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Runoff and Sediment Transport in the Arid Regions of Argentina and India – A Case Study in Comparative Hydrology

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Abstract : Comparative hydrology attempts to identify regions with similar environmental attributes and then compares the hydrological activities in these regions to facilitate the transfer of knowledge and exchange of techniques. As a case study, the arid zones of Argentina and India are compared. Runoff in both the regions is often generated by the Hortonian infiltration-excess overland flow, and runoff response to precipitation input tends to be rapid. The sediment transport is governed by the transport capacity of runoff rather than the availability of erodible material to be transported. The magnitude of hydrological processes is different in response to the different rainfall regimes. This study identifies some of the strengths and weaknesses in our current knowledge of arid zone hydrology in both countries, and suggests that a more comprehensive treatment of the subject is likely to improve the prediction of the hydrological behaviour of such regions.

Key words : Comparative hydrology, arid zone, precipitation, runoff, sediment transport.

There is a greater diversity in hydrological characteristics within arid regions; the probable differences are the type of runoff producing storms, the relative relief, and climatological differences (Pilgrim *et al.*, 1988). Comparative hydrology studies the character of hydrological processes as influenced by climate and the nature of the earth surface and subsurface (Falkenmark and Chapman, 1989). Comparative studies enhance our understanding of the hydrological processes occurring in various geographical regions, and increase our predictive ability through the transfer of information obtained in areas sharing similar attributes. It is necessary to examine the timing, the intensity and the spatial variations of the generating processes and their resulting hydrological activity to contribute to the extension and development of models.

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Arid Regions of Argentina and India

As a case study we compare the runoff and sediment transport processes in the arid regions of Argentina and India. The Patagonian arid zone (670,000 sq. km) extends the entire length of Argentina, bordering the eastern face of the Andes Mountains to the west, stretching eastward an average distance of 600 km into the plains, and extending southward all the way to the sea (McGinnies, 1968). The Thar desert (286,000 sq. km) lies in the northwest of India (Anonymous, 1989). The climate in Patagonia is cold temperate, very dry and windy; precipitation varies from 150 to 300 mm per annum falling principally during the warm season of October to March. In Thar, small and irregular rainfall of 100 to 420 mm per annum occurs from monsoon circulation in summer during June to September (Bell, 1979).

The Thar is covered with a deep mantle of alluvial and wind borne deposits, and con-

