Agric. Rev., **26** (3) : 195 - 202, 2005

IMPACTS OF SOIL EROSION BY WATER - A REVIEW

D. Esther Shekinah and R. Saraswathy*

National Bureau of Soil Survey and Land Use Planning,
Amravati Road, Nagpur - 440 010, India

ABSTRACT

Soil is a finite resource. Though the impacts of soil erosion are varied in different spheres, understanding it in the context of impacts on agriculture is very important as it lays the foundation for planning to conserve and protect the resource base. This review deals with the major effects of erosion on soil and nutrient losses, soil and crop productivity, sedimentation of reservoirs etc. The nutrient losses of soil, especially under situations where there is no or low addition of fertilizers is a cause for concern. Thus, the study of impacts of soil erosion helps in developing techniques for soil conservation that are technically viable and socially acceptable to small land holders in the tropics.

Soils are a finite resource created and degraded through both natural and human induced processes. The relationship between humans and soil is characteristic of the ways through which humans interact with the environment, responding to potentials, recognizing limits and adapting the environment to suit human needs. Human activities both influence the structure, fertility and composition of soils and are influenced by the properties and availability of soils. Soils are formed in a low, continuous and gradual process. Scientists estimate that 2.5 cm (1 inch) of new top soil is formed every 100 to 1000 years (Pimental *et al.*, 1976). Under normal agricultural practices, 2.5 cm of soil can form in 100 years which is equivalent to a rate of 0.4 - 4.0 Mg/ha/yr. Schumm and Harvey (1979) discussing ratio of soil formation concluded that $10^5 - 10^6$ years are required to develop weathered surfaces on granite rocks and larger periods are required for non-granitic class. Hall *et al* (1979) reported that a very significant aspect of soil formation is made up of many facets with gains, losses and transformations of different components taking place at different rates in different horizons. The rate varies widely, influenced by land use, climate, vegetation, soil disturbances and the nature of the land (Brady and Weil, 1999).

Types of erosion

Erosion has been a problem since the dawn of human existence. Cultivated fields and cut-cover forest lands have always suffered from erosion. The normal rate of erosion under natural vegetation is in approximate equilibrium with the rate of soil formation thereby maintaining a nearly constant soil depth at any one place. There are two agents of erosion (i) wind and (ii) water. Water erosion is more prominent in cultivated areas. The accelerated water erosion has several types (i) splash erosion (ii) sheet erosion (iii) rill erosion and (iv) gully erosion.

In India, 148.9 m ha land is affected by water erosion out of the total geographical area of 326.8 m ha (Sehgal and Abrol, 1994). Human activities accelerate the natural degradative process so that the rate of soil formation is greatly outweighed by soil loss as a result of degradation. Kodumura and Yamamoto (1978) estimated the natural erosion for the world to be in the order of 1.5 to 7 t ha^{-1} for mountainous regions and 0.1 to 7 t ha^{-1} for undulating uplands. However it is estimated that accelerated soil erosion has irreversibly destroyed some 430 m ha in different countries - i.e. about 30 % of the present cultivated area of the world. Worldwide natural erosion is estimated to total some 9.9

* Central Soil and Water Conservation Research and Training Institute, Regional Centre, Bellary.

billion tons of soil a year, but human induced accelerated erosion is more than 2.5 times higher - 26 billion tons/year (Brown, 1984).

Impacts of erosion

The effects of degradation on soil resources can be grouped into two categories (i) those that are reversible (*eg*) nutrient levels, pH, organic matter and biological activity and (ii) those that are irreversible given the present technological and economic resources (*e.g.*) rooting depth, WHC, structure and texture. According to Loch and Silburn (1997), research by agronomists, agricultural engineers, soil scientists and agro-ecologists have identified the following effects:

(i) reduction in soil depth and potential rooting depth

(ii) reduction in soil nutrient availability

(iii) non-uniform removal of topsoil within a field

(iv) exposure of and/or mixing of top soil with subsoil of poorer physical, biological and chemical properties

(v) changes in soil physical properties (e.g. bulk density, water infiltration, WHC, texture or structure)

(vi) some combination of the above factors

Though the effects of erosion are varied in dimensions and spheres, this review will focus on the soil, nutrient and productivity losses and a few related impacts.

