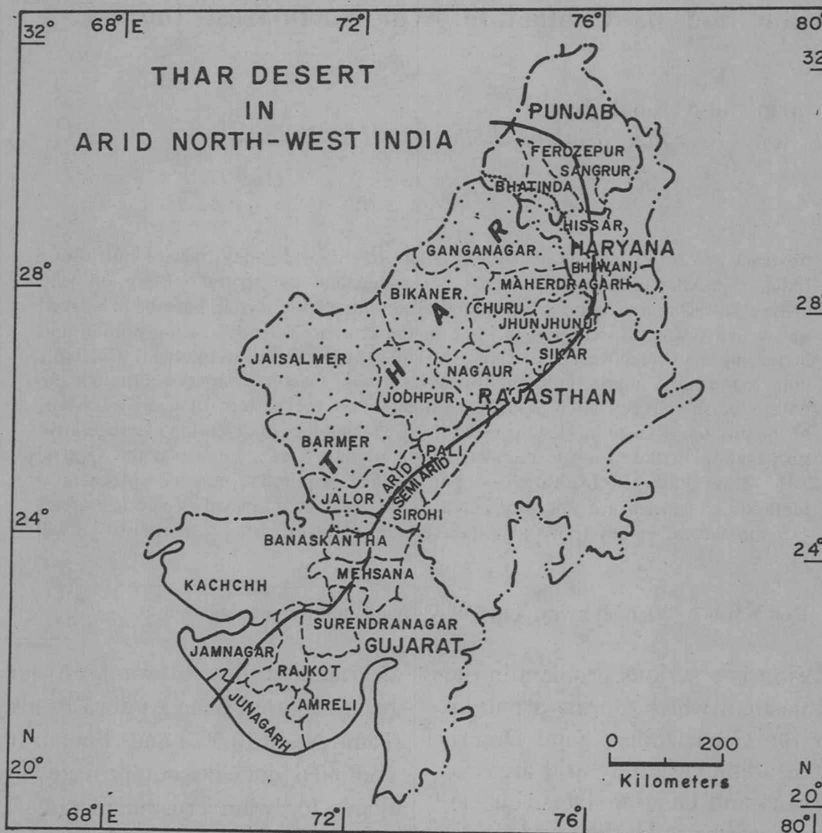

Fig. 1. Thar desert in arid north-west India.

to the plant roots during the sand storms. With the erosion of the soil, the plant roots get exposed and are eventually uprooted. Moreover, the small plants are buried under thick pile of sand under the situation where new sand encroaches a site. Apart from its adverse effects on the soil and plants, wind erosion causes serious problems for the infrastructural facilities. Many roads, railway tracks, canals and settlements are choked with sand during the sand storms, causing serious concern for the inhabitants. The present article provides a short review of the work carried out so far in the arid west India on the wind erosion, its spatial dimension and its control measures.

Table 1. Wind erosion categories in west Rajasthan

Severity of wind erosion	Area (sq. km)	Percentage of total area
Slight	55,121	26.41
Moderate	57,890	27.73
Severe	29,540	14.15
Very severe	220	0.10

Source : Unpublished note, CAZRI, Jodhpur (1993).

Spatial dimension of wind erosion

The two most important determining factors of wind erosion and its spatial variation are the erosive nature of the wind and the erodibility of the terrain. These are again dependent on the climatic characteristics and nature of the terrain, including its vegetation cover. In the arid Thar desert of west Rajasthan, there is a climatic gradient from east to west. While the eastern margin of the arid zone has a mean annual rainfall of 500 mm, the western margin experiences a mean annual rainfall of 150 mm or less. More than 90% of the rain falls during the monsoon which arrives at the eastern margin by the end of June, while in the west it reaches by the middle of July. The wind speed decreases everywhere with the onset of the monsoon. The mean wind speed is higher in the west than in the east.

The terrain in west Rajasthan is dominated by aeolian sand. Sandy landforms, consisting of flat sandy plains, sandy undulating plains, sand dunes and interdune plains, cover about 70% of the total area. The sand dunes are of many kinds (Fig. 2; Kar, 1993), but could be broadly grouped under "old" and "new" categories. Most old dunes were formed at least 10,000 to 15,000 years ago, when the climate was far drier than at present (Singhvi and Kar, 1992). They are naturally stabilised. The new dunes are forming now and consist mostly of the barchans, barchanoids, megabarchanoids, low sand streaks and zibars. Such dunes are mobile and are bare of vegetation. Most of the linear, parabolic, transverse, star and network dunes are old and stabilised to a large extent due to natural causes. They support numerous vegetation communities, including trees, shrubs and grasses (Saxena, 1977), and have many calcified root casts in them (Ghose *et al.*, 1977). However, these dunes are also prone to reactivation under induced conditions.