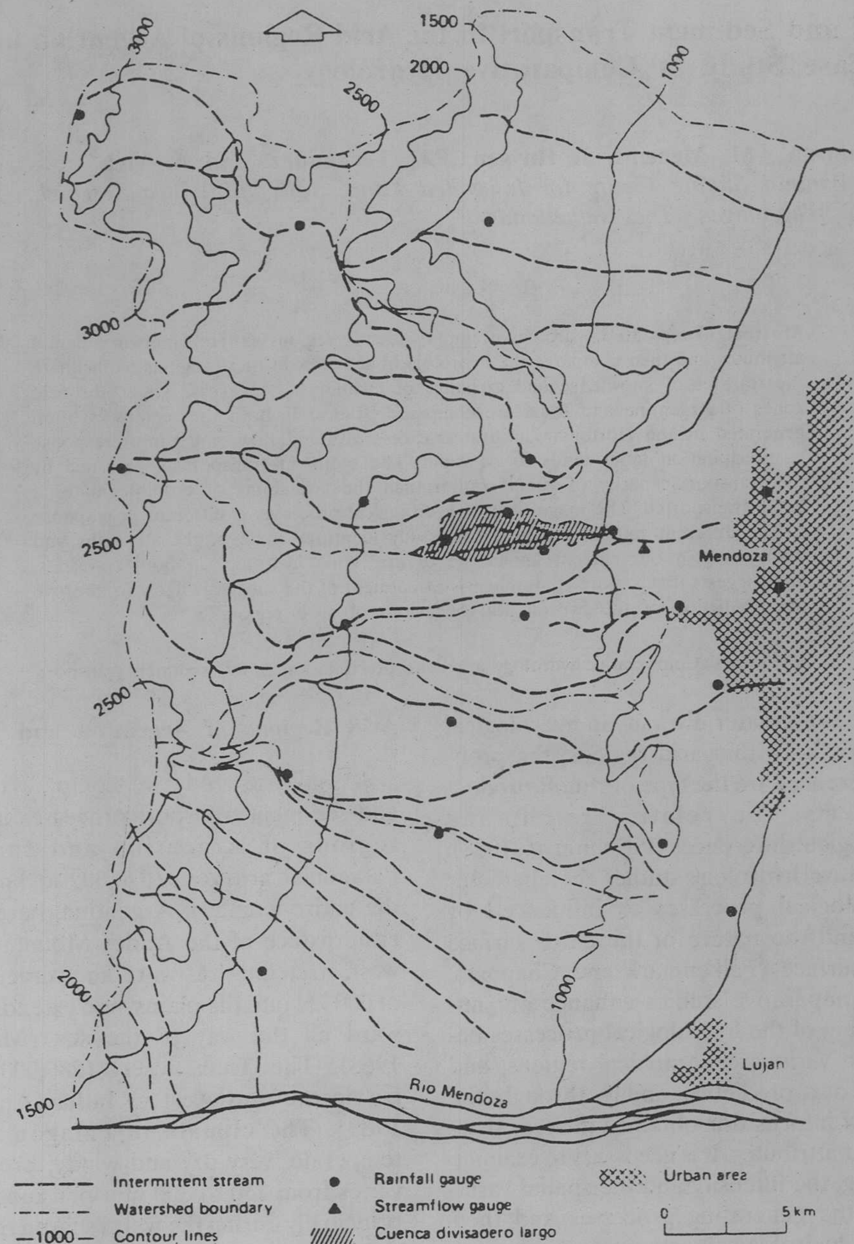

Fig. 1. Hydrometeorological network, Mendoza, Argentina.

sists of level or gently sloping plains, broken up by dunes and low barren hills, whereas, extensive plateaux, more than 900 m high in many places, and dissected by stream valleys, dominate the Patagonia (Goodall and Perry, 1979). The surface soils are mainly gravelly grading from coarse to medium textured towards the plains. The vegetation in

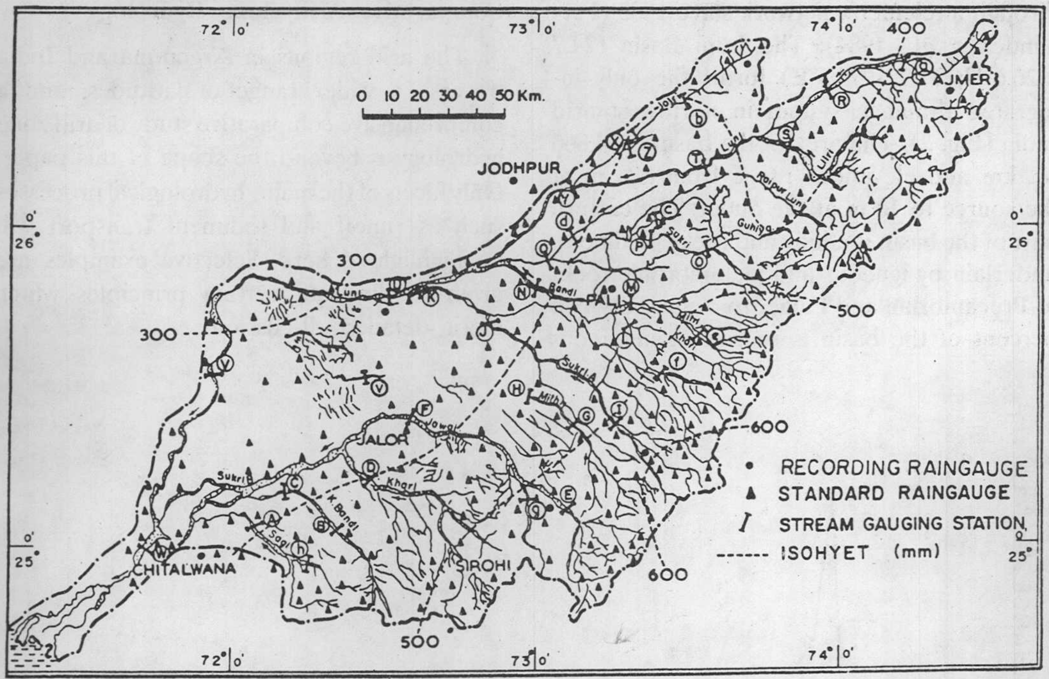

Fig. 2. The Luni Basin, northwest arid India.