1. Soil loss

The serious erosion problem in our country is mainly in the form of sheet erosion in which the top soil is removed. The rate of soil erosion in different soils by sheet erosion is estimated as 4 to 10 t/ha/yr in red soils, 17-43 t/ha/yr in black soils and 4-14 t/ha/yr in alluvial soils. The rate of soil erosion from gullies is computed as 33 t/ha/yr in ravine regions. Similarly, the range of soil erosion from the hillside varies more than 80 t/ha/yr (Suresh, 2002). Singh *et al.* (1992) have reported that improper land management in North Eastern Hills region generated a very high soil loss (< 80 t/ha/yr) which far exceeds the permissible soil loss limit of 4.5 to 11.2 t/ha/yr.

The highest soil loss in Indonesia and Thailand has been reported to be about 500 t/ha under farmer's practices corresponding to about 1 cm of top soil per year. This means that crop production may not be possible after 15 years when all the fertile surface soil (about 15 cm) has been lost (Sajjapongse, 1997). The studies by Englestad and Shrader (1961) and Longdale and Shrader (1982) also indicated that the topsoil removal deteriorated both physical and chemical properties of soils. Highly weathered tropical soils are more vulnerable to erosion effects than temperate soils. This is primarily due to higher concentrations of crop nutrients and favourable growth conditions in the upper part of the soil profile and the more accelerated rates of erosion in the tropics (El Swaify, 1990). In India, the states of Gujarat, Maharashtra, Andhra Pradesh, Tamil Nadu and Kerala suffer from severe erosion and soil loss (Lal, 1990). The soil loss in different land resource regions of India is given in Table 1. The highest soil loss is in the Black soil regions followed by North East Forest regions. Different land uses also affect soil loss. Reports documented by Tripathi and Samraj (1994) in Southern Hills with reference to Nilgiris district bring out the fact that Shola forest has the least soil erosion as it is the natural forest that leads to geological erosion. Singh *et al.* (1990) reported that agriculture lead to more soil loss (2.45 t/ha) compared to trees and grasses (0.90 t/ha) and grasses + mechanical measures(0.40t/ha). This is mainly because the grass is able to bind the soil and also the impact of raindrops is brought down by the ground cover of grasses. Chinnamani (1982) reported that there exists a great disparity in soil loss between well managed and ill managed soils of different land

Table 1. Soil loss in different land resource regions in India

Land resource regions	Area ('000 km²)	Soil loss (t/km²)	Major land use
North Himalayan Forest Region	137.7	287	Forest
Punjab Haryana Alluvial plains	101.25	330	Agriculture
Upper Gangetic Alluvial Plains	200.00	1440-3320	Agriculture
Lower Gangetic Alluvial Plains	145.50	287-940	Agriculture
North Eastern Forest regions	161.00	2780-4095	Agriculture/shifting culture
Gujarat Alluvial Plains	62.75	240-3320	Agriculture
Red Soil Regions	68.00	240-360	Agriculture
Black Soil Regions	67.34	2370-11250	Agriculture
Laterite Soils	61.00	3930	Agriculture

(Source: Dhruv Narayana and Ram Babu, 1983).

Table 2. Implications of soil loss tolerance

Rooting depth	Soil loss tolerance values (t/ac)	
	Renewable soil	Non-renewable soil
0-25	2.2	2.2
25-50	4.5	2.2
50-100	6.7	4.5
100-150	9.0	6.7
150-	11.2	11.2

(Source: McComarck and Young, 1997).

uses. Soil tolerance value for different depths of renewable and non-renewable soils is indicated in Table 2, where renewable soils are those with favourable substrata that can be renewed by tillage, fertilizer, organic matter and other management practices and non-renewable soils are those with unfavourable substrata such as rock on soft weathered material that cannot be renewed by economical means.

The tillage method used also influences the amount of soil lost from agricultural lands due to water erosion. Studies indicate that longer no till history decreases soil losses and increases crop yields and also benefits from improvement in soil structure over time. Annual soil losses averaged 16.0 t/ha for no till corn for grain at 5 % slope (McGregor and Mutchler, 1983). Studies were conducted in Vasad, Gujarat for sixteen years to determine the amount of soil lost at different slope and length. The maximum soil loss was 9.76, 56.37, 27.46, 17.99 t/ha at 9, 6, 3 and 2 % slope. Similarly 66, 44, 22 and 11 m length of slopes produced a soil loss of 19.96, 16.91, 14.05 and 10.3 t/ha (Kurothe and Singh, 1999) while at Bellary, the smallest length gave the maximum runoff and soil loss. The soil loss per unit area was linearly correlated with steepness of slope (Nalatwadmath *et al.*, 2000). Attempts to measure splash erosion at Kanpur in two years (1986 and 1987) revealed that it was maximum in fallow plots (48.6 and 22.5 t/ha) and minimum in plots having cowpea (26.0 and 9.4 t/ha) (Suraj Bhan *et al.*, 1992).

