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WIND EROSION AND LAKE SEDIMENTATION IN DESERT AREA

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ABSTRACT

Soil erosion from the nearby catchment area of the lakes and its subsequent sedimentation in the lakes, is one of the major hydrologic problems of our lakes. The fury of wind forces is considerable in the desert area to make substantial wind erosion. As per the estimate made by the National Commission of Agriculture, about 32 million hectare land in India is affected by wind erosion which includes 23.5 million hectares of The Great Indian Desert in the arid zone of north western India. About 19 million hectare of the desert area is subjected to the soil erosion by wind. The eroded soil from the desert area poses major menace to the lakes and other water bodies in the form of sand drifts, reactivation of the sand dunes in the desert area of Rajasthan. Sand dunes are very susceptible to wind erosion and fragile. Man made activities often reactivate the stabilized dunes. The annual soil loss is high and ranges between between 1500 t/ha and 2500 t/ha.

In this report, various processes and mechanism of wind erosion, factors which contribute to the increase or decrease of wind erosion in a desert area have been discussed with reference to Indian desert. The method of estimation of soil loss in a desert area due to wind as suggested by Woodruff and Siddoway in the line of universal soil loss equation is also explained. The method is comprehensive and is based on the relationship between potential soil loss from field and eleven primary field and climatic factors influencing erosion. However, these eleven factors could be conveniently reduced to five equivalent variable depending on certain field condition.

1.0 Introduction

Moving air, like moving water, is capable of picking up loose debris and moving it to another location. A "unit air particle" is moved by forces resulting from differences in air pressure caused due to differential temperature over the region. Wind erosion is the process by which loose surface material is picked up and transported by the wind and surface material is abraded by wind-borne particles. Although wind erosion is not restricted to arid and semi arid regions, it is most effective in these areas because of conducive soil,vegetative and climatic conditions. These conditions are:

(i) The soil is loose, dry, and finely divided,

(ii) The soil surface is smooth and vegetative cover is absent or sparse,

(iii) The area is sufficiently large, and

(iv) The wind is sufficiently strong to move soil and precipitation is inadequate.

In humid regions, moisture binds particle together and vegetation anchors the soil and wind erosion is negligible. Wind erosion differs from stream erosion in two significant ways. First, wind has a low density compared to water and thus is not capable of picking up and transporting coarse materials. Second, wind is not confined to channels and can spread over large areas and high into the atmosphere (Turback and Lutgens, 1988). The causes of wind erosion in the desert region are low rainfall, high wind velocity, and sandy soils with loose single grained structure, overgrazing and deforestation.

An estimate made by National Commission on Agriculture earlier indicate that about 32 million hectare land in India is affected by wind erosion. This includes 23.5 m ha of desert - The

Great Indian desert, also, called the arid zone of north western India. The desert extends between 22° 30'N and 32° 05'N latitude and from 68°05'E to 75°45'E longitude. The desert area is spread over the States of Rajasthan (16.7m ha), Gujarat (0.7m ha), and Haryana (1.4 m ha). Because of existence of pockets of agricultural activity in the desert, 80% of the desert area, i.e., 18.8 m ha has been considered to be subjected to soil erosion by wind (Tripathi and Singh, 1993). Some investigators (Singh, 1990) has assumed a percentage of 50% instead of 80% and wind erosion is one of the major problems in the Indian or Thar desert. The landforms comprise of barren rocky stretches, shifting dunes and sandy plains, saline flats, alluvial plains, dead streams, barren gravelly stretches, and undulating topography. The entire zone is characterised by vast tracks, almost covered by thick blanket of dune sand except a few places which are rocky desert. The area experiences low and erratic rainfall, frequent occurrences of drought, hot summer, low humidity, and large variation of diurnal temperature. The mean annual rainfall varies from 100 mm to 450 mm in Rajasthan and 78% to 98% of rainfall annual occurs during the south west monsoon season. The Indian desert area can be divided into three zones on the basis of rainfall pattern. These are: (i) 500 mm to 300 mm of rainfall from the foot hills of Aravallis in the east to the desert plains in the west; (ii) 300mm to 100mm of rainfall in the hot sandy desert, and (iii) rainfall below 100 mm in the extremely sand desert with dunes. The area is devoid of well defined drainage system. The general slope is towards the south west.

Nearly, 70% of the desert region is covered by wind-worked sandy soils-sands, loamy sand and sand dunes (Dhir, 1977). Strong winds cause considerable soil loss through saltation, suspension, and surface creep. Soil particles are picked up from one location and blown to another, often hundreds of kilometers away. Wind erosion causes dust storm, forms sand dunes, buried localities with deposition and creates drier conditions. This wind erosion is one of the major menace to lakes and other water bodies in the form of sand drifts, reactivation of the sand dunes in the desert area of Rajasthan. Sand dunes in deserts are very susceptible to wind erosion and specially when a stabilized sand dune is disturbed due to man's interference like construction of roads, canals etc. Nearly 40% of the area of Rajasthan has dunes and are located primarily in the Jaisalmer, Barmer, Jodhpur, Bikaner and Churu districts. Situations where dune bodies form more than half of the surface area constitute about 20% of State of Rajasthan (Alexander, 1985). The rate of of annual sand drift is 35 m and from stable dune is 1 m due to wind. The annual soil loss is as high as 1500 to 2500 t/ha (Singh, 1995). The processes of wind erosion in Indian desert environment and their detrimental effects on the lakes and other water bodies are focused herein.

2.0 Mechanics of wind erosion

Erosion consists of two things;-(i) detachment of soil particles from the surface, and (ii) their transportation, that requires an agency like wind to carry the detached particle away. Wind erosion is basically a dry weather phenomenon and is augmented if (i) the soil is loose, dry and finely divided; (ii) the vegetation is limited or absent; (iii) area is very large; and (iv) the wind is strong. Wind loosens the soil particles first and then lifts, rolls or bounces along the surface of the ground due to the turbulence of wind, mainly eddies and irregularities of wind movement. Turbulence adds a vertical component to the wind and makes it more erosive. The ability of wind to move and pick up soil particles varies square to cube of the velocity. A wind velocity scale is given in Table 1 (Tripathi and Singh, 1993).