Patagonia is dominated by widely spaced clumps of xerophytic grasses and low cushion type shrubs, where as, in Thar the vegetation is strongly influenced by edaphic conditions, with communities varying distinctly among sand, gravel and rock areas; trees and shrubs appear to be more common (Clodsley-Thompson, 1977). This wide assemblage of arid zone characteristics in Argentina and India ensures that there may be contrasting features of runoff and sediment transport processes within each country.

Study Area

In Argentina, the study area (Fig. 1) is located within the piedmont and precordilleran regions of Andes mountain in the west of Mendoza (33.0 - 33.5°S; 68.8 - 69.1°W). The altitude ranges from 950 m in the east to 3000 m. in the west. The basement of the area is formed by Triassic and Tertiary sediments and are covered discordantly by alluvial fan deposits from Quaternary age (Roby *et al.*, 1990). The region is intersected by steeply eroded gullies and rock outcrops. The soils are shallow, undeveloped and consist of medium to fine sand. The vegetation consists of low shrubby pastures ranging from 5 to 45% cover, with less cover on steep slopes. The area lies in a subtropical arid climate and is characterized by convective summer thunderstorms that cause flash floods and high sediment delivery rates. The annual average precipitation is 201 mm, 77% of which is received within the summer months.

The hydrological network consists of 22 automatic raingauges covering about 600 sq. km area of small contiguous basins and 1 runoff gauging station (Amorocho *et al.*, 1983a) measuring runoff and sediment transport from a small basin, Divisadero Largo (5.47 sq. km). The hydrological data have been recorded through a telemetry network since 1983 (Fernandez *et al.*, 1984). The Luni Basin (24.7 - 26.6°N; 71.2 - 74.5°E) forms the only integrated drainage system in northwest arid India (Fig. 2). The area of the basin is 34,866 sq. km and elevations range from 886 m at the source to 10 m at the outlet. The eastern part of the basin is a hilly and rocky piedmont, underlain by igneous and metamorphic rocks of Precambrian and Palaeozoic age. Fifty-two percent of the basin is rugged mountainous terrain with shallow soils and minor amounts of unconsolidated alluvium.

Annual precipitation in the Luni basin ranges from 600 mm in the southeast to 300 mm in the northwest. The rainfall season is relatively short with 80% of the rainfall occurring during July and August. The hydrological network comprises of 250 standard raingauges, 8 recording raingauges and 33 runoff and sediment transport gauging stations located on various tributaries in the basin. The data were collected for a period of nine years during 1979-1987.

Comparative Arid Zone Hydrology

The arid regions in Argentina and India traverse a wider range of latitudes, and a comprehensive comparative study of arid zone hydrology is beyond the scope of this paper. Only facets of the major hydrological processes such as runoff and sediment transport will be highlighted here. Selective examples are given to illustrate certain principles which merit detailed discussions.