2. Nutrient losses

Soil erosion results in huge loss of surface soil along with essential plant nutrients through runoff, reducing the productivity of soils. The topsoil, *ie.* the nutrient rich organic and clay particles that tend to be the soil particles, is dislodged and carried away by erosion. This loss of soil organic matter, nutrients and WHC causes significant qualitative changes in soils. Extraction of agricultural chemicals, nutrients form the soil surface into surface runoff and import of chemicals of percolation from the root zone to ground water are of concern for both economical and environmental stand points.

Baker and Laflen (1982) have reported that the fertility value of a ton of eroded soil can be calculated by using the following assumed values. (i) An average temperate region topsoil contains about 3 % organic matter but an average ton of sediment contains more colloids so it has about 6% organic matter (ii) The soil organic matter is about 5% N, 0.5% P and a little K apart from that held by cation exchange. The mineral matter contains little N, about as much total P as the organic matter and about 1.5 % K. (iii) the amounts of nutrients that will become available annually in a temperate region can be estimated as 3 % of the N, 5% of the P and 1% of the K (these percentages may be as high as 25% in tropical climate and as low as 1% of the N in a cold climate with the other nutrients in proportion).

Lowrance (1992) determined N runoff from a cropping system with summer row crops and winter cover crops during a period of four years to find that mean yearly subsurface runoff was 36.5 kg ha^{-1} N from subsurface flow and 2.7 kg ha^{-1} from surface flow. The solute PO_4 and PO_4 associated with sediment in surface runoff have been found to vary linearly with P application rates and increases in soil test P (Pote *et al.*, 1996). For non-sandy soils, the leaching of PO_4 with percolating water is extremely low or non-detectable (Hubbard *et al.*, 1985). Soileau *et al.* (1994) found greater P runoff in conservation tillage where fertilizer P cannot be incorporated than in conventional tillage. Baker and Laflen (1982) determined that P broadcasting on the surface soil resulted in 110 times more soluble P in runoff, compared with incorporating P to a depth of 5 cm. The concentrations of N and P in the sediment, however, are usually higher with conservation tillage than with conventional tillage. Since soil losses are lower from conservation tillage than from conventional tillage, the total losses of N and P are consequently lower from conservation tillage system. Sewa Ram and Khola (2000) have reported nutrient losses of available NPK to the tune of 12.2, 0.5 and 6.6 kg ha^{-1} in 0.5 % slope to 34.9, 1.6 and 16.7 kg ha^{-1} in 9.5 % slopes as a result of erosion from field studies conducted at Selakui Research Farm, Dehradun for 3 years.

In erosion prone steep slopes in north western region of India which is under maize, about 50 % of the rainfall is lost as runoff carrying with it 20 t/ha/yr soil and 18.66 kg N, 17.02 kg P_2O_5 and 412 kg K_2O /ha/year. Prasad *et al.* (1993) reported that the loss of nutrients was higher in fallow as the loss of soil was more in fallow plots. Soil loss of 4229 kg/ha has been reported from the fallow plots with a loss of 6.65, 0.68 and 10.95 kg/ha of available NPK while the plots with intercropping of greengram with castor lead to lower soil loss (62 kg/ha) and consequently lower nutrient loss due to the beneficial effect of greengram in reducing the runoff loss and the impact of raindrops. High soil loss (40.9 t ha^{-1}) has been measured in shifting cultivation with a loss of 698 kg ha^{-1} of organic carbon, 0.15 kg ha^{-1} of available P_2O_5 and 7.1 kg ha^{-1} of available K_2O while agriculture with bench terracing recorded the minimum soil loss (2.3 t ha^{-1}) and minimal nutrient loss (Narain *et al.*, 1994). Sewa Ram *et al.* (2001) reported that the nutrient loss was greater in land with higher slopes.

Nutritional replenishments to eroded soil (as added fertilizer) are, by themselves, insufficient to restore original soil productivity. Physical and biological rehabilitation steps are critical for this purpose (El Swaify, 1990).

3. Soil and crop productivity

By far, the most important impact of soil erosion from our agricultural perspective is the impact on crop productivity. Soil degradation can also be defined as the substantial decrease in a soil's biological productivity or usefulness due to human interference assuming other factors such as technology, management and weather remain constant (Bojo, 1996). Soil productivity is the productive potential of the soil system that allows the accumulation of energy in the form of vegetation.