The sand dunes are constituted of noncoherent sand, but the sandy plains have a sandy loam to loamy sand soil with a dominantly structureless surface layer, followed by a weakly developed subangualr blocky structure in the subsurface.

Erosivity of wind

Wind erosion in the Thar desert is restricted to the period of strong south-west monsoon wind during the summer months. The weak north-east winter wind is a poor agent for such activity. A distinct spatial gradient is noticed in the effectiveness of the process from the wetter eastern margin of the arid zone, adjoining the Aravalli hill ranges, to the very dry western margin (Kar, 1988). There is a gradual fall in the wind velocity in the east, concomitant with the increase in precipitation effectiveness index (PE) in that direction. Kar (1992, 1993) used the following modified Chepil formula (Chepil *et al.*, 1962; Yaalon and Ganor, 1966) to estimate the spatial efficacy of wind erosion :

$$C = \frac{100\,v^3}{2.9(PE)^2}$$

where,

C is climatic wind erosion index;
v is the mean wind velocity at 10 m height;
PE is the Thornthwaite's measure of precipitation effectiveness; and
2.9 is the annual average climatic index at Garden City, Kansas; values at other stations are expressed as a percentage of this figure.

The sand and dust raising winds start blowing in this zone from March onwards when

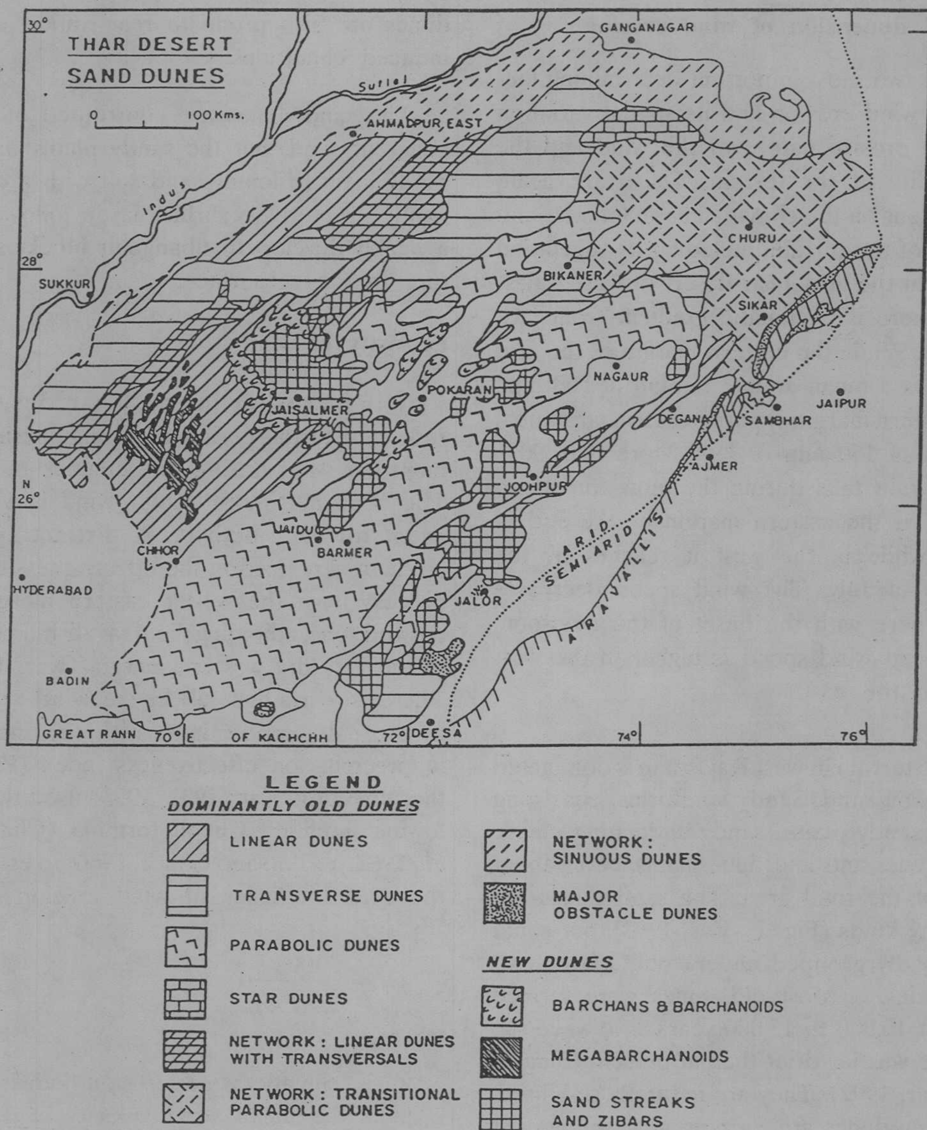

Fig. 2. Types of sand dune in Thar desert.