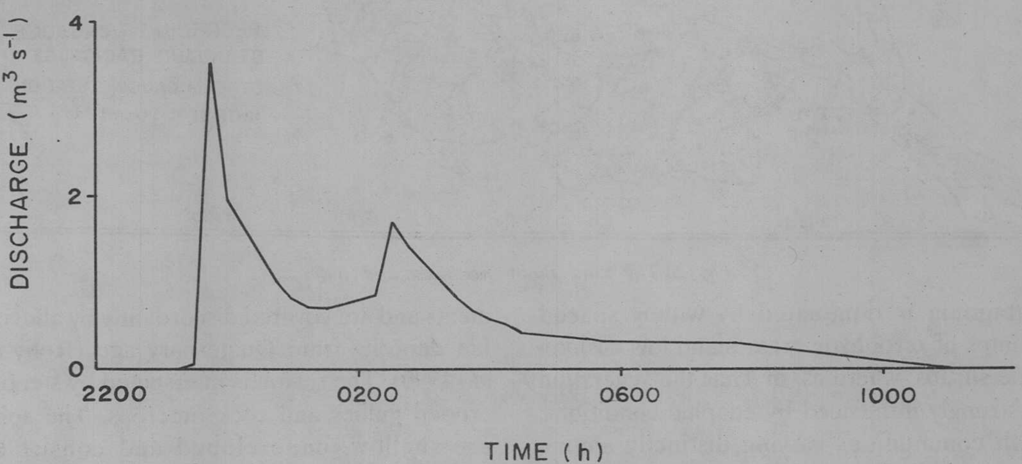

Fig. 3a. Hydrograhs of small arid zone drainage basins - Divisadero Largo Basin, Argentina on 221185.

Precipitation

Strong local advection of moist Atlantic air opposing Pacific air troughs cause convective thunderstorms in the Divisadero Largo Basin. Many of these convective cells have 5 to 10 km length and 2 to 5 km width. Narrow multicell systems exceeding 40 km in length have also been observed frequently (Amorocho *et al.*, 1983b). Frequency distribution of magnitude of rainfall shows that 73% storms were of small magnitude (20 mm each) and only 4% were greater than 40 mm each. The small magnitude storms contributed the

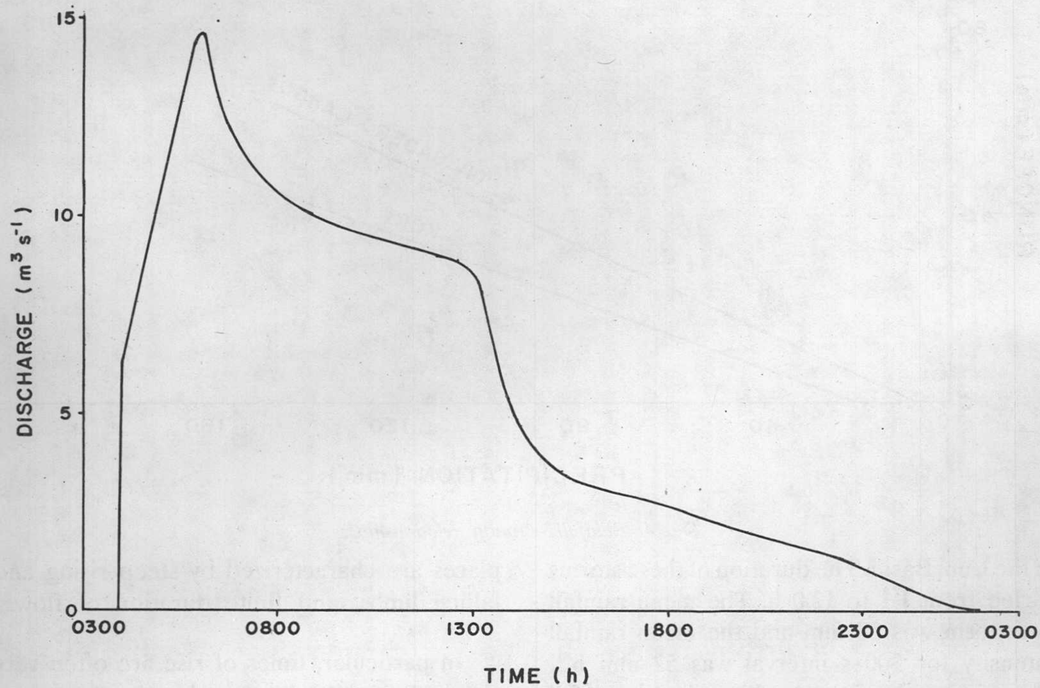

Fig. 3b. Hydrographs of small arid zone drainage basins - Kori Basin of the Luni River Basin, India on 050884.

maximum amount of rainfall (57%) as against only 1% rainfall being contributed by the large magnitude storms (Mulders *et al.*, 1990). The rainfall intensity was less than 60 mm h^{-1} for 75% of the storms contributing 69% of the rainfall. On the other hand, only 1% of the storms were greater than 120 mm h^{-1} intensity and contributed about 1% of the total rainfall. The duration of these storms, varied from 0.67 to 7.17 h. The mean rainfall per storm and the mean rainfall intensity for 300 s interval, were observed to be 17 mm and 49 mm h^{-1}, respectively.

