Hazards of Erosion and Its Effects on the Water Resources of Pakistan

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Abstract

The economy of Pakistan is fundamentally based on agriculture, and its surface water storage reservoirs play an important role in providing irrigation water to the largest canal-irrigated system of the world. To determine the adverse effects of soil erosion and sedimentation or silting in reservoirs, one such being the reduction in storage capacity, a study was carried out in the catchment areas of the Tarbela, Mangla, and Khanpur dams. Due to high rates of precipitation in some parts of the catchment area, the geological setting and erodibility of clays in the predominant alternate hard and soft formational lithology, the silting rate has attained considerable proportions. A 13 per cent reduction in surface water storage capacity has occurred since the construction of these dams, threatening the supply of water for irrigation in future. In Tarbela, a 8.28 per cent reduction has occurred since 1974 while Mangla Reservoir has reduced its capacity by only 4.6 per cent since 1967, due to high-quality management of the watershed soon after its construction. It is found that, in addition to high precipitation, differential erosion in the alternate hard and soft formations prevailing in the area, deforestation, and unstable slopes, particularly in highly seismic zones of the catchment area, are the major causes of silting. In order to demarcate different zones susceptible to high erosion, data such as geological mapping on different scales, precipitation, seismicity, slope instablility, and geomorphic variations were used. The stabilisation of soils, construction of check dams, and proper management of the watershed are recommended.

Introduction

The irrigation system of Pakistan is the most intricate and well-developed in the world. This system covers a total area of 33 million acres, of which 24 million acres are irrigated annually, and was developed entirely from the unregulated runoff river flow of the Indus River system. Due to seasonal variations in precipitation, crop failures were common. This problem of scarcity of water in the system became alarming after independence of Pakistan in 1947, following a dispute with India. The need for developing reservoirs in the Indus basin, therefore, seemed urgent. A treaty (Indus Water Treaty) was concluded in 1960 to resolve the dispute. According to this treaty, the waters of eastern rivers were to be replaced by waters of western rivers in time for three eastern rivers to be diverted by India in 1970. The three eastern rivers (Fig 1), the Ravi, Bias, and

Sutlej, with a total annual flow of 33 million acre-feet (MAF), were allocated to India, and three western rivers, the Chenab, Jhelum, and Indus, with a total annual flow of 135 MAF, to Pakistan. The Indus Basin Project was therefore designed to replace irrigation supplies in Pakistan by constructing huge dams and canals. The Mangla and Tarbela dams are major parts of the Indus Basin Project. Other parts include a network of eight canals and two barrages.