the terrain is sufficiently dry after the previous monsoon rainfall of July-September. As the monsoon rains reach the eastern margin by the third week of June and the western extremity by the middle of July, the sandy surface provides a greater resistance to the wind, because of the moisture content in the near-surface sediments and sprouting of vegetation. Moreover, the wind speed falls gradually. In other words, the effectiveness of the wind, on an average, could be considered for the period, March to July. Hence, the above equation was applied for March-July only. A new scale of wind erosivity was also prepared and

Table 2. Wind erosion categories for meteorological stations in west Rajasthan and its surroundings

Wind erosion index (%)	Category	Station
480 & above	Extremely high	Jaisalmer
120 - 479	Very high	Phalodi
60 - 119	High	
30 - 59	Moderate	Bikaner, Jodhpur, Pachpadra, Barmer
15 - 29	Low	Ganganagar, Churu, Nagaur
1 - 14	Very low	Hisar, Sikar, Sambhar, Ajmer

Source : Kar (1993).

the spatial pattern of the potential wind erosion was mapped, using the data from the sparse meteorological stations (Fig. 3; Kar, 1993). The results matched well with the spatial distribution pattern of the aeolian bedforms of different kind in the desert, which could be taken as the manifestations of wind erosion. Table 2 describes the wind erosion categories and the meteorological stations in each of the categories.

It is apparent that the area to the south-west of Jaisalmer is under extremely high wind erosion index, while the area roughly between Barmer, Shergarh, Phalodi and Jaisalmer has very high wind erosion index (Fig. 3). To the east of Barmer and Shergarh, and up to Nagaur and east of Bikaner, including Jodhpur and Pachpadra, the erosivity is moderate to high. Beyond Jalor, Pali and Churu in the east it is very low (Kar, 1993).

The present-day mobile dunes in the Thar, including the barchans, form under natural environment mostly to the west of 120 contour of wind erosion index. Megabarchanoids occur in the extremely high index zone, bounded by the 480 contour. The sandy terrain in these areas is highly vulnerable to reactivation (Kar, 1996). Using Bagnold's (1941) formulae of sand transport rate, the long term climatic average of Jaisalmer and the average grain size characteristics of Phalodi - Jaisalmer tract, the average annual theoretical sand transport rate in the very high wind erosion index zone was calculated as about 35 t m^{-1} width (Kar, 1994).

Wind erodibility

One of the crucial factors in sand movement is the nature of the terrain. The characteristics of the near-surface sediment composition, including the soil aggregates and soil texture, make a vast difference in the erodibility of the soil. Gupta and Gupta (1981) observed that a ploughed field in the medium textured soil had 42.4% more clods of more than 5 mm size, with an average weight of 111.8 g $clod^{-1}$, while another field in the same soil, that was ploughed and planked, had only 12.7% aggregates, with an average weight of 1.7 g $clod^{-1}$. During the sand storm of 27 June to 31 July 1979, the ploughed field lost sediments to the tune of 0.5 t ha^{-1}, but the loss from the other field was 40 t ha^{-1}. They noticed that excessive tillage before the *Kharif* sowing reduced the percentage of clods of more than 5 mm size in the soil and, thus, increased wind erosion.

Dhir *et al.* (1992) found that the soil becomes extremely erodible to wind when the clay content in it is less than 5%. The sediments then become structureless and single grain With 6 to 8% clay content (very weak subangular blocky structure), the erodibility is high. As the clay content increases to 9-12% (weak sub-angular blocky structure), the