Wind erosion is mainly a surface phenomenon and is influenced directly by wind velocity in various strata near the ground. The erosion causing wind is always turbulent. Its flow is characterised by eddies moving in all directions at variable velocities. However, zero velocity is somewhere above the roughness elements of the surface. As shown in Fig. 1, the estimated zero velocity is at height of Z_o+ d in which Z_o is an aerodynamic surface and d is the height above Z_o where velocity is zero. The air is near-calm or slow moving in the Z_o zone. The zero velocity at height Z_o+d is obtained for impervious surfaces. However, over porous vegetative surface, the velocity at Z_o is greater than zero (shown by discontinuous line in Fig.1). The total surface roughness is actually Z_o+d and depends on the vegetation height, density and other characters of the surface features. The idea of d is a conceptual one and is used to express the wind profile over rough surface and to provide a relation between wind speed U and height Z above the surface

$$U = \frac{1}{k}\left(\frac{\tau}{\rho_a}\right)^{0.5} \ln \frac{Z-d}{Z_o} \qquad \text{for } Z > H > Z_o+d \qquad (1)$$

where, U = wind speed at height Z

k = van Karman's constant (approximately 0.4)

τ = shear stress (the flux of horizontal momentum transferred vertically and absorbed by the ground)

ρ_a = density of air

H = crop height

At some point near the ground surface, usually less than 2.5

mm for a bare, relatively smooth surface, the wind velocity is zero. For a very short distance above this level, the flow of air is smooth and laminar and ends into turbulent flow at higher elevations. It is this turbulent flowing air which produces the force to cause soil movement. As shown in Fig.1 the average forward velocity of a turbulent wind increases exponentially with height above Z_o.

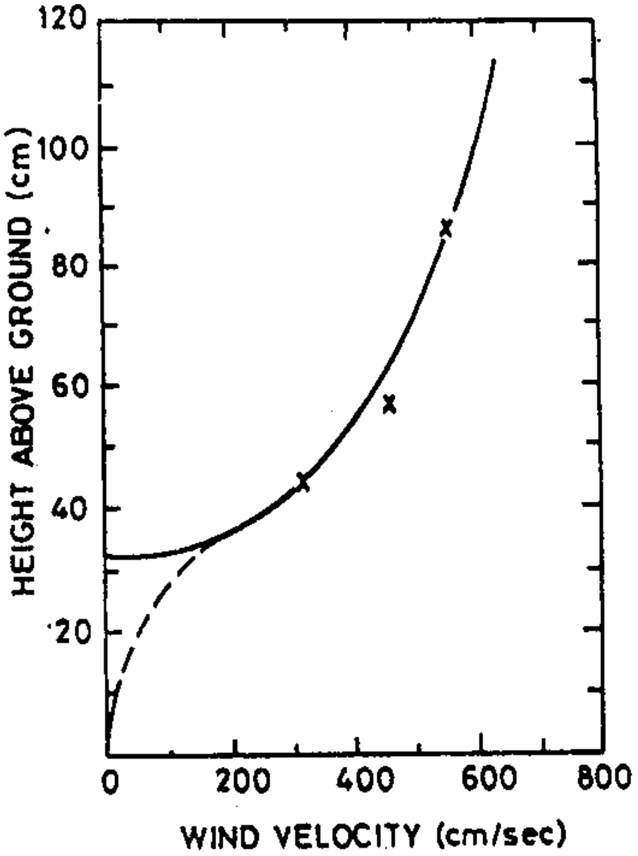

Fig.1- Wind velocity above sorghum stubble 53 cm high (Chepil and Woodruff, 1963 vide Tripathy and Singh, 1993).

Table 1. Wind velocities, Beaufort scale at standard anemometer elevation of 10 m above the ground (vide Tripathi and Singh, 1993)

Beaufort number	Descriptive word	Velocity (miles/hour)	Specification for velocities	Wind erosion hazard
0	Calm	less than 1	Smoke rises vertically	
1	Light	1 to 3	Direction of wind shown by smoke but not by vanes	None
2	Light	4 to 7	Wind felt, leaves rustle, ordinary vane moves	
3	Gentle	8 to 12	Leaves & twigs in constant motion	Begins to muck soil
4	Moderate	13 to 18	Raises dust & loose paper, small branches moves	Slight
5	Fresh	19 to 24	Small trees begin to sway, Crested wavelets form on the lake	
6		25 to 31	Large branches in motion, whistling heard in telegraph wires, difficult to use umbrellas	Considerable

Cont'd Table 1

Table 1. Wind velocities, Beaufort scale at standard anemometer elevation of 10 m above the ground (vide Tripathi and Singh, 1993)

Beaufort number	Descriptive word	Velocity (miles/hour)	Specification for velocities	Wind erosion hazard
7	Strong	32 to 38	Whole tree in motion, inconvenience in walking	
8	-	39 to 46	Breaks twigs off trees	
9	Gale	47 to 54	Slight structural damage	Severe
10		55 to 63	Trees uprooted, considerable structural damage	
11	Whale Gale	64 to 75	Rarely occurs, widespread damage	
12	Hurricane	Above 75	Severe damage to life and property	

2.1 Wind forces causing soil movement

Moving air exerts three types of pressure on a soil grain resting on the ground. One is a positive pressure against that part of the grain facing into the direction of movement. This pressure results from the impact of air against the grain and is called the impact or velocity pressure. The velocity pressure causing soil movement varies directly as square of the fluid velocity. It is expressed as force per unit cross-sectional area of the grain normal to the direction of fluid in motion. The second type is a negative pressure on the lee side of the grain, known as viscosity pressure. It is depended on the air's coefficient of viscosity, density and velocity. The third type of pressure is a negative pressure on the top of the grain caused by the Bernoulli effect. According to Bernoulli law, wherever the fluid velocity is speeded up, as at the top of the soil grain, the pressure is reduced.

The impact or velocity pressure on a soil grain over the ground is known as 'form drag', and the pressure due to viscous shear in the air close to the surface of the soil grain is called 'skin friction drag'. The sum of the two forces is called the 'total drag' or simply drag. The drag F_c, on the top of grain at the threshold of its movement is due to the pressure difference against its windward and leeward sides.

Lift on the grain is caused by decrease in static pressure at the top of the grain as compared to that at the bottom. It is determined by the pressure difference against the top and the bottom halves of the grain.

The threshold drag acting on a spherical grain can be expressed as :

$$F_c = (0.52g\ D_s^3\ \rho'_s - L_c) \tan \varphi' \qquad (2)$$

where, F_c = threshold drag force acting on the top soil grain.

D_s = diameter of the grain

ρ_s = difference in density between grains and the air (immersed density of the grain)

g = acceleration due to gravity

$0.5gD_s^3$ = immersed weight of spherical grains

L_c = Lift on top of the grain ($\approx 0.85\ F_c$ for any size of spherical grain)

φ' = the angle of repose of the grain with respect to the average drag level of the air.