Rainfall in the Luni Basin occurs in spells associated with monsoon depressions (low pressure areas) originating in the Bay of Bengal, passing across the country and curving over the Indian arid zone. These depressions, often stretching over an area of 1000 sq. km, usually bring copious rainfall over the area covered by it. On an average annually two to three depressions, each causing heavy rainfall for five to seven days, are formed during July and August. In all, 54% of the storms were less than 20 mm each and 30% were greater than 40 mm each. The small magnitude storms (< 20 mm) contributed only one-fourth amount of rainfall as against 58% rainfall being contributed by the large magnitude storms (> 40 mm).

Similar to the Argentinian arid zone, the rainfall intensity in the Indian arid zone was less than 60 mm h^{-1} for 73% of the storms contributing 71% of the rainfall. However, as against only 1% storms contributing only about 1% rainfall in the Divisadero Largo Basin, 9% storms having greater than 120 mm h^{-1} intensity contributed 14% of rainfall

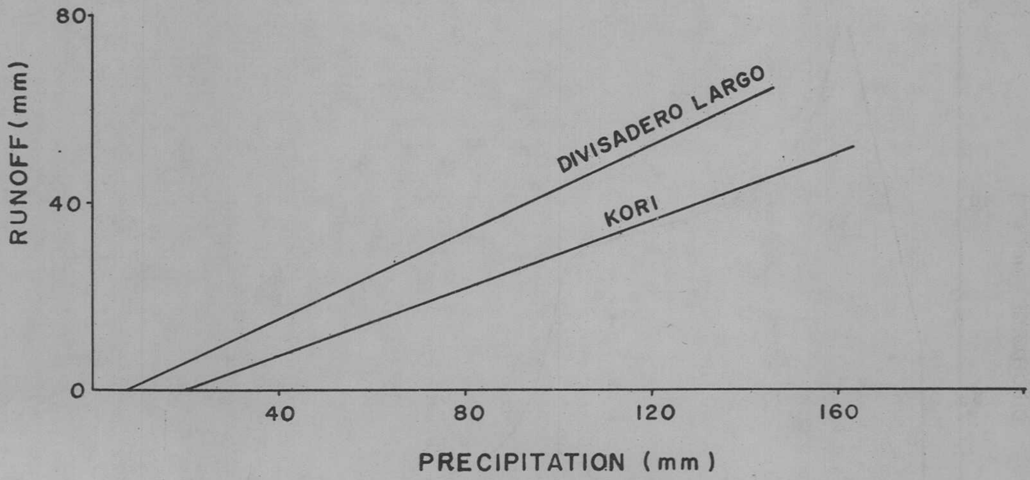

Fig. 4. Rainfall - runoff relationship.

in the Luni Basin. The duration of these storms varied from 1.1 to 12.0 h. The mean rainfall per storm was 28 mm and the mean rainfall intensity for 300 s interval was 52 mm h^{-1}. These data suggest that although the rainfall intensity in both the regions is in the same range yet the longer storm duration in the Luni Basin results in the greater rainfall magnitude than in the Divisadero Largo Basin.

Runoff

In arid regions the mere existence of flow is exceptional and the common thing is its flashiness and its extreme degree of variability. The infrequency of flood flows, therefore, has restricted our attention to discrete events only. An understanding of runoff generating processes is useful in defining the timing, magnitude and hydrograph behaviour of arid zone drainage basins.

Comparing hydrographs in the Divisadero Largo Basin and the Kori Basin (area 10.04 sq. km) in the Luni River Basin indicates that runoff regimes can be classified as pluvial, i.e., rainfall dominant. The 54 hydrographs observed during the study period at both the places are characterized by steep rising and falling limbs, and finite duration of flow.