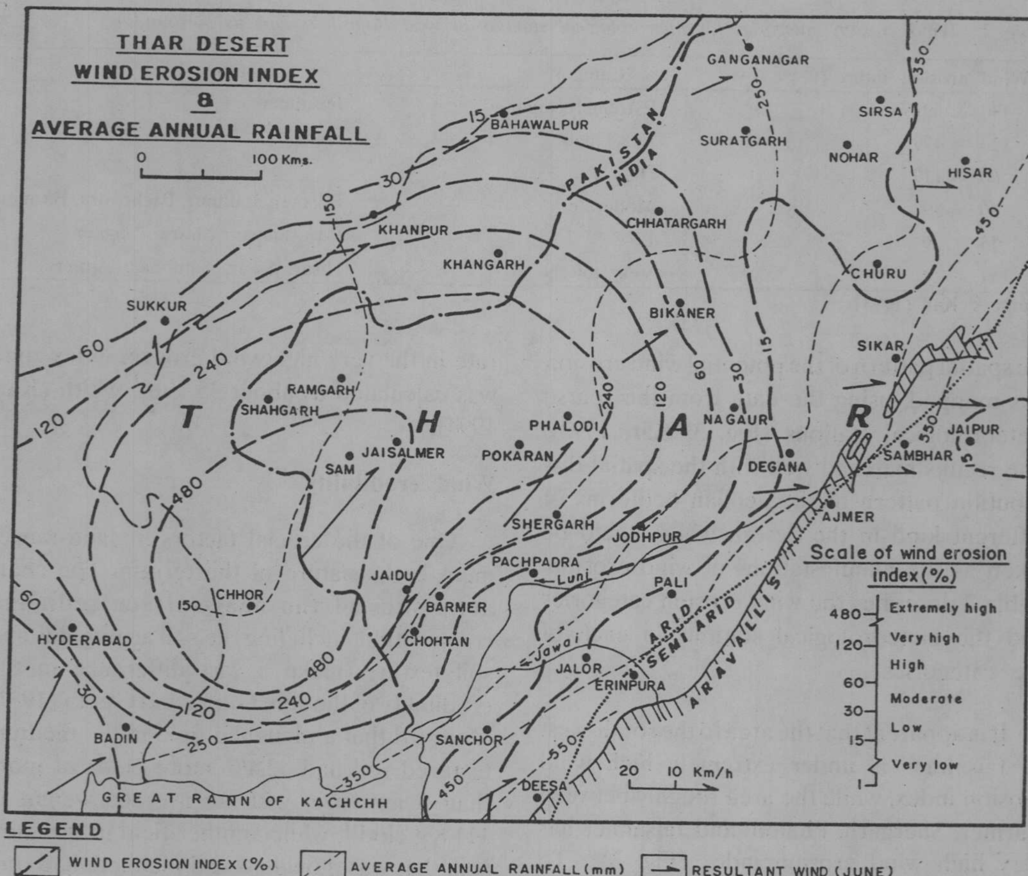

Fig. 3. *Wind erosion index and average annual rainfall in different regions of Thar desert.*

erodibility becomes moderate, and when it is 13 to 16% (weak to moderate, sub-angular blocky structure with distinct peds), the erodibility is negligible.

Ramakrishna *et al.* (1990) found that during the periods of severe gust wind at Shergarh which lies in the high wind erosion index zone (Kar, 1992), the peak rates of erosion of grains up to 0.2 mm size were about 46 kg per sq. km per hour. Sand movement from a barchan was 43% more than that from a partially reactivated parabolic dune near by. According to them, the minimum mean daily wind speed (as against the true hourly wind speed) necessary for sand movement from the barchan crest was 4 km h^{-1}. The movement increased rapidly beyond 9 km h^{-1}, while at more than 14 km h^{-1} wind it was very high. Using the Bagnold (1941) formulae of average sand transport rate and considering the threshold wind velocity as 4 m sec^{-1} (14.4 km h^{-1}), the hourly wind speed as 29 km h^{-1} (during a sand storm) and the average grain diameter of barchan dunes of Pokaran-Jaisalmer tract as 0.20 mm, Kar (1994) calculated the rate of movement of an isolated barchan dune of 2.25 m height at Selvi near Pokaran as 0.019 m h^{-1} (1.14 m in three days). Actual measurement of the dune during a three day

Table 3. Wind erodibility classes in west Rajasthan, using the soil aggregate method of Skidmore

Soil character	Average stable aggregate (%)	Erodibility class
Very deep, very fine and sand in dune complex	1-5	Very severe
Deep, loamy fine sands and fine sand, in sandy plains and some dunes	5-10	Severe
Shallow, loamy fine sand	5-8	Moderately severe
Deep flood plain soils, fine sand, sandy loam and loam	30-40	Slight
Loamy medium sand of scattered dunes in above flood plains	7-10	Severe
Deep brown sandy loam and loamy fine sand on flat plains	10-15	Moderate
Sierozem soils with sandy loam, loam, clay loam and silty clay loam	20-50	Slight
Medium to fine textured gray brown soil	40-50	Negligible

Source: Kar and Joshi (1992).

period of sand storm, when the average wind speed was 29 km h^{-1}, revealed a movement of 1.7 m. It suggested that the Bagnold formulae could be used for reasonable accuracy, if the parameters involved are properly evaluated and used.

Following Skidmore's (1988) method of relating dry soil aggregates of more than 0.84 mm size to wind erodibility, Kar and Joshi (1992) identified eight erodibility classes in west Rajasthan (Table 3).