On substituting the value of L_c and transposing,

$$F_c = \frac{0.52gD_s^3\ \rho'_s\ \tan\varphi'}{1+0.85\ \tan\varphi'} \qquad (3)$$

Similarly, for winds of uniform velocity, the drag and lift per unit horizontal area occupied by the topmost grain can be expressed as :

$$\tau_c = \frac{0.66g\ D_s\rho'_s n' \tan\varphi'}{(1+0.85\ \tan\varphi'} \qquad (4)$$

where, τ_c = threshold shear stress for winds of uniform velocity

n' = ratio of drag and lift on the whole bed to drag and lift on the topmost grain moved by air

Since movement of soil grains by wind occurs normally by the maximum lift and drag impulses of turbulent flow, Eq.(4) can be modified in the form :

$$\bar{\tau}_c = \frac{0.66g\ D_s\rho'_s n' \tan\varphi'}{(1+0.85\ \tan\varphi')T_f} \qquad (5)$$

where, $\bar{\tau}_c$ = mean threshold shear stress for turbulent flow

T_f = turbulence factor (ratio of maximum to mean drag and lift on the soil grain)

The drag on the topmost grains on the bed acts at an average level of about one-third of the grain diameter below the top of these grains and the angle of repose of the topmost grains with respect to the mean level of drag is about 24°. Therefore, tan φ' is equal to about 0.45 and the value of n' may be about 0.2 and T_f as 2.5.

Lift and drag on soil grains change rapidly as the grains move up from the surface of the ground. Lift decreases with height and becomes almost negligible a few grain diameter heights above the ground. The greater the ground roughness and drag velocity of the wind, the higher is the lift due to steeper velocity gradients. Drag on the other hand, increases with height just as wind velocity increases with height, and apparently is due mainly to the direct pressure of the wind against the grain.

2.2 Initiation of soil movement

Movement of soil particles in wind erosion is initiated when the pressure by the wind against the surface soil grains overcomes the force of gravity on the grains. The impact or velocity results positive pressure against that part of the grain facing in the direction of wind. The magnitude of force exerted is governed by wind velocity above the ground surface. Fine dust particles offer higher resistance to movement by wind partly due to cohesion among the particles (which raises the threshold value) and to the fact that the particles are too small to protrude above the laminar and viscous layer of air over the ground surface. Fine dust particles are, therefore, ejected into the atmosphere mainly by impacts of larger grains.

A certain minimum velocity is needed to initiate the movement of soil particles. The velocity at which the movement of most erodible soil particle is initiated is known as the minimum air threshold velocity. This minimum air threshold velocity depends on the size and weight of soil particles and the friction provided by neighbouring particles. This threshold velocity is the lowest for grains of 0.1 to 0.15 mm diameter. Observations show that surface winds exceeding about 3 km/hr velocities are turbulent and are responsible for initiating the process of wind erosion. In fact, the threshold velocity depends not on the average forward velocity but on the maximum momentary velocity of turbulent flow. It has been observed that maximum wind speed in Jaisalmer area of Rajasthan during summer is as high as 20 to 27 km/hr whereas the threshold velocity of wind for initiating soil movement is 14 km/hr for desert condition (Mann, 1982).

The determining factors of soil movement are those related to size and density of detachable soil particles and the turbulent force on them. With a given surface configuration or roughness the height of zero velocity is constant for all turbulent winds. Turbulent flow occurs for all winds of speed over 1.6 to 3.2 km/hr. However, the height of zero velocity is greatly influenced by the surface roughness which is dependent on ridging, presence of large size particles, vegetation, vegetative residues, or other barriers on the surface. This helps to protect the erodible particles from being picked up by air current.

The rate of increase of wind velocity with logarithm of height can be expressed in terms of the drag velocity according to the relation :

$$v = \frac{v_z}{5.75\ \log(z/d)} \tag{6}$$

where, v = drag velocity, cm/sec

v_2 = velocity at any height, z, above z_o.

Equation (6) shows that drag velocity increases with wind velocity. The minimum wind velocity required to initiate the movement of the most erodible soil particle (of about 0.1 mm dia) is about 16 km/hr at a height of 30.5 cm. The most practical limit under field conditions where a mixture of sizes of single grained material is present is about 21 km/hr at a height of 30.5 cm. Particles of about 0.1 mm in diameter have a size-weight relationship which is most conducive to initiate the movement.

2.3 Transportation of soil particles

In general, the soil transportation by wind is caused by three distinct types of soil movement viz., saltation, suspension and surface creep.

Saltation

The bouncing or ejecting off the particle from the surface bed into the airstream and subsequent moving forward is referred to as saltation. Saltation is caused by the direct pressure of wind on the soil particles and their collision with other particles. The soil particles skip or bounce along the surface of the ground. After being pushed along the ground surface by wind the particles suddenly leap almost vertically in the first stage of saltation movement rotating from 20 to 1000 revolutions per second and travel about 10 times their height of rise and return to the surface with an angle of descent of about 6^o to 12^o with the horizontal. Some grains rise only a short distance; others leap about 30 cm or more depending upon the velocity of rise from the ground. The higher the grain rise, the more the energy they derive from wind. This energy is liberated in bombarding action of the particles on the other particles. Once saltation begins, the erosion is accelerated mainly by the saltating particles except on the windward edge where the direct presence of wind against the ground is the main eroding force.

The soil moved by saltation consists of fine grains ranging in diameter from 0.1 to 0.5 mm. More than 75% of the grains carried by saltation spin rise almost vertically, rotating at a speed of 200-1000 revolutions per second and travel 10-15 times of their height of rise before returning to the surface.

On striking the surface they either rebound and continue their movement in saltation, or loose most of their energy by striking other grains, causing them to rise and sinking themselves into the surface or forming part of the movement in surface creep. They also break down clods and crusts. Most of dislodged particles in the size range from 0.5 to 1.0 mm roll and move by surface creep. About 50% to 70% of the movement of soil particle is through saltation (Fairbridge et al, 1979).

Suspension

Transportation of very fine dust particles (less than 0.1 mm dia) by wind occurs in true suspension in the turbulent air-stream when the soil is bombarded by the saltation movement. The upward eddies of erosive wind having a velocity more than 3 km/h are capable of lifting silt and very fine sand particles to heights greater than 3-4.5 km. Suspension may move 3 to 36 per cent of soil loss by wind erosion. Such movement of sand particles are observed during dust storms. The atmosphere has a large capacity to transport the soil particles. Estimates show that the potential carrying capacity of 4.2 km^3 of the atmosphere is about 114.3 million kg of soil depending upon the wind velocity. The soil particles carried in suspension are deposited when the sedimentation force is greater than the force holding the particle in suspension.