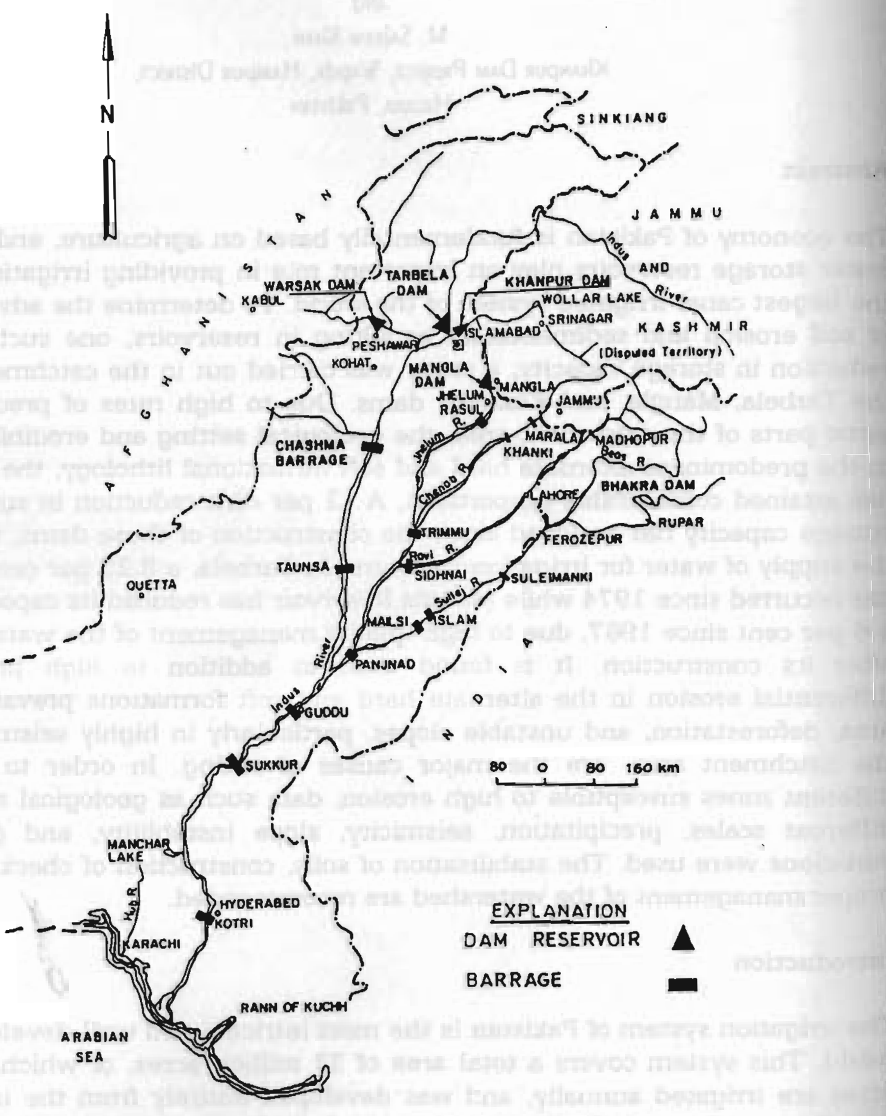

Figure 1: Map of Pakistan Showing the Location of Surface Storage and the Surface Water Management System

The Indus Basin Project is the largest single water development project ever undertaken in the world, with Mangla and Tarbela as the largest dams of their kind. The 700-mile network of inter-river canals will transfer 18 MAF of water annually to six million acres of irrigated land on the eastern rivers. Four of these canals carry ten times as much water as the average flow of the River Thames.

The catchment areas of these huge dams produce enormous quantities of sediments in the reservoirs, particularly in the flood season (July to September), i.e., during the monsoon. For instance, the average annual sediment load of 75 million tons in the river in Mangla will deplete the storage of water at a rate of one MAF every 20 years (the total reservoir being 5.88 MAF); under the present rate of sedimentation, the capacity of the Mangla Reservoir could be reduced by 25 per cent in the next 20 years. The Jehlum River at Mangla has a total catchment area of 12,870 square miles (and a mean annual flow of 23 MAF), of which 82 per cent is higher than 4,000 feet and 28 per cent is higher than 10,000 feet above sea level.

The basins of Tarbela and Mangla are bounded in the north by the Himalayan Mountains, which are young, tectonically and seismically active, and where destructive earthquakes have occurred from time to time. The great system of thrust faults (main boundary fault) passes 30 miles from Mangla.

Afforestation in the catchment area and management of the watershed area by the construction of check dams, dykes, retaining walls, and, to some extent grouting, if possible, in critical areas are recommended on the basis of geology, lithology, seismic activity, differential erosion, and the geotechnical characteristics of soils and rocks.

Methodology

Data regarding rates of sedimentation were collected from surveys by the Water and Power Development Authority, Lahore. Geological maps of the critical areas were prepared on different scales. Soil samples from typical parts of the catchment area were collected during a field survey. Various tests, such as an analysis of grain sizes, Atterberg limits, and unconfined compression strength, were performed to find out the characteristic features of the soils and their susceptibility to erosion.

Other related factors, such as seismic activity, the effects of precipitation, slope angle, and environmental phenomena, were discussed. The deposition of sediments in the lakes of storage dams and the reduction in their storage capacity were studied with relation to the adverse effects of erosion.

Geological mapping , Landsat images, and areal photographs were initially used for a broader demarcation and identification of critical areas. From these, areas were carefully selected for detailed mapping on scales of 1:500 and 1:1000.

For the study of pores, diagenesis, and grain fabric, a computerised digitiser and Scan Electron Microscope were used. It is generally assumed that the strength of clastic rocks is controlled by the strength of constituent minerals and by grain size, shape, packing, and nature or extent of cementation. The sandstones in the area were studied in detail for their mineralogy, the distribution of voids, and the effect of the matrix and fabric of grains on strength.

Results and Discussion

Altitude and Slope

The physiographic and hydrogeologic units of Pakistan (Fig. 2) display a wide variation in their elevation above sea level (Surface Water Hydrology Project 1995). The catchment area ranges in height from 610 to 6,096m. All the major surface water storages in Pakistan are located in the northern part of the country (Fig. 2). The Tarbela, Mangla, and Khanpur dams and the Chashma barrage are situated at altitudes of 305 to 914m. The catchment area of Mangla, Tarbela, and Khanpur dams extend from 22 to 93km to the north or northeast, but the difference in altitude is more than 6,096m. This high gradient within a small span of space renders the area unstable as far as slopes are concerned (Olivier et al. 1994).

Precipitation

Heavy monsoon rains and storms are responsible for erosion and mass movement and silting (Khan 1992). The soft material gets washed down by extensive runoff, which contributes to silting. Thus landslides and silting go together, apart from the usual erosion of softer materials in the prevailing hard and soft lithology. Heavy silting of reservoirs and increased landslide activity have been reported in the northern part of Pakistan (Malik and Farooq 1995a, 1995b). The rainfall pattern in Pakistan is presented in Figure 3.