Soil texture also influences the erodibility of the surface, irrespective of wind velocity. Studies so far in the region suggest considerably higher soil loss from a sandy soil than a loamy sand soil. At Bikaner the erosion from a bare sandy surface was measured as 273.7 kg ha^{-1} day^{-1} during a mean wind speed of 20 km h^{-1}. With the same wind speed the loamy sand at Jodhpur, with clod formation, lost only 15.6 kg ha^{-1} day^{-1} (Table 4).

When all other physical parameters are the same, the vegetation cover and the land use practices play the most crucial role in wind erosion. During the sand storms in April-June 1979, the soil loss from the bare sandy plain at Bikaner was recorded as 1449 t ha^{-1}, whereas the nearby cultivated fields with a cover of 45 cm high pearl millet stubbles lost only 22 t ha^{-1} (Gupta and Aggarwal, 1980). Long stubbles of small grain crops have generally been found to be more effective than an equal quantity of short stubbles

Table 4. Relative soil loss due to wind from west Rajasthan*

Mean wind speed (km h^{-1})	Soil loss (kg ha^{-1} day^{-1}) Chandan (sandy)	Jodhpur (loamy sand)	Bikaner (sandy)
5	1.0	0.3	0.5
10	8.0	1.4	120.8
20	76.7	15.6	273.7
40	1276.0	No data	1605.2

Source : Gupta (1993).

(Gupta, 1993). During the sandstorm of June 1985, the uprooting of natural vegetation from a shallow sandy plain at Chandan in the very high wind erosion index zone led to the loss of 15-18 cm thick soil cover, amounting to a loss of 3128 to 3754 t ha^{-1} (Kar, 1988). During the same spell of sand storm, measurements elsewhere revealed that a 8-12% cover of vegetation protected the sandy surface adequately, whereas the deep ploughed fields in the sandy plains, using tractors, lost soil heavily (Table 5). Wasson and Nanninga (1986) estimated a loss of 124 tonnes/ha of organic matter and 100 t ha^{-1} of N, P and K from the bare sandy surfaces during a 17-day sand storm in July 1970, at Jaisalmer.

Criteria for mapping

Because of the complexities of relationships between wind velocity, air flow pattern, terrain characteristics, particle size and vegetation cover, it is difficult to classify areas into zones of exclusive erosion and deposition. Studies at the Central Arid Zone Research Institute (CAZRI), Jodhpur, have indicated that a quick and reliable method of estimating the areas of long-term aeolian hazard is to consider the present aeolian bedforms and their morphological characteristics as surrogates of the present processes and their intensities (Kar, 1988, 1992). Remote sensing, using multi-spectral satellite images with 30 m or better resolution, and repeated viewing of the same area at regular intervals, provide macro-level information for mapping of the phenomena, monitoring of the processes and an understanding of the regional aeolian dynamics. Using this technique, in conjunction with the field information, Singh *et al.* (1992) mapped the land degradation pattern and consequent desertification in west Rajasthan. A simplified version of the field methods followed by them for recognition of wind erosion is provided in Table 6.

Observation of forms and processes in west Rajasthan indicate that the acceleration of the aeolian processes due to human activities (including the domestic animals), is at present the most important factor of sand reactivation and movement of aeolian sand bodies. Cultivation along the dune slopes, overgrazing and other forms of destruction of natural vegetation on the dunes are reactivating the stable dunes and encouraging the formation of new mobile bedforms. Such hazards are most conspicuous near the settlements (Kar, 1992). Even along the eastern margin of the region, where the average annual rainfall is 500 mm and the sand dunes are so stabilised that many of them have been gullied, the

Table 5. Wind erosion in relation to land use in west Rajasthan, June 1985.

Land use/management	No. of sites	Mean soil loss (t ha^{-1}) Range	Mean
Cultivated			
Long fallow	12	124-320	207
Untilled since previous crop	16	220-377	283
Tilled	11	756-1180	932
Disc ploughed	3	2630-3160	2837
Pasture land			
Undegraded	6	Nil	Nil
Degraded	9	217-683	472

Source : Dhir *et al.* (1992).