Surface creep

Surface creep is the movement of soil particles due to impact of particles descending and hitting during saltation. The movement of particles by surface creep causes an abrasion of soil surface resulting into breakdown of non-erodible soil aggregates due to impact of moving particles. Quartz grains of about 0.5 to 1.0 mm diameter are too heavy to be moved by saltation but are pushed along the surface by the impact of particles in saltation to force surface creep. Laboratory studies have shown that about 7 to 15% soil may be moved by surface creep. It is observed that at low wind speed, the grains move in jerks, a few millimeter at a time, but as the wind speed is increased, the distance moved increases and more grains are set in motion until the whole surface appears to be creeping forward under wind action (Fairbridge et al, 1979).

The three types of soil movement described above usually operate simultaneously depending on the soil type. For a sandy soil, Chepil (1945, vide Tripathi and Singh, 1993) reported 67.7% by saltation, 15.7% by surface creep, and 16.6% by suspension.

In general, wind moves the finer and lighter particles faster than the coarser and denser ones despite the fact that the finer particles are less erodible. This results into sorting or separation of particles into the following distinct grades :

(a) Residual soil materials containing non-erodible clods and massive rock materials.

(b) Lag sands, lag gravels and lag soil aggregates which are semi-erodible grains moved primarily by surface creep.

(c) Sand and clay dunes formed by accumulation of highly erodible grains moved primarily in saltation.

(d) Loess comprising of dust particles lifted off the ground by saltation, carried in air by suspension and deposited in uniform layers both near and far from dunes.

However, there are no distinct demarcations of size between the various grades of wind-sorted materials.

2.4 Dunes

The word 'dune' is derived from the English word 'Dun' emphasising hilly character of the topography. Wind formed deposits of sand are described as dunes. Dunes may vary in size from very small mounds, a few feet in height, breadth and length, to hillocks, of considerable dimensions. The presence of any barrier across the direction of wind causes a zone of wind shadow within which the wind velocity is much reduced. Sand particles, travelling along with the wind get the first chance of dropping down within wind shadow zone and a dune is gradually built up. Once formed, a dune acts as a barrier itself, causes further deposition of sand and gradually grow in size. Dunes have gentle slope along the wind-ward side and a comparatively steep gradient along the lee-ward side. The lee-ward slope of a dune is described as a slip-face as sand particles slip down this face and rest finally at the angle of repose which varies from 20^{o} to 35^{o} with the horizontal plane in a desert area where sand particles are predominant (Mukherjee, 1964). Based on their mode of occurrence and physical features, the dunes of Rajasthan can be divided into the following types:

Longitudinal dunes

Dunes which lie parallel to the direction of wind are known as longitudinal dunes. These types of dune develop under strong wind and are confined to the southern and western part of the Thar desert. Sand particles within these dunes are usually stratified. Upon the wind-ward slope of such dunes, movement of sand along with the blowing wind produces ripple marks.

Traverse dunes

These dunes orient themselves across the direction of wind. These types of dunes predominate in eastern and northern portion of the Thar and develop where south westernly wind is not strong. The existence of big trees on the leeward side of the traverse dunes is indicative of stabilisation of a considerable time.

Crescent shaped dunes

Dunes which are more or less crescent shaped, are commonly described as "barchans". They are convex towards the wind ward side and the tapering horns of the crescent point towards the direction of wind. Such type of dunes develop in central part of the Thar desert.

While dunes develop near the core, aeolian sand (wind deposited sand) and loesses are deposited in the peripheral area of the desert. Being south westernly, the Thar desert slopes towards the Indus plain with general surface unevenness. Dunes in south are higher, rising sometimes to 150 m whereas in north they are lower and rise up to the height of 15 m. The formation of sand dune depends on 3 factors; a prevailing moderate wind, plenty of sand and an obstacle like rock or a tree that acts as a nucleus around which sand may slowly collect. The sand dunes are highly deficient in organic matter and moisture. Dunes commonly migrate from one place to another due to changes in the direction and velocity of wind. While in motion, dunes cover up cultivable land, villages, roads, railways, etc. Inspite of these destructive activities of the dunes, stabilized dunes have, on many occasions, been found to be beneficial. Precipitation that occurs during occasional rainfalls in deserts with extremely dry climate, is stored within the pore spaces between sand particles of the stabilized dunes. This water is commonly available in shallow wells and is often sufficient in quantity to support vegetation with the consequent of an oasis. The finest particles of dust, travelling in suspension with the wind, are transported to a considerable distance. When dropped down, under favourable conditions, these have been found to accumulate in the different continents in the form of paper thin laminae, which have aggregated together to form a massive deposit known as loess. Loess is a buff-coloured deposit made of angular fragments of unaltered mineral grains and is characteristically unstratified. The thickness of such deposits may vary from a few inches to hundreds of feet. Deposit of sand in the form of dune and of dust in the form of loess constitute two remarkable types of aeolian deposits. It is certain that some portion of the wind borne dust is irregularly disseminated all over the land masses as well as upon the surface of the oceans, seas, lakes and rivers.

3.0 Factors affecting wind erosion

Major factors that affect the amount of erosion from a given field are soil cloddiness, surface roughness, water stable aggregates and soil crusts, wind and soil moisture, field length, organic matter, barriers, vegetative cover, topography and soil.

Soil cloddiness

The cloddiness of a given soil largely indicate whether the wind will erode it. Soil clods prevent wind erosion because they are large enough to resist the forces of the wind and because they shelter other erodible materials.

Several criteria are commonly used to specify the cloddiness required to control erosion on field soils. For example: (1) about 50% of the soil surface ought to be covered with clods greater than 10 mm in diameter, (2) about half the surface clods should to be greater than 1.0 mm in diameter; and (3) about two-third of the surface soil by weight ought to be non-erodible size (>0.84 mm). These criteria are approximate, but soils that meet any one of these criteria usually will resist all but the very strongest winds. Soils loss by wind varies directly as the 2.5 power of the surface drag of the wind and the 3.5 power of the per cent of soil fractions less than 0.42 mm in diameter.

Surface roughness

In addition to clods, soil aggregates and ridges, depressions formed by tillage also alter wind speed by absorbing and deflecting part of the wind energy away from the erodible soil. Rough surface also trap saltating particles. This reduces abrasion and the normal build-up of eroding material downwind. A smooth soil surface is generally more erodible by wind than a rough one (Table 2) because of being less effective in slowing the wind velocity near the ground. Although, a smooth surface reduces wind turbulence but its effect in reducing wind erodibility is not compensated by the increased surface velocity.