Seismic Activity

The major structures of the Mangla and Tarbela dams and their catchment area lie in a highly seismic zone.The seismic centre established at Tarbela Dam has recorded more than 50 earthquakes between 1983 and 1992, with intensities ranging between 5.0 to 7.6 on the Richter Scale. Cohesionless materials, such as sand within clays, develop high porewater pressure and liquify earlier than clay, and this may be responsible for the ultimate collapse of the clays as well. Materials with high porosity (silts and sands), if free of clays, have a high potential for liquification during an earthquake (Blyth and Defreitas 1984). The accumulation of deltas under the Tarbela and Mangla reservoirs is posing just such a threat of liquification (Armbruter et al. 1977, Ambrasey et al. 1974).

Geological Setting

The geological setting of the catchment area is rather complicated. It contains rocks from Recent to Precambrian in age. The entire area is highly folded and faulted, being in a young mountain system. These thrust faults happen to be located in a seismically active zone.

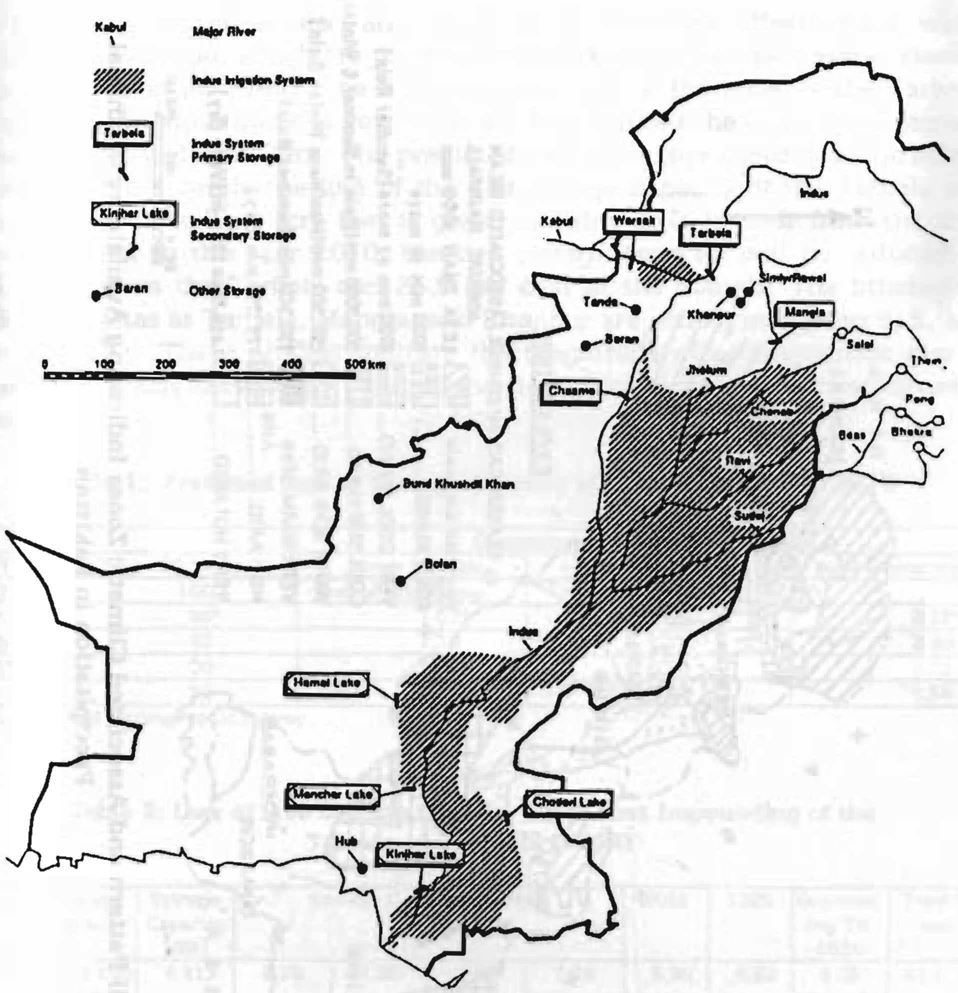

Figure 2: Irrigation System in Pakistan Based on Surface Storage Management

The effect of geological history is very important in determining the loss in storage capacity of the reservoirs. The Siwalik ranges for example (Plio- to Pleistocene epoch) were deposited by streams rejuvenated by a major uplift of the Himalayas in the Miocene. Since the Pleistocene, i.e. , one million years ago when the last uplift took place, about 1,525 to 6,096m have been eroded. Recently, the alternate hard and soft formational lithology prevailing in the area has contributed to sedimentation due to differential erosion. The variation in sandstone lithology is also a major factor: 90 per cent of the sediments are very friable and lose their strength (70-100%) on saturation, while 10 per cent are harder ribs and very resistant to erosion. Similarly, clays and shales shrink, producing shallow slopes of debris.