Table 6. Field criteria for assessing wind erosion/deposition in the Thar desert

Topography	Rainfall zone (mm)	Major criteria for assessment	Severity
Flat sandy plains with dominantly loamy sand to sandy loam soil.	100 – 550	Fresh sand sheeting upto 30 cm thick. New fence line hummocks upto 100 cm high.	Slight
Moderately sandy undulating plains and sand dunes with loamy sand soils; thickly sand sheeted plains.	Abvoe 300	Presence of reactivated fresh sand of 50 to 150 cm thickness on stable dunes, sandy plains and fence line hummocks	Moderate
Moderately sandy undulating plains and sand dunes with sand to loamy sand soils.	Below 300	Reactivated and fresh sandy undulations in the form of hummocks and sand ridges of 90-300 cm height. Sand sheets of 60-150 cm thickness between undulations. Exposed plant roots to a depth of 40 to 100 cm in the sandy plains indicate erosion.	Moderate
Moderate to strongly undulating sandy plains with closely spaced hummocks and high sand dunes with sand to loamy sand soils.	100 – 550	Closely spaced sandy undulation in the form of hummocks and transverse and longitudinal ridges of 1 to 4 m height with fresh sand cover. Sand deposits of 100-300 cm thickness are usually present between undulations. Highly reactivated sand dunes are covered with fresh sand from all sides and superimposed by barchan dunes of 2 to 4 m height.	Severe
Barchan dunes and very thick sand sheets with loose sand throughout the profile.	100 – 500	Active and drifting sand in the form of individual and coalescing barchan dunes of 2 to 5 m height, encroaching upon roads, settlements and agricultural fields.	Very severe

Source : Singh *et al.* (1992).

wanton destruction of the vegetation cover through grazing and for fuel and fodder, and ploughing along the dune slopes have created localised problem of sand movement (e.g. Pushkar - Budha Pushkar lake region near Ajmer; Kar, 1986). Such destructive trends could still be reversed through well planned programme of wind erosion control measures.

Wind erosion control measures

Several studies have been carried out at CAZRI to control the mobile sand of the Thar desert in west Rajasthan, especially through vegetative propagation (Bhimaya and Kaul, 1960; Ganguly and Kaul, 1969; Kaul, 1985; Muthana, 1982; Harsh and Tewari, 1993; Venkateswarlu, 1993). The major emphasis has been on (1) stabilization of sand dunes and (2) shelterbelt plantation.

Stabilization of sand dunes

Since 1953 reactivated old dunes in parts of the Thar were taken up for stabilization. The methods mainly consisted of planting the suitable tree, shrub and grass species on the dune slopes under a carefully laid out plan of activities. These included:

(a) Protection of the dune from human and livestock encroachment, through fencing.

(b) Erection of low barriers across the dune slopes, either in a checker board pattern or in parallel strips, so as to create micro-wind breaks. Locally available shrubs are used to carry out the activity.

(c) Direct seeding or transplantation of indigenous and exotic plant species in the enclosed areas. The standard nursery techniques are used to raise the plants before transplantation.

(d) Plantation of grass slips or direct sowing of the grass seeds on the leeward side of the micro-wind breaks.

(e) Management of the revegetated site and monitoring of the progress for about 10-15 years, so that the cost is recovered and the dune attains sufficient stability (Muthana, 1982).

Although barbed wire fencing was used earlier for protection of the sites, there is a growing thinking that the locally available thorny and other non-palatable bushes can be more viable and economic. The species usually suitable for such bio-fencing are *Ziziphus nummularia* and *Euphorbia caducifolia*.

The micro-wind breaks could be raised through the use of locally available shrubs and brush wood species. Different rainfall zones in the desert have different combinations of such species on different landforms (Saxena, 1977). Usually the most common species are: *Crotalaria burhia*, *Leptadenia pyrotechnica*, *Aerva psudotomentosa*, *Panicum turgidum*, *Ziziphus nummularia* and *Calligonum polygonoides* in the different rainfall zones. The species are collected and then thrust into the loose sand, crownside down, in 2 to 5 m apart rows. This checks the wind velocity over the treated part. In high wind velocity zones a closer spacing of such barriers is recommended in a checker board fashion. The whole operation is carried out before the onset of the monsoon.

As the monsoon arrives the planting of tree, shrub and grass species should begin. The choice of the species depends on the rainfall zone in which the dune occurs. The recommended species are (Venkateswarlu, 1993):

(i) Annual rainfall zone 150-300 mm

Trees : *Prosopis juliflora, Acacia tortilis* and *Acacia senegal.*

Shrubs : *Calligonum polygonoides* and *Ziziphus nummularia.*

Grasses : *Lasiurus sindicus.*

(ii) Annual rainfall zone 300-400 mm

Trees : *A. tortilis, A. senegal, P. juliflora, Prosopis cineraria, Tecomella undulata, Parkinsonia aculeata, Acacia nubica, Dichrostachys glomerata* and *Colophospermum mopane.*

Shrubs : *Ziziphus jujuba, Z. nummularia* and *C. polygonoides.*

Grasses : *Cenchrus ciliaris, C. setigerus, L. sindicus* and *Saccharum munja.*

(iii) Annual rainfall zone more than 400 mm

Trees : *A. tortilis, P. cineraria, P. juliflora, A. senegal, Dalbargia sisoo, Ailanthus excelsa, Albizzia lebbeck, Parkinsonia aculeata, T. undulata, Dichrostachys glomerata* and *C. mopane.*

Shrubs : *Ziziphus jujuba* and *Cassia auriculata.*

Grasses : *C. ciliaris, C. setigerus, S. munja* and *P. antidotale.*

The tree seedlings are to be watered only at the time of plantation. Thereafter, usually there is no need to water them (Bhimaya and Kaul, 1960; Raheja, 1963; Kaul, 1985).