Table 2. Initial rates of erosion over rough and smooth surface of fine sandy loam under different wind velocities (Chepil and Milne, 1941 vide Tripathi and Singh, 1993)

Wind velocity at 30cm heigh, (km/h)	Rate of erosion, g/cm width/sec, on Smooth surface	Rough surface
27.4	0.32	0.10
35.4	0.88	0.19
48.3	2.10	0.70

Roughening is not always effective in reducing wind erosion. If the soil is composed mostly of erodible fractions, roughening the surface does little good because the roughness elements continue to erode with the wind.

In general, greater the surface roughness, the lower is the wind velocity against the ground and lower is the rate of erosion. The rate of soil blow under a wind force varies inversely with the roughness of the surface. Surface roughness in turn is dependent on the height and lateral frequency of the surface obstructions.

The ratio of height of projections to distances between projections which will barely prevent the movement of erodible fractions is defined as critical roughness coefficient. Under a given wind velocity the critical roughness coefficient remains unaltered for the total range of size and proportion of the non-erodible clods. The critical surface roughness coefficient required to assure soil stability varies with other factors such as wind velocity and size and density of erodible fractions.

Since surface roughness also increases wind turbulence and exposes smaller areas to greater wind forces, excessive roughening may substantially reduce the benefits. Optimum roughness for wind erosion is 5 to 12.5 cm.

Water stable aggregates and surface crusts

The drifted particles of discrete sand grains and clay aggregates are water stable and exhibit greatest mechanical stability. Secondary aggregates falling next in the order of mechanical stability are held together in dry state by water dispersible contents forming clods. Depending upon the quantity of silt and clay dispersible in water contents present, these clods maintain their identity for some time after repeated wetting and drying. The greater the quantity of fine particles dispersible by water, the greater the degree of cementation among the structural units and the greater is the mechanical stability. The mechanical stability tends to reduce wind erosion by resisting the break down of non-erodible units to smaller erodible particles.

As shown in Table 3, a surface crust formed by wetting (spraying water) and drying (condition b) reduced soil erosion greater than when the crust formed by wetting and drying was subjected to abrasion (condition c).

The order of mechanical stability from the highest to the lowest for different structural units in a dry soil follows : (a) water stable aggregates; (b) secondary aggregates or clods; (c) surface crusts; and (d) fine materials among the clods cemented together and to the clods after the soil has been wetted and dried.

Table 3. Influence of state and stability of structure on soil erodibility by wind (Chepil and Woodruff, 1963 vide Tripathy and Singh, 1993)

Soil texture	Rate of soil erosion (Tonnes/acre)		
	Condition*a	Condition*b	Condition*c
Sandy loam	3.4	0.4	13.0
Silt loam	4.5	0.2	5.6
Silty clay loam	2.9	0.3	9.4
Clay	9.5	3.4	11.0

*Condition a - exposure to wind of well-mixed, loose and dry soils till movement ceased; b- exposure to wind after consolidating the soil by spraying with 2.5 cm of water and drying exposed till movement ceased; c - exposed to wind and a stream of wind borne sand after consolidating the soil.

Wind and soil moisture

Wind speed and soil moisture both affect wind erosion. Wind erosion decreases as soil moisture increases. Only dry soil particles are readily moved by wind.

In general, wind erosion can only happen when the soil surface is dry or only slightly moist, because surface tension holds the soil particles together when wet. Therefore, soils that have a tendency to retain moisture and to conduct it to the surface are fairly resistant to drifting. The severity of wind erosion increases with periods of drought. Moisture film between individual particles provide the cohesive force to hold them together. Damp and moist soil particles are, therefore, virtually stable. Wind velocities must create a force in excess of these film forces in order to cause soil movement. Force of cohesion between erodible soil particles varies directly with moisture content. Observations indicate that wind is seldom strong enough to overcome even the cohesive force of soil water at about 15 bar tension (Table 4). In the Table, the equivalent moisture of 1.0

designates the 15 bar tension. The equivalent moisture is a ratio of the water content in question to water content at 15 bar tension.

Table 4. Influence of equivalent moisture of a silt loam on soil erosion under different wind velocities at 15 cm height

Equivalent moisture	Rate of soil erosion mg/cm width/sec,under 32km/hr velocity	41.8km/hr velocity	51.5km/hr velocity
0.01	315	650	820
0.25	295	630	780
0.29	235	590	710
0.34	230	540	640
0.71	68	290	390
1.03	2	49	40

Field length

Erosive winds vary highly in direction and seldom follow field boundaries. Therefore, the amount of soil lost from a given field cannot be determined by the width or length of field alone. The distance across the field along the direction of the prevailing wind must be known. Fields with their broad sides at right angles to, and their narrow sides parallel with, the prevailing wind direction will have the minimum overall rate of erosion. Field orientation is of little consequence where erosive winds blow equally from all directions.

A distance equal to 10 times the height of the barrier is usually subtracted from the total distance across a field, when using the wind erosion equation to calculate the amount of soil loss.

Vegetative cover

The most important basic cause of wind erosion is destruction of vegetation or vegetative residue on the land. Good vegetative cover on the land is the most permanent and effective way to control wind erosion. Living or dead, vegetative matter protects the soil surface from wind action by reducing wind speed and by preventing much of the direct wind force from reaching erodible soil particles.

Protection depends on the quantity, size and orientation of the residue in relation to prevailing wind direction (Table 5). The denser the residue, the more it slows the wind and the more it reduces wind erosion. For example, wheat stubble is more effective than sorghum or corn stubble. The higher the residue stands above the ground, the more it slows the wind speed and lowers the rate of erosion. Effects of type, quality, and orientation of vegetative cover can be expressed as a single factor. Soil loss by wind erosion varies inversely as the 0.8 power of the weight of surface residue. The threshold velocity for undecomposed crop residues and weeds, even when these are nearly scattered on the surface of the ground, is higher than for most of the erodible soil grains.

In Chandan, 50 km east of Jaisalmer, the removal of grass cover over an area of 2000 m^2 resulted in soil depletion of 1065 m^3 within 3 years (Krishnan, 1977). There was a continuous removal of sand from a bare sandy plain, while both removal and deposition of sand occurred from grass cover and bajra stubble cover fields (Gupta and Aggarwal, 1980). Kar (1988 vide singh et al, 1994) estimated a soil loss of 3128 to 3754 t/ha from the bare field stripped of its grass cover for the 1985 sandstorm. Cumulative sand removal from bare sandy plain was 9.66 cm, while it was only

0.17 cm from bajra stubble cver and almost no removal but deposition of 0.09 cm occurred on grass cover during the 75 day period from April to end of June, 1977.