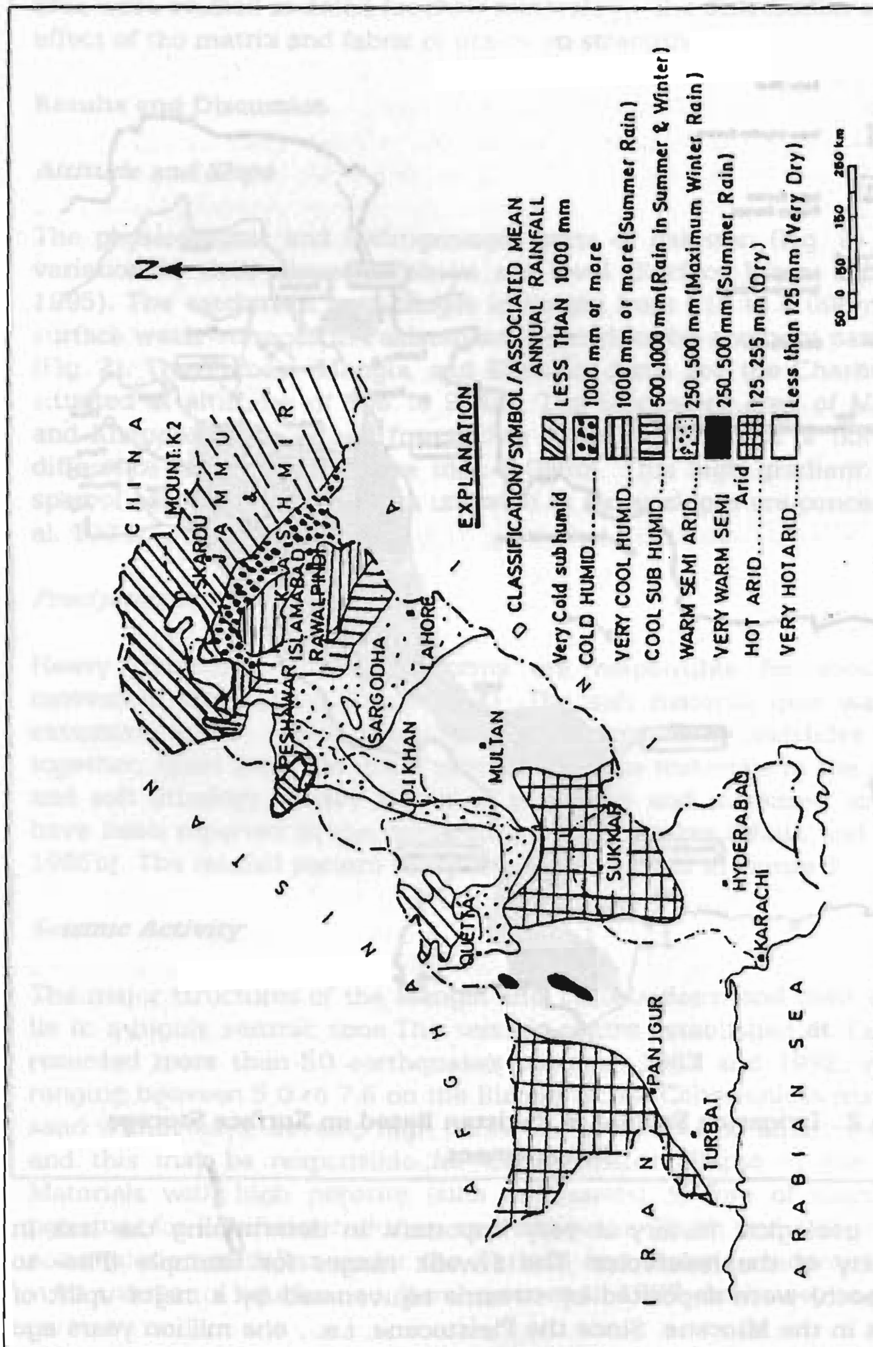

Figure 3: Rainfall Pattern and Associated Climatic Zones Indicating Availability of Annual Precipitation in Pakistan

Deforestation

In Pakistan, only five per cent of the country is covered with forests, much less than the 25-30 per cent required. Extensive afforestation in the catchment areas has been recommended in the past and some progress has been made (Riestenberg 1994).

Erosion

The high level of soil erosion and landslides is adversely affecting the water resources of Pakistan, which are predominantly based on a surface water storage system (Bhatti et al. 1995). The sedimentation rate in the lakes of the Tarbela, Mangla, and Khanpur dams is very high and has reduced the cumulative storage capacity by up to 15 per cent. The predicted loss in storage capacity of Tarbela is given in Table 1, while the loss of the live storage capacity of the Tarbela and Mangla dams in million acre feet is given in Table 2. It is clear from the data presented that in the year 2010, the live storage capacity will be reduced by 31.5 per cent at the Tarbela and 25.5 per cent at the Mangla. The lithological profiles of deltas at Tarbela, Mangla, and Khanpur are shown in Figures 4, 5, and 6, respectively. These profiles indicate the magnitude of sedimentation due to soil erosion which has directly reduced the storage capacity of water resources in Pakistan.