Shelterbelt plantation

Since high and desiccating winds cause injuries to the young seedlings, leading to crop failure and consequent low yield, CAZRI has suggested erection of shelterbelts along the boundaries of cultivated fields. Usually a three row wind break of *Acacia tortilis, Cassia siamea* and *Prosopis juliflora* as the side rows and *Albizzia lebbek* as the central row is suggested (Venkateswarlu, 1993).

The shelterbelt plantation at the Pali Regional Station of CAZRI was taken up in 1954 (Raheja, 1963). *Prosopis juliflora* was planted through direct seeding along the periphery of the farm, using the furrow planting technique. The furrows were 7.5-10 cm deep and 7.5-10 cm wide. This provided a high germination and the plants developed rapidly without any biotic interference, as the area was fenced. Inside the farm, a system of trench and ridge plantation was carried out. The cross section of the trenches was 0.6 x 0.5 m. A mixture of the seeds of *Acacia arabica, P. cineraria, A. lebbek, Azadirachta indica* and *T. undulata* was sown on the ridges where the soil was loamy sand (Raheja, 1963). Although droughts took a heavy toll, many plants could survive.

Experiences in the shelterbelt plantation in dune covered areas of Barmer, Bikaner and Jhunjhunu districts have shown that a 13 m wide tree belt, planted in pits and interspersed with 60 m wide grass belt, at right angle to the prevailing wind, provide the best results. Among the various species trid, *Albizzia lebbek* had shown a survival rate of 80%, followed by *Azadirachta indica* (50%) and *P. juliflora* (50%) (Raheja, 1963).

The per cent reduction of wind speed at different locations downwind of different shelterbelts during the monsoon season was also measured (Table 7). Shelterbelts of *A. tortilis* performed better in reducing the wind speed than those of *P. juliflora*.

The shelterbelts were also found to conserve more soil moisture in their lee side and reduce the soil loss.

Other vegetative methods

Among the other vegetative methods suggested by CAZRI, notable is the establishment of micro-shelterbelts in the arable lands. It consists of tall and fast growing plant species like castor bean plants on the windward side and shorter plants like vegetable crops in the sheltered areas to the lee of the tall plants. Such combinations led to 41% increase in the yield of lady's finger and 21% increase in the yield of cowpeaover the control (Venkateswarlu, 1993).

Aerial seeding of inaccessible sand dunes was also suggested by CAZRI (Shankarnarayan and Kumar, 1986; Kumar and Shankarnarayan, 1988). The package of practices included the broadcast from an aircraft the pelletized seeds of grasses like *Lasiurus sindicus* (in the less than 200 mm annual rainfall zone), along with the seeds of other suitable trees and shrubs for the region. The prerequisites are the clearing of the dune

Table 7. Per cent reduction of wind speed behind shelterbelts

Plant species	Distance from shelterbelt		
	2 height	5 height	10 height
Prosopis juliflora	38	26	21
Acacia tortilis	46	36	20

Source : Venkateswarlu (1993).

slopes of the unproductive low bushes wherever these occur densely, and ploughing the areas of hard pan soil in the interdune plains.

Mechanical methods of sand stabilization

A number of mechanical and chemical methods of sand stabilization are practiced in many deserts (Kerr and Nigra, 1952; Watson, 1985; Mainguet, 1991). These have rarely been tried on the mobile dunes of this region, mainly because the results are inconsistent. The aerodynamic principles and the nature of obstructions play a crucial role in the occurrence of the problems sought to be tackled by mechanical means. For example, Kar and Singh (1989) found that the wind shadow zone in the lee of a high hill remains largely free of sand drift problem, but after a certain distance down-wind, determined largely by the height of the hill and the nature of the terrain, the problem recurs. This is why a certain length of Jodhpur-Osian road, running across the path of sand-laden SW wind, is regularly affected by sand drift near Nevra, while a railway track in the upwind direction of the road is relatively sand-free. Many of the problems of sand accumulation along the highways could be solved if the aggregate heaps along the roads are shifted to the downwind side of the road and are given a shape which allows a smoother wind and sand flow around them (Kar, 1994). Transposing of sand from the affected stretches of roads and railway tracks is still a major problem faced by the concerned Government agencies.