Table 5. Effects of type and orientation of crop residue on the erosion of sandy loam by wind of uniform velocity (Chepil and Woodruff,1963 vide Tripathy and Singh, 1993)

Quantity of crop residue on the soil surface(Kg/ha)	Quantity of soil eroded in a wind tunnel			
	Covered with wheat residue		Covered with sorghum residue	
	Standing 25cm high, kg/ha	Flat, kg/ha	Standing 25cm high, kg/ha	Flat, kg/ha
0	36280.00	36280.00	36280.00	36280.00
566	6349.00	19273.75	29250.75	32878.75
1132	226.75	5668.75	18366.75	23582.00
2265	T	226.75	8843.25	12017.75
3397	T	T	3174.50	4988.50
6795	T	T	T	453.50

T = traces, insignificant.

Organic matter

High organic matter content of soil is conducive to high fertility and good tilth but facilitates erosion by wind. Observations showed that wheat straw in the process of decomposition increased soil cloddiness and decreased erodibility by wind but the trends were reversed after the straw decomposed.

Numerous cementing substances responsible for binding soil particles together are produced in the initial stages by soil-organisms as they attack the vegetative matter.

Vegetative matter spread on the surface is more effective in aggregation than when incorporated in soil because the former decomposes less rapidly and, therefore, continues to replenish the cementing products for much longer periods. The products concentrate in and around the water stable aggregates. These cementing products are not entirely water soluble and, therefore, increase the size of the aggregates or clods large enough to resist wind erosion.

Barriers

Wind barriers such as shelterbelts hedges etc., reduce wind velocity near the ground surface for some distance downwind. Although, highly effective for only relatively short distances, they are most advantageous for localised control around farmsteads, fields, etc.

In dryland areas trees should be planted at low lying areas where water tends to accumulate during rains. The effectiveness of windbreak in lowering the surface velocity of wind depends upon the shape, height, length and density of the barrier and the velocity of the wind. The windbreak should be planted perpendicular to the direction of the prevailing wind.

Topography

Level land is generally more liable to wind erosion than uneven land, because the wind encounters less resistance. Some of the greatest erosion hazards exist on knolls, ridges and in the lee of pockets, because the wind presses against such areas instead of flowing parallel to the surface.

Soil

Sand erodes easily as it has a great proportion of particles of saltation size, but little binding material. High sand percentage are also not conducive to clod formation and generally undergo high erodibility. Soils, high in clay and silt, are rather stable because they are coherent (clay acting as binding agent) and easily form a protective crust at the surface. A soil containing 20 to 30% clay, 40 to 50% silt and 20 to 40% sand produced a greater proportion of non-erodible and mechanically stable clods. Following relationship has been observed between the soil erodibility index I_v and the amount of clay (Chepil, 1952 vide Tripathy and Singh, 1993).

$$I_v = a\ G^b\ C^d \tag{7}$$

where, G = per cent of clay in soil g/g, and a,b,C are constants.

Clayey soils are highly variable with respect to wind erosion. Those containing high proportion of fine water dispersible particles tend to puddle and resist erosion by wind relative to those containing less water dispersible particles. The latter remain as fine granules which are subjected to rapid erosion by wind. Coarsely granulated soils erode mostly in saltation, and finely pulverised soils in saltation and suspension.

4.0 Method of estimating wind erosion

Several types of wind erosion equations have been developed from time to time to compute the amount of soil loss. The universal soil loss equation based on relationship between potential soil loss from field and eleven individual primary field and climatic factors that influence erosion (Woodruff and Siddoway, 1965) is the comprehensive one. The equation is designed to serve: (1) as a tool for determining the potential amount of wind erosion on any field under local climatic conditions; and (2) as a guide for determining the conditions of surface roughness, soil cloddiness, vegetative cover, sheltering or width and orientation of field necessary to reduce the potential wind erosion to an insignificant amount. The eleven primary variables, governing wind erodibility of land surfaces are described.

Soil erodibility, I

Soil erodibility is the potential soil loss in tonnes per acre per annum from a wide, unsheltered, isolated field with a bare, smooth, non-crusted surface. It is related to soil cloddiness and its value increases as the percentage of soil fraction greater than 0.84 mm in diameter decreases. It can be determined by standard dry sieving procedure and use of Table 6.

Knoll erodibility, I_s

It is a factor needed to compute erodibility for windward slopes less than about 500 ft long. It varies with slope and is expressed in terms of per cent slope (Fig.2). The erosion rate for windward slopes longer than 500 ft is about the same as from level land, therefore, I_s is taken as 100% for this situation.

Table 6. Soil erodibility I for soils with different percentages of non-erodible fractions as determined by standard dry sieving (Woodruff and Siddoway, 1965)

Percentage of soil fractions > 0.84 mm	Units									
	0	1	2	3	4	5	6	7	8	9
0	-	310	250	220	195	180	170	160	150	140
10	134	131	128	125	121	117	113	109	106	102
20	98	95	92	90	88	86	83	81	79	76
30	74	72	71	69	67	65	63	62	60	58
40	56	54	52	51	50	48	47	45	43	41
50	38	36	33	31	29	27	25	24	23	22
60	21	20	19	18	17	16	16	15	14	13
70	12	11	10	8	7	6	4	3	3	2
80	2	-	-	-	-	-	-	-	-	-

* For a fully crusted soil surface, regardless of soil texture, the erodibility I is, on the average, about 1/6 of that shown

Surface crust stability, F_e

The surface crust disintegrates readily due to abrasion after wind erosion has started and hence for big areas and for large time it is disregarded. It is of significance and is taken into account where erodibility of a field at a given moment is considered.

Soil ridge roughness, K_r

Soil ridge roughness is a measure of soil surface roughness other than that caused by clods or vegetation. It is the natural or artificial roughness of the soil surface in the form of ridges or small undulations. It can be determined from a linear measure of surface roughness.