Table 1: Predicted Loss of Storage Capacity of Tarbela Dam up to 2010

		Cummulative Loss of Storage (MAF)		
Year	Trap efficiency (%)	Active Storage	Dead Storage	Toral Deposition
1974	100	Year of first filling		
1994*	98*	1.37*	0.85	2.22*
1999	82	1.79	1.19	2.98
2002	30	1.93	1.29	3.22
2010	30	2.14	1.42	3.56

* As per 1994 Hydrographic Survey

Table 2: Loss of Live Storage Capacity Since First Impounding of the Tarbela and Mangla in MAF

Dams	Storage Capacity	Storage Capacity 1993	Storage Capacity till 2020				2015	2020	Impounding Till 2020	Total % loss
Tarbela	9.680 (1974)	8.413	8.28	7.95	7.62	7.29	6.96	6.63	3.05	31.5
Mangla	5.340 (1967)	4.680	4.63	4.50	4.37	4.24	4.11	3.98	1.36	25.5

Materials

The typical soil samples from the catchment area of the Mangla Dam were tested for their strength and erodibility. Representative samples, A, B, C, and D, of clays and shales were tested. The direct shear tests yielded a range of from 33-39 degrees in the angle of internal friction, which corrersponds to the unconfined compressive strength values of 2.75 to 37.4 psi, while cohesion ranges from 7 to 8 psi (Table 3 and Figs. 7a and b). The grain size analysis of various soil samples and shales (*in situ*) reveals a predominance of silt. This is comparable with the grain size distribution of sediments deposited in reservoirs: sand 10 per cent, silt 65 per cent, and clay 25 per cent (Mangla Dam Periodic Inspection Report, 1995).