Erosion-productivity relationship is a reversible one, reducing erosion preserves soil productivity and productive systems are often very protective against soil erosion. Table 3 and 4 gives the mean annual loss in production as a result of erosion in USA and Canada (den Biggelaar *et al.*, 2001). Some soils experience consistent productivity reductions with degradation while others suffer no loss until some critical point in one or more yield determining factor is reached at which time significant yield losses occur with further degradation (Hoag, 1998). Productivity can reflect soil erosion if yields decline with progressive erosion or if input use increases to compensate for declines in soil quality due to erosion (ERS, 1997). The effects of degradation may also vary from year to year so that long term degradative effects are not easily apparent. *eg.* eroded soils with reduced plant available water holding capacity or infiltration rates often show greater yield losses in drought years compared with uneroded soils (Swan *et al.*, 1987).

During years with normal or above-average rainfall, however, yields on eroded and uneroded soils may be identical. In tropical soils and crops, erosion effect on productivity is dependent on crop type in order grain cereals>grain legumes>root crops (El Swaify, 1990). Row crops such as maize, cotton, wheat and soybeans are crops for which yields are most affected by erosion. Forage crops such as alfalfa, clover and perennial grasses are frequently more tolerant of erosion damage. Erosion on these soils reduces yields because of the presence of zone of compaction, or a toxic level of exchangeable Al that limits root growth and reduction in supply of plant available water. Under such conditions, loss of even a few centimeters of soil may be very important. 5-10 tones of soil are eroded for each tonne of grain produced in Indian rainfed conditions (Yule and Srivastava, 1990). Experimental results in Doon valley (Sewa Ram *et al.*, 2001) indicated that higher slopes led to greater erosion. This has lead to decline in productivity of rice and barley.

Table 3. Mean annual loss in production as a result of erosion in USA and Canada

Crop	Soil order	Mean yield	Erosion rates	Annual loss of production
USA				
Maize	Alfisols	7.5	11.6	111.1
	Mollisols	7.9	11.54	86.1
	Ulfisols	5.8	9.78	32.0
Canada				
Wheat	Alfisols	2.5	7.2	2.5
	Mollisols	2.2	4.8	19.0
Maize	Alfisols	7.0	7.2	5.3

(Source: den Biggelaar *et al.*, 2001).

Table 4. Effect of soil erosion severity on crop yield

Crop	State	Crop yield (kg/ha)		
		Slight erosion	Moderate erosion	Severe erosion
Corn	Wisconsin	5018	4202	3763
Grain		4234	3360	2890
Grain	Minnesota	2419	2016	1546

(Source: den Biggelaar *et al.*, 2001).

Sometimes it may not be the decrease in depth of topsoil or solum which causes significant qualitative changes, or a root restrictive layer per se that impacts yields, but rather the changes the loss of soil brings about in other soil factors such as nutrient levels, pH, water holding capacity, texture, infiltration rates and soil organic matter over time, possibly rendering agriculture unprofitable or even impossible. Long term productivity depends on maintaining the thickness of the A horizon and a favourable rooting depth (den Biggelaar *et al.*, 2001).

However, Littleboy *et al.* (1996) concludes that the precise relationship between erosion and productivity are also not independent, both are influenced by other factors. Moreover, the loss in productivity set in motion by accelerated erosion may be a self-sustaining process. Loss of production on eroded soil may further degrade its productivity (through loss of crop cover, poor stands and reduced amount of residues returned to the soil), which in turn, may accelerate erosion (Ponzi, 1993).

4. Textural change

Coarse grains are left near their original location while finer ones are transported some distance. This selective removal makes original sandy soil even sandier. However, medium and fine textured soil may not be altered seriously because the water sorts aggregates not individual soil particles. Long continued erosion removes the entire surface horizon. The new topsoil, really the exposed subsoil is generally fine textured and poses serious physical problems in preparing a seedbed and in other phases of crop production.

5. Field dissection

When channels across field become gullies too large to be crossed with ordinary farm machinery, the field must be farmed in two or more smaller units with shorter lands and much more turning. Net profits go down because of higher production costs, less cultivable land and lower yields.