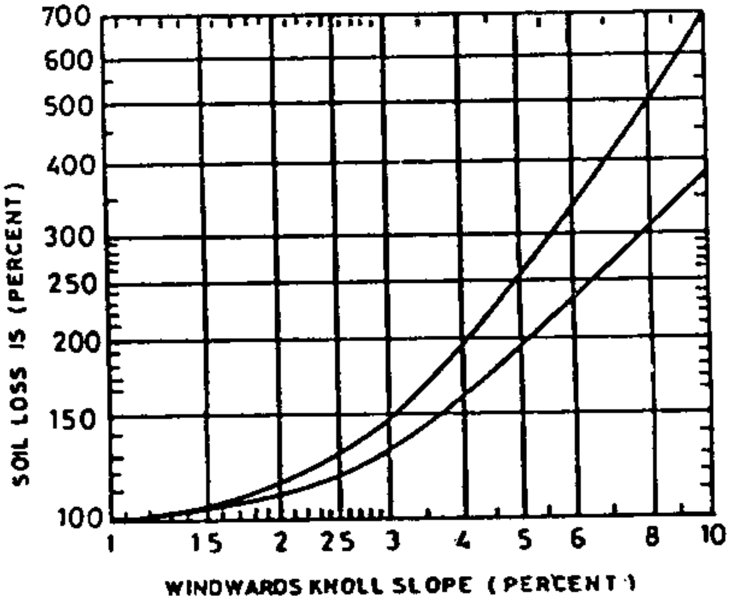

Fig.2 Potential soil loss from knolls, exposed as per cent of that on level ground; (a) from top of knoll, (b) from that portion of windward slope where drag velocity and wind drag are the same as on the top of the knoll (Woodruff and Siddoway, 1965)

Velocity of erosive wind, V

It is observed that rate of soil movement varies directly as a cube of the wind velocity. Where average annual soil loss determinations are desired, the mean annual wind velocity corrected to a standard height of 30 ft is used.

Soil surface moisture, M

The rate of soil movement varies approximately inversely as the square of effective surface soil moisture. Generally, the detailed surface soil moisture is not available for different geographic locations, as such, M is assumed to be proportional to the Thornthwaite potential evaporation index.

Distance across the field, D_f

D_f is the total distance across a given field measured along the prevailing wind erosion direction. Fig. 3 presents an alignment chart for determining the distance, D_f, along the wind direction for different widths of fields. On an unprotected, eroding field the rate of soil flow is zero on the windward edge and increases with distance to leeward side until the flow reaches a maximum that a wind of particular velocity can sustain (for large fields). The distance required for soil flow to reach this maximum on a given soil is the same for any erosive wind.

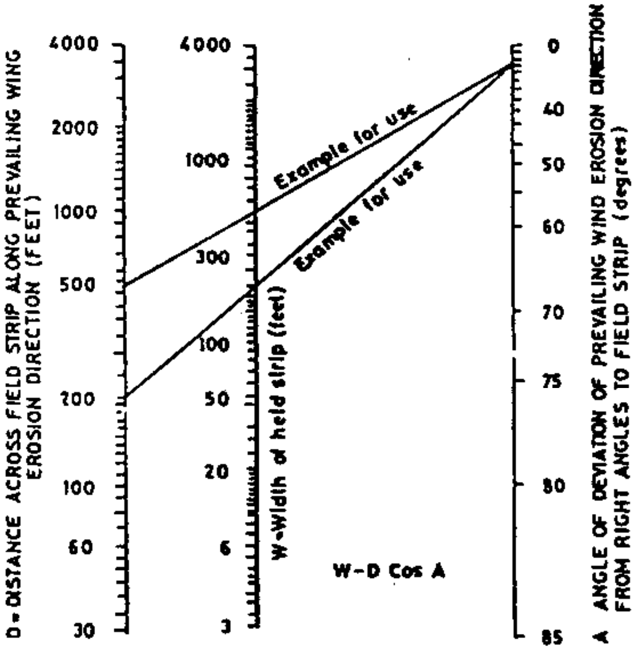

Fig. 3 Alignment chart to determine: (i) Distance across field strip along the prevailing wind erosion direction from width of field strip and prevailing wind erosion direction and (ii) Width of field strip from prevailing wind erosion direction ((Woodruff and Siddoway, 1965)

Sheltered distance, D_b

Sheltered distance, D_b, is the distance along the prevailing wind erosion direction that is sheltered by a barrier, if any, adjoining the field. D_b is determined by multiplying the height of the barrier by 10.

Quantity of vegetative cover, R

The total amount of vegetative residue connected with the wind erosion equation are based on washed, oven dry, weighed and multiplied by 1.2 to make them comparable to the usual field measurements where samples are air dried.

Kind of vegetative cover, S

S is the total cross-sectional area of the vegetative material. The finer the material and the greater its surface area, the more it reduces the wind velocity and the wind erosion. Values of S assigned to different kinds of vegetative materials are as given in Table 7.

Table 7. Values of S for different kind of vegetative material

Sl.No.	Kinds of vegetative material	Value
1.	Small grain stubble	1.00
2.	Sorghum stubble	0.25
3.	Corn stubble	0.20
4.	small grain in seeding and stooling stage, dead or alive	2.50

Orientation of vegetative cover, K_o :

The more erect the vegetative matter and the higher it stands above the ground, the more it slows the wind velocity near the ground and lower is the rate of soil erosion. K_o includes the influence of distribution and location of vegetation such as width and direction of rows, uniformity of distribution and whether the vegetation is in a furrow or on a ridge. K_o has been assigned a value of 1.0 for absolutely flat, small grain stubble with straw aligned parallel with wind direction on smooth ground in rows 25 cm apart at right angles to wind direction. For other orientations and other residues, K_o varies as a power function of the amount of residue, R' , for values of R' greater than 1000 lbs/acre. The exponent ranges from approximately 0.5 for flattened small grain or sorghum to 0.25 for standing small grain and 50 cm high sorghum.

Relationship between variables

Considering the relationship between soil erodibility and some of the primary variables, some variables have been disregarded, some grouped together and some converted to their equivalents and are given below.

Soil erodibility Knoll erodibility, I	Soil and knoll erodibility, I'
Surface crust stability, F_s	Disregarded
Soil ridge roughness, K_r	Soil ridge roughness factor, K'

Wind velocity, V Surface Soil moisture M	Local wind erosion climatic factor, C'
Distance across the field, D_f Sheltered distance, D_b	Field length, L'
Quantity of vegetative cover, R' Kind of vegetative cover, S Orientation of vegetative cover, K_o	Equivalent quantity of vegetative cover, V

The eleven primary variables, thus, have been reduced to five equivalent variables. The general functional relationship between the potential average annual soil loss, X'_a tonnes/acre, and the equivalent variables may be expressed as:

$$X'_a = F(I',C',K',L',V) \qquad (8)$$

The relation between X'_a and V is exponential and is of the form $X'_a = f(e^V)$, while that between X'_a and L' is a power function of the form $X'_a = f(L'-b)^n$. The variables L', K', C' are simple product functions. A single equation expressing X'_a as a function of the five dependant variables is not available. A general description for computing the variables is given.