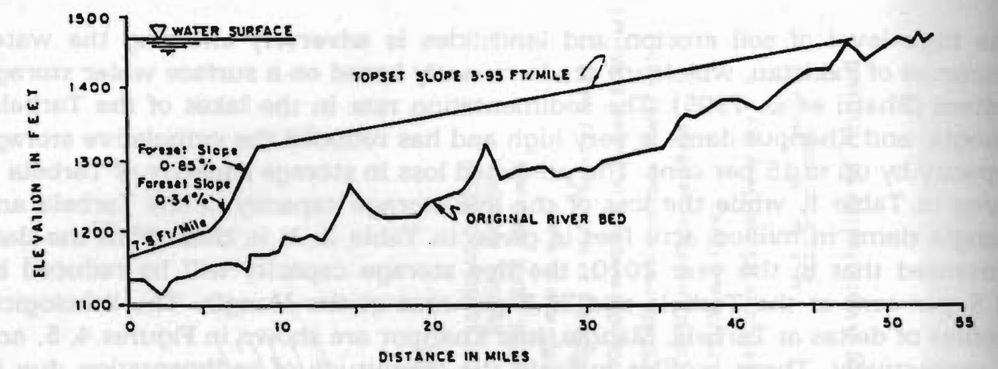

Figure 4: Longitudinal Profile of the Delta at Tarbela Dam

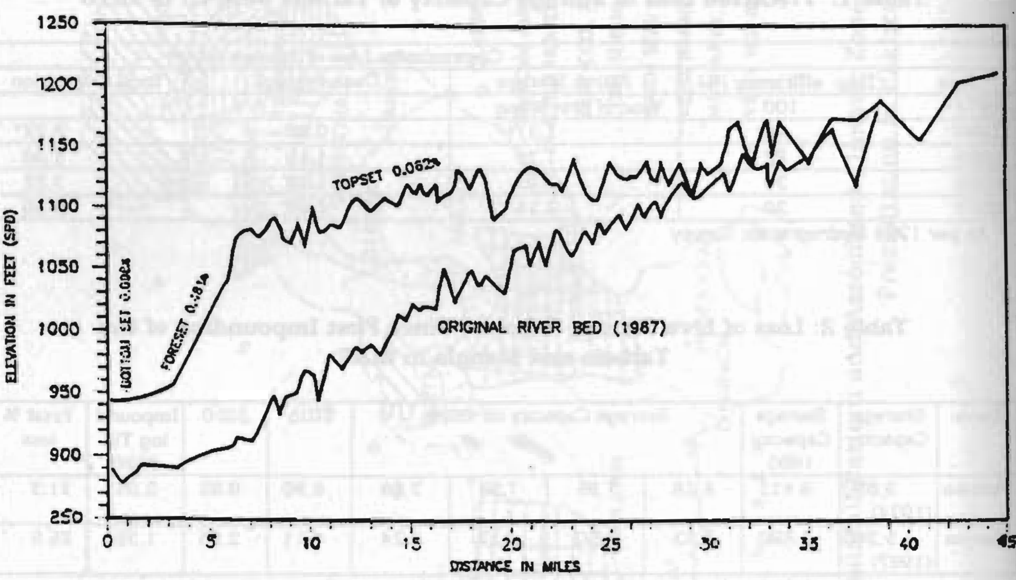

Figure 5: Longitudinal Profile of the Delta at Mangla Dam

Alternate clay and sandstone sequences of the Siwalik group, which are abundant in the vicinity of the reservoirs and which contribute greatly to silting, were studied in detail for their erodibility by using unconfined compressive strength as an index. A more detailed study was carried out on sandstones because of their abundance and weakness. Understanding the basic mineralogical and textural factors is essential in order to ascertain the mechanical behaviour and erodibility of sandstones. The weathering of sandstones varies with local climatic conditions but is in any case very detrimental to strength (low near the surface and high at depths). Test results of strength and the factors that affect them were, therefore, used.

Table 3: Summary of Test Results on Typical Soils and Shales in the Catchment Area of Khanpur Dam to Determine Erodibility

1. Grain Size Analysis:					
Barrow Area	*A*	*B*	*C*	*D*	*Shale*
Sand	5.00%	4.50	5.30	11.90	1.00
Silt	77.00	74.00	77.70	71.00	84.00
Clay	18.00	21.50	17.00	18.00	15.00
2. Atterberg Limits:					
Description	*A*	*B*	*C*	*D*	*Shale*
Liquid Limit	29.50	35.00	21.20	30.50	
Plastic Limit	21.55	21.72	25.40	21.60	
Shrinkage Limit	17.95	23.55	15.50	21.55	
Shrinkage Ratio	1.74	1.55	1.94	1.76	
Volumatic Shrinkage	22.15	16.17	25.78	11.90	
Specific Gravity	2.52	2.44	2.77	2.70	
3. Un-confined Compression Strength of Soil Samples:					
	A	*B*	*C*	*D*	*Shale*
Mixed unconfined Compression strength	38.4 PSI at 2.6% strain	17.80 PSI at 3%	24.50 PSI at 3%	37.40 PSI at 3.5%	9.75 PSI at4% strain
4. Direct Shear Test (Strain controlled Quick Test)					
Description	*A*	*B*	*C*	*D*	*Shale*
Cohesion	6.0 PSI	6.2 PSI	7.0 PSI	7.0 PSI	6.2 PSI
Angle of internal Friction	34°	33°	35°	39°	33°
5. Triaxial Test of Soil Samples:					
Description	*A*	*B*	*C*	*D*	*Shale*
Cohesion	11.5 PSI	6.5 PSI	8.0 PSI	10.0 PSI	0
Angle of Internal cohesion	27°	24°	32°	28°	25°
6. Specific Gravity Test	2.733	1.732	2.737	2.737	2.691
7. Organic Content Test	11.008%	10.406%	10.863	10.864	11.180%
8. Permeability Test (Constant Head Method)					
Sample A = 6.5×10^{-6} cm.sec.					
Sample B = 8.4×10^{-6} cm/sec.					