In the areas where barchans move across the roads periodic manual clearance is a viable proposition than to tamper with the shape of the barchan (Kar, 1994). Destruction and levelling of the dune may not yield the desired result, as the air flow pattern over the area will soon recreate the bedform and create more menace.

Construction activities within the desert often lead to some sand reactivation which, in due course of time, threaten the structures constructed. In order to minimise such hazards, it is advisable to follow some precautionary measures during the construction activities. For example, when the pipeline for natural gas was being laid between Gamnowala Tar and Ramgarh to the west of Jaisalmer, Kar *et al.* (1994) suggested that the dug out and reworked sand and gravel along the route of construction activities should be levelled after the job is over. The heavier particles, including soil aggregates and gravel, may be spread sparingly over the loose sandy surface to protect them from faster movement. Care should be taken to protect the natural vegetation cover along the route. As far as practicable, the plants should not be uprooted. They may be cut or scrapped. This will help in the regeneration of vegetation. In the deflated interdunes between the linear dunes additional protection measures were suggested, like compaction of the back-filled material in the trench, first with a mat of *Panicum turgidum* grass, and then with a layer of *kankar*. This will provide a greater resistance to the high wind in the narrow interdune corridors and along the flanks of the dunes (Kar *et al.*, 1994).

Elsewhere in the arid zone a number of chemical methods, like the use of a polymer, *Jalshakthi*, and the spreading of coal tar or petroleum products have been suggested by the researchers, but these products are yet to be tested for field application.

Economics of wind erosion

The Government of Rajasthan (GOR) was provided with Rs. 3,922 million by the Government of India (GOI) under the Desert Development Programme from 1979 to March 1993, especially for the control of wind erosion through improvement of pasture lands, soil and water conservation and minor irrigation. The GOR covered an area of 0.3 million ha under the programme. This meant that a little over Rs. 13,000 was spent per hectare.

There was no economic evaluation combining the tangible and the non-tangible benefits from these activities. However, one point emerges clearly that if the GOR/GOI have to continue this effort at the present rate, they would require as much as Rs. 117,000 million to cover the moderately and severely affected areas. This would be a colossal amount.

On the other hand, the stakeholders of the region have been dealing with the problem individually. About 58% of the sand dune areas are owned by the farmers. Wherever possible they are trying to keep a minimum plant cover in these areas, as well as the roots and stubbles of previous season's crops.

Future strategies

For successful implementation of the wind erosion control measures, people's participation in the programme is most essential. Awareness of the problem and voluntary participation in its control have to be encouraged. The scientific database on the critical areas needs to be regularly updated by the research organisations and the details of the areas causing more sand drift should be provided to the villagers. The mechanisms for control, along with their alternatives, should also be placed before them.

The need of the critical area approach is felt in view of the vastness of the problem. As pointed out earlier (Table 1), 26.4% area is subjected to slight wind erosion, as against 27.7% area under moderate wind erosion. In other words, about 54% area can be treated at the stakeholders' level, with small support from the Government, through technical backstop and supply of the needed tree/shrub/grass saplings or slips. It is the rest (14.3% of west Rajasthan, 2.9 million ha) that needs government support to a large extent. Even within this 2.9 million ha, the specific sites which warrant urgent considerations for treatment are to be discussed and marked.

Coming to the alternatives, it starts from the tree/shrub/grass solution. Fortunately, the choices are now available. For instance, if the farmer is not willing to consider *A. tortilis* on the sand dune, he may opt for other tree species like *Colophospermum mopane* (in more than 350 mm average annual rainfall zone), *Cordia rothii*, or even *A. nubica*. He has also the choice of shrubs like *Calligonum polygonoides* (in low rainfall zone) and *Z. nummularia* and grasses like *Saccharum munja* in more than 400mm average annual rainfall zone (Harsh and Tewari, 1993). Similarly, if sand dune fixation by checker board technique is not acceptable, the farmer can go in for broader strips of tree, followed by grass in the upper slopes. He can also resort to some cultivation in the lower slopes, but leaving the stubbles.

The shelterbelts are least acceptable to the farmers in their arable lands, because the trees are normally cut across their fields. As an alternative, it is now agreed to plant trees on field bunds across the direction of wind.

Finally, before any activity is taken up, the farmers have to be made aware of the productivity of their land, the proper land use for a given piece of land and the means to achieve the same. As was rightly pointed out by Hudson (1992), care for the improvement of land should come first, followed by the control of erosion.

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