Soil and knoll erodibility, I', is obtained by multiplying soil erodibility, I (Table 6) by knoll erodibility I_s (Fig. 2) if a knoll or hill is present. The local wind erosion climatic factor, C', can be calculated from the relationship

$$C' = 34.483\ V^3/(P-E)^2 \qquad (9)$$

where, V = mean annual wind velocity for a particular geographic location corrected to a standard height of 30 ft,

P - E = Thornthwaite's (P - E) ratio = 10(P/E)

$= 115(P/T^{-10})^{1.111}$

C' may also be calculated by using modified index suggested by FAO (1977)

$$C' = (1/100) \sum_{1}^{12} V^{3} \times \frac{PET - P}{PET} \times n \qquad (10)$$

where, V = mean monthly wind speed at 2 m height in m/s

P = Precipitation, mm

PET = potential evapotranspiration, mm

$\frac{PET-P}{PET}$ = - refers to the number of erosive days in a month.

The soil ridge roughness factor, K', is expressed in terms of height of standard soil ridges spaced at right angles to the wind and with a height-spacing ratio of 1:4. Figure 4 presents a curve for obtaining the equivalent soil ridge roughness factor, K', from a measure of K_r. The curve is based on a design velocity of 50 miles per hour at 50 ft height with wind direction at 45^o to the ridges. Ridges of 4 to 10 cm are most effective in controlling erosion.

The equivalent field length, L', is the unsheltered distance across the field along the prevailing wind direction. Thus, $L' = D_f - D_b$. The equivalent vegetative cover variable, V, is obtained by multiplying the variables R', S, and $K_o = f(R')$. A graphical solution for this part of calculation has been suggested since L' and V are not simple functions of X'_a (Woodruff and Siddoway, 1965). X'_a can be finally expressed as :

$$X'_a = I' \times K' \times C' \times f(L') \times f(V) \qquad (11)$$

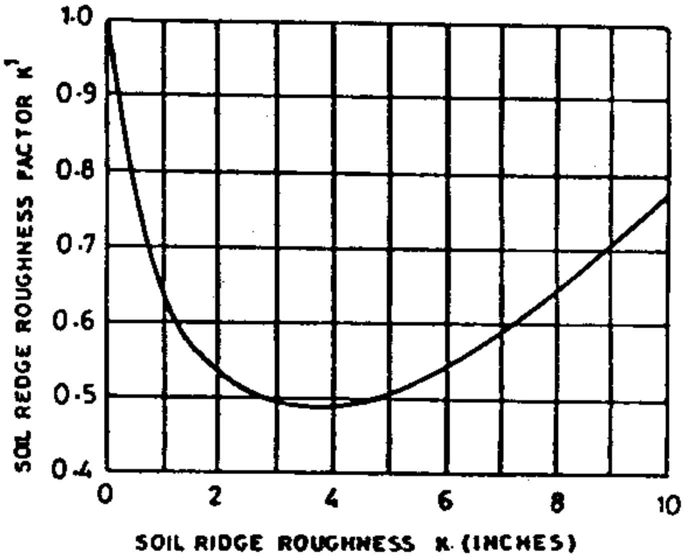

Fig.4 Chart to determine soil ridge roughness factor K' from the soil ridge roughness K_r (Woodruf and Siddoway, 1965)

5.0 Discussion and conclusions

India has about 60 million hectares of desert and semi-arid area and about 50% of which is affected by wind erosion, this include about 23.5 m ha of desert- The Great Indian desert, also, called the arid zone of north western India. The desart area is highly susceptible to wind erosion as there is a lack of precipitation (less than 750 mm) together with predominantly high temperatures and high wind speed. The highest wind speeds during the onset stage of a dust storm in Indian desert are 66.1 km/hr at 1 m height and 83.2 km/hr at 30 m height. The wind direction recorded during different stages of a duststorm revealed that dust storm arrives over the region from south to south westerly (SSW) direction indicating its coincidence with the arrival phase of SW monsoon in the desert and nearby area. Later on the wind direction changes to south east and finally after the withdrawal of the dust storm, it becomes almost southerly (Singh et al, 1992).

The magnitude of sand movement and soil loss has been found to be 2630 to 3160 t/ha for sandy plains during the sand storm of June-July, 1985, while those having 2 to 4 per cent vegetative cover or lying fallow lost 207 to 283 t/ha of soil (Dhir, 1989 vide Singh et al, 1994). Wind erosion/ deposition activities in the form of sand drifts, sand sheets, sand ridges, barchan dunes and reactivation of stabilized sand dunes are detrimental not only to lakes, canals and other water bodies, but also menace to agricultural lands, grazing lands, roads, railway tracts and other utilities. The disturbance caused to stable dunes during the canal construction of Indira Gandhi Canal Project, lying mostly in the less than 200 mm rainfall zone and the landscape dominated by the dune-interdune sequence, has led to large scale reactivation of the sandy landforms and accelerated the aeolian processes all along the the canal. As a result, the roads, settlements, and even the canal beds are affected (Singh et al, 1994). The annual soil loss is estimated to be in the order of 1500 to 2500 t/ha, resulting in the formation of sand sheets, sand ridges and barchan dunes on the nearby area. The wind erosion and water erosion have resulted into the silting of the Pushkar lake which has decreased its surface water area and desertification around the lake. In the Pushkar valley and adjoining area, wind erosion/ deposition accounts for 28% of the total desertification (Singh, 1995). Islands of sand have cropped up in the lake and an Indo-Canadian project is aiming to save the lake from siltation by shifting desert sand at a cost of over Rs. 4 crore. The project includes an integrated watershed management and water storage in the Pushkar lake.

The desert and semi-arid areas constitute a distinct ecosystem. The decisive factor in wind erosion is the vegetation, the importance of which for soil conservation increases with increasing aridness. More than three-fifth of the Indian hot desert is located in Rajasthan (78 mm) and about one-fifth area lies in Gujarat(76 mm). Besides, there are small pockets of hot desert in Punjab (76 mm), Haryana (76 mm) , Maharashtra (68 mm), Andhra Pradesh (68 mm), and Karnataka (68 mm). Figures in bracket indicate the mean aridity.

Majors lakes and their adjoining area in the desert should be studied and sediments received due to wind erosion should be estimated using the principles and method discussed herein. Soil erosion menace can not be totally controlled but could be minimised by appropriate land and water conservation measures in the arid areas. The experience of Pushkar lake project will be very useful and will probably serve as a guiding pilot project for taking up further programme in this direction to protect and converse our valuable lakes in the desert area from the sedimentation due to the furies of wind force and other natural agencies.

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