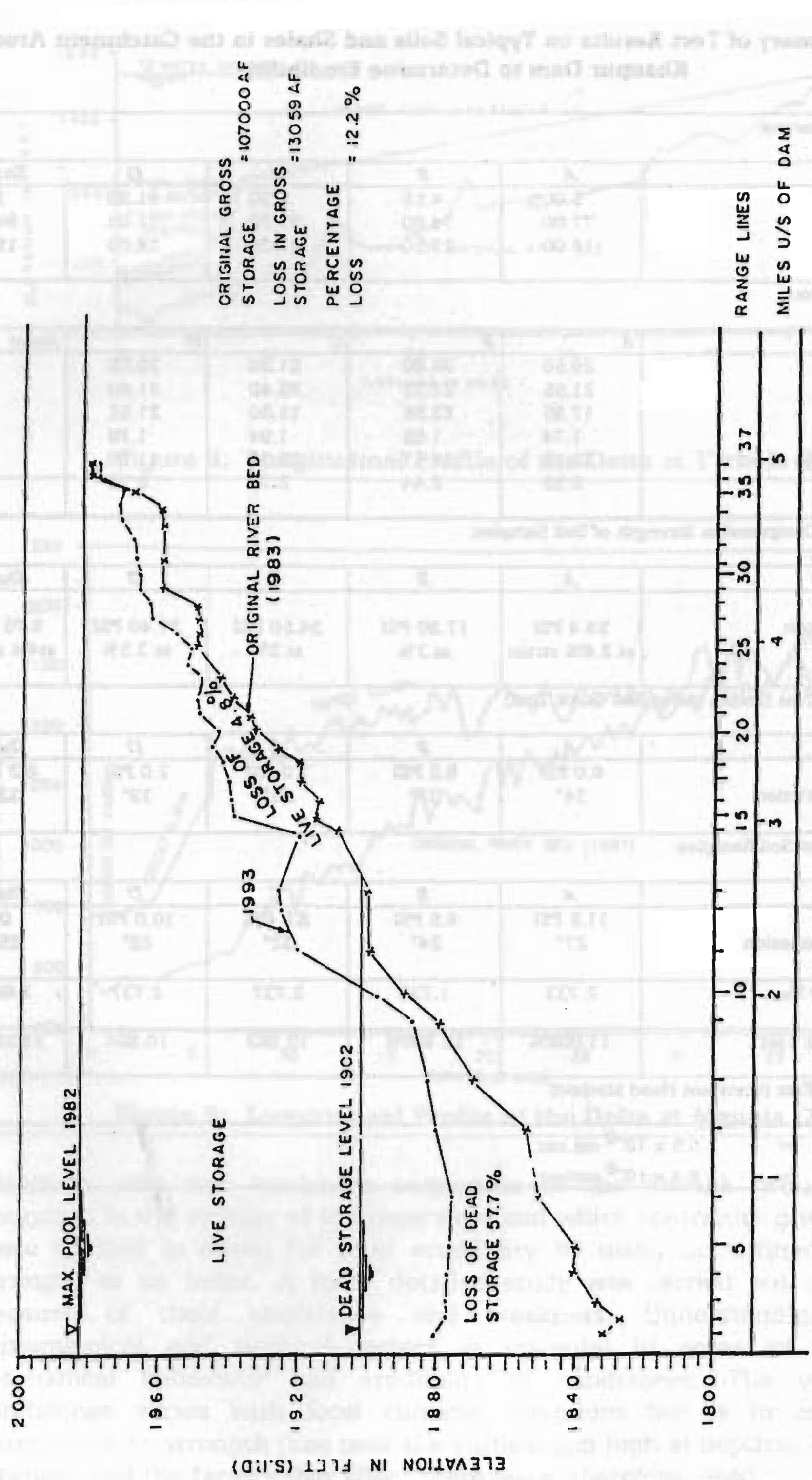

Figure 6: Longitudinal Profile of the Delta at Khanpur Dam

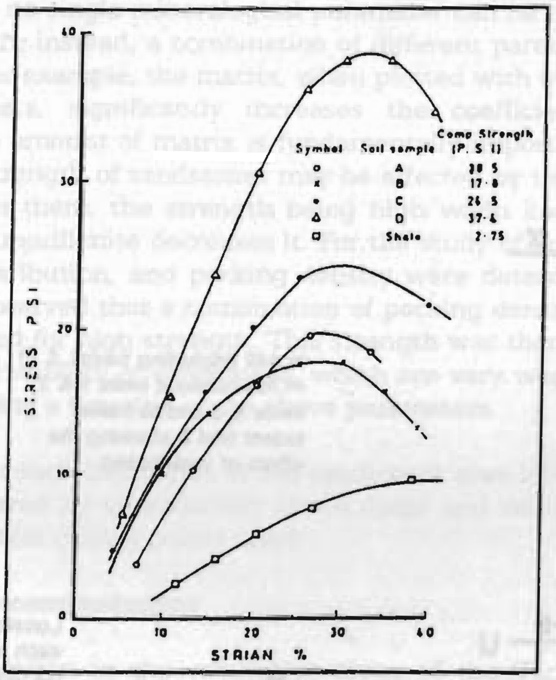

Figure 7a: Unconfined Compressive Strength of Soil Samples A, B, C, D and Shale

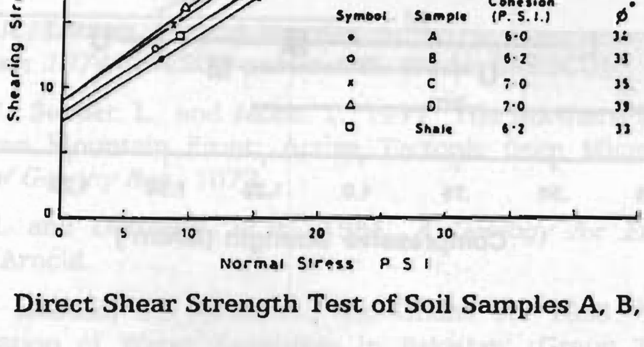

Figure 7b: Direct Shear Strength Test of Soil Samples A, B, C, D and Shale

Various combinations of mineral constituents were plotted against strength, and their correlation coefficients determined (Fig. 8). Similarly various factors were differentiated with respect to strength for determining the variability of these factors at different horizons in the sandstone beds. For the sake of brevity, only one such relationship is given here in the form of Figure 8.