6. Sedimentation

Apart from all the above mentioned impacts of erosion, the negative impacts on a higher level would be the accelerated sedimentation of reservoirs. The present capacity of Nizamsagar reservoir is 338 mm^3 as against the initial 898 mm^3. Not enough water is therefore available to irrigate the designated command area for growing sugarcane and paddy, while the all round productivity is also reduced (Bowonder *et al.*, 1985). The mean annual soil loss from Kinnaur and Spiti Himalayas contribute 1/3rd of annual sediment deposited into Bhakra reservoir. The high sediment concentration of 5 g/l in the waters of Sutlej river draining Kinnaur during June to August would also lower the operational efficiency of many large and medium hydroelectric projects in Sutlej river (Sharma and Minhas, 1990).

On an average, the Himalayan hills are reported to generate 28.2 t/ha/year sediment (Singh and Gupta, 1982) resulting in siltation of reservoirs and affecting hydroelectric generation adversely. Siltation of

Bhakra reservoir is at the rate of 35.8 x 106 m^3 annually, half of which comes from Himalayan basin (Sharma *et al.*, 1991). It has been estimated that at this rate, the effective life of Bhakra reservoir to generate electricity has been reduced by 40 per cent and the reservoir will be fully silted up in 400 years. Siltation led to the abandonment of electrical production in 1955 and water supply in 1975 in Katery (Ketty) reservoir (Chinnamani, 1982). Desilting the reservoir only could resume water supply. However, if proper soil and water conservation measures are applied in the upstream catchments, these huge sedimentation rates can be minimized (Dhruv Narayana, 1987; Chaudhary and Sharma, 1999).

CONCLUSION

The above review indicates a decrease in productivity with accelerated soil erosion. This concurs with earlier findings of the relationship between soil erosion and productivity. The decline in yield, however is not the same for different soils and crops. Added to this is the nutritional losses of soil, especially under situations where there is no or low addition of fertilizers. The other major changes like the dissection of the field will occur under extreme conditions when erosion is left unchecked for a long time.

Researchers in the tropics need to be more original in studying the basic processes of soil erosion and in developing techniques for soil conservation that are technically viable and socially acceptable to small land holders in the tropics. However, den Biggelaar *et al.* (2001) opined that since the estimated losses are small relative to the total value of agricultural production of crops and likely to be masked over in the short term by inter-annual variation in yields and net returns that arise from weather, pests and market conditions, the effects of erosion can be expected to provide farmers with relatively weak incentives to adopt erosion mitigating conservation practices in the short run.

However, it is necessary to impress upon the farmer and provide him incentives to adopt soil conservation measures in order to realize conservation goals that are important to society as a whole and to sustain productivity levels over the long term. Also, there is need to improve upon the conservation practices to keep up with the changes of time and adoption behaviour of farmers.

REFERENCES

Baker, J.L. and Laflen, J.M. (1982). *Trans. ASAE.*, **25**: 344-348.

Bojo, J. (1996). *Ecol. Econ.*, **16**: 161-173.

Bowonder, B. *et al.* (1985). *Land Use Policy*, **2**: 148-154.

Brady, N.C. and Weil, R.R. (1999). Nature and Properties of Soil. 12th edition, Prentice-Hall, Upper Saddle River, NJ.

Brown, L.R. (1984). *J. Soil Water Conserv.*, **36**: 255-260.

Chaudhary, R.S. and Sharma, P.D. (1999). *Indian J. Soil Cons.*, **27**: 1-9.

Chinnamani, S. (1982). In: Proc. Working Group Meeting of Soil Conservation from Southern Hill Region. CSWCR and TI, Dehradun (India). pp. 43-46.

den Biggelaar, C. *et al.* (2001). *Adv. Agron.*, **72**: 1-47.

Dhruv Narayana, V.V. and Ram Babu. (1983). *J. Irrigation and Drainage Engg.*, **109**: 419-434.

Dhruv Narayana, V.V. (1987). *Mountain Res. Develop.*, **7**: 287-298.

El Swaify, S.A. (1990). In: Proc. Int. Symp. Natural Resources Management for a Sustainable Agriculture, 6-10 February, 1990, New Delhi.

Englestad, O.P. and Shrader, W.D. (1961). *Soil Sci. Soc. Am. Proc.*, **25**: 497-499.

ERS (Economic Research Service, USDA), Natural Resources and Environment Division. (1997). Land and Soil Quality. In: Agricultural Resources and Environmental Indicators, 1996-97. pp. 41-49. USDA Economic Research Service, Washington, DC.

Hall, G.F. *et al.* (1979). In: Proc. Symp. Determinants of Soil Loss Tolerance. Soil Sci. Soc. Amer. Ann. Mtg., Ft. Collins Co., August, 1979.