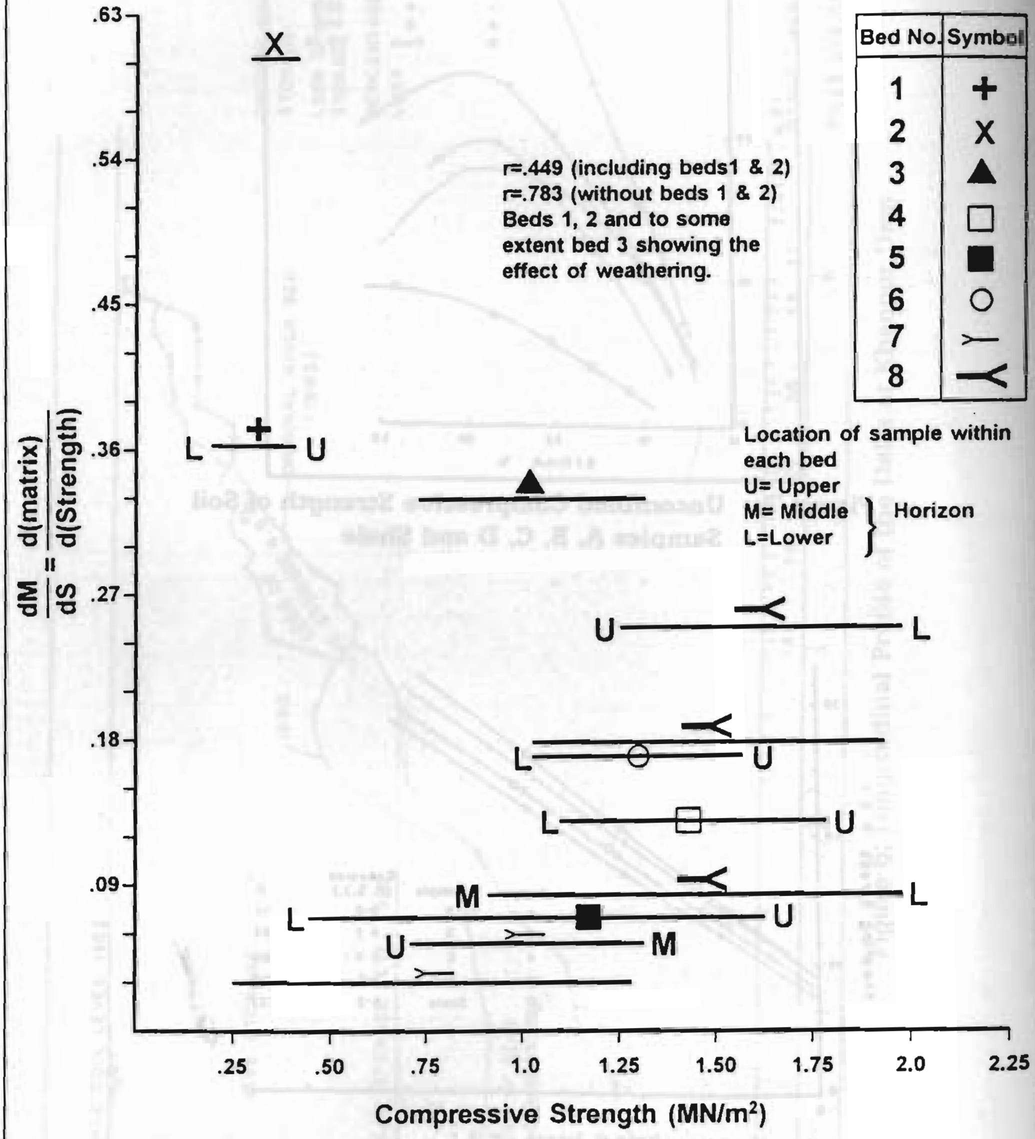

Figure 8: Variability of Matrix vs Strength

It is observed that no single mineralogical parameter can be held responsible for changes in strength; instead, a combination of different parameters seems to be acting together. For example, the matrix, when plotted with other contents, such as quartz or clasts, significantly increases the coefficient of correlation, indicating that the amount of matrix is fundamentally important for an increase in strength. The strength of sandstones may be affected by the amount and type of clay minerals in them, the strength being high when kaolinite is the main clay, even as montmorillonite decreases it. For the study of fabric, types of grain contacts, their distribution, and packing density were determined for different horizons. It was observed that a combination of packing density and distribution of matrix is required for high strength. This strength was then indirectly used as an index for the erodibility of sandstones, which are very weak, the variation in their erodibility being a function of the above parameters.

Soil stabilisation in such lithologies of the catchment area is therefore essential. This may be achieved by constructing check dams and retaining walls and by grouting treatment (at critical points only).

Conclusion and Recommendations

The rate of soil erosion in the catchment areas of the Tarbela, Mangla, and Khanpur dams is very high due to differential erosion of the area, which is further worsened by the impact of environmental factors such as deforestation and earthquakes. The alarming rate of sedimentation in surface water storage reservoirs threatens future water releases for irrigation from the lakes, due to the reduction in their storage capacity. The strength of sandstones can be used as an index of their erodibility.

Watershed management to control the soil erosion and water management to ensure proper use of existing water resources are recommended.

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