Hoag, D.L. (1998). *Agric. Sys.*, **56**: 415-429.

Hubbard, R.K. *et al.* (1985). *Trans. ASAE.*, **32**: 1239-1249.

Kodumura, H. and Yamamoto, H. (1978). *J. Geogr.*, **87**: 1-15.

Korothe, R.S. and Singh, H.B. (1999) Annual Report, 1998-99, CSWSR and TI, Dehradun. p. 19.

Lal, R. (1990). *Adv. Soil. Sci.*, **11**: 122-172.

Littleboy, M. *et al.* (1996). *Aust. J. Soil Res.*, **34**: 127-128.

Loch, R.J. and Silburn, D.M. (1997). In: Sustainable Crop Production in the Sub-tropics: An Australian Perspective. (Clarke, A.L. and Wylie, P.B. Ed.) Dept. of Primary Industries, Brisbane, Qld. pp. 27-63.

Longdale, G.W. and Shrader, W.D. (1982). In: Determinants of Soil Loss Tolerance. ASA Special Publication No: 45, p. 1536.

Lowrance, R. (1992). *J. Environ. Qual.*, **21**: 602-607.

McComark, D.E. and Young, K.K. (1997). *Soil Conservation: Problems and Prospects.* (Moregan, R.P.C. Ed.) John Wiley and Sons, New York. pp. 177.

McGregor, C.K. and Mutchler, C.K. (1983). *Trans. ASAE.*, **26**: 785-788, 794.

Nalatwadmath, S.K. *et al.* (2000). Annual Report, 1999-2000, CSWCR and TI, Dehradun. p. 20.

Narain, P. *et al.* (1994). *Indian J. Soil Cons.*, **22**: 42-62.

Pimental, D. *et al.* (1976). *Science*, **94**: 149-155.

Ponzi, D. (1993). Soil Erosion and Productivity: A Brief Review. Desertification Control Bulletin No. 22, pp. 36-44.

Pote, D.H. *et al.* (1996). *Soil Sci. Soc. Am. J.*, **60**: 855-859.

Prasad, S.N. *et al.* (1993). *Indian J. Soil Cons.*, **21**: 25-30.

Sajjapongse, A. (1997). Soil Conservation Extension-From concepts to adoption. Sambal Panits, S. *et al.* Ed. John Wiley and Sons, New York.

Schumm, S.A. and Harvey, M.D. (1979). In: Proc. Symp. Determinants of Soil Loss Tolerance. Soil Sci. Soc. Amer. Ann. Mtg., Ft. Collins Co., August, 1979.

Sehgal, J. and Abrol, I.P. (1994). *Soil Degradation in India: Status and Impact.* Oxford and IBH Publishing Co. Pvt. Ltd., New Delhi. p 80.

Sewa Ram and Khola, O.P.S. (2000). *Indian J. Soil Cons.*, **28**: 131-137.

Sewa Ram *et al.* (2001). *Indian J. Soil Cons.*, **29**: 43-49.

Sharma P.D. and Minhas, R.S. (1990). In: Proc. Int. Symp. Natural Resources Management for a Sustainable Agriculture, 6-10 February, 1990, New Delhi.

Sharma, P.D. *et al.* (1991). *Mountain Res.Develop.*, **7**: 287-298.

Singh, D.D. and Gupta, P.N. (1982). In: Proc. Int. Symp. Hydro-aspects of Mount Watersheds, Roorkee, Nov. 4-6, Moglik Prakashan, Saharanpur. pp VII, 60-65.

Singh, G. *et al.* (1990). *Indian J. Soil Cons.*, **18**: 16-22.

Singh, S. *et al.* (1992). *Ann. Arid Zone*, **31**: 237-246.

Soileau, J.M. *et al.* (1994). *J. Soil Water Cons.*, **49**: 82-89.

Suraj Bhan *et al.* (1992). *Indian J. Soil Cons.*, **20**: 72-76.

Suresh, R. (2002). *Soil and Water Conservation Engineering.* Standard Publishers, New Delhi. p. 824.

Swan, J.B. *et al.* (1987). *Soil Sci. Soc. Am J.*, **51**: 1025-1032.

Tripathi, K.P. and Samraj, P. (1994). *Indian J. Soil Cons.*, **22**: 94-101.

Yule, D.F. and Srivastava, K.L. (1990). In: Proc. Intl. Symp. Natural Resources Management for a Sustainable Agriculture, 6-10 February 1990, New Delhi.