In particular, times of rise are often very short. Typically, large volumes of surface runoff move into the ephemeral channel network in a short period of time causing flash floods. Peak flow rates also reached almost instantaneously in Walnut Gulch Basin in Arizona (Lane, 1982). The basin response, therefore, is considered to be quick (Ligtenberg *et al.*, 1992; Sharma and Murthy, 1996) as a result of torrential rainfall, steep slopes, sparse vegetation and limited water storage capacity due to the shallow soil mantle. As an example two representative hydrographs recorded in both the basins are shown in Figs. 3 a, b.

In general, the shallow and structureless soils found in the arid regions tend to crust upon wetting (Sharma, 1987) and therefore, generating the Hortonian infiltration-excess overland flow in the study basins. The threshold rainfall - the minimum rainfall to generate runoff, in both the regions varies between 8 and 21 mm (Fig. 4). A remarkable

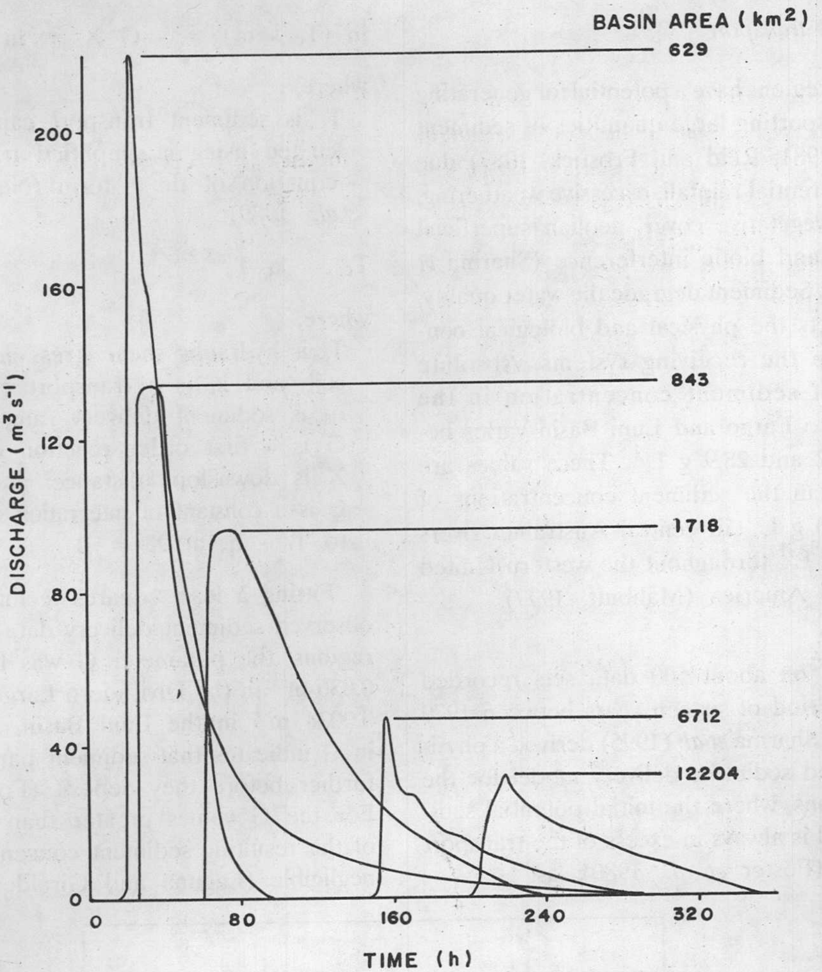

Fig. 5. Downstream changes in the hydrographs in Luni Basin, India. Note the progressive integration of basin area as the river flows downstream.

feature in the Argentinian and Indian arid zones is the high correlation ($r = 0.84$ to 0.96; $P > 0.01$) between runoff volume and peak discharge from a particular basin (Hoefsloot *et al.*, 1992; Sharma, 1992). Such a relationship has also been reported by Murphy *et al.* (1977) in southwest United States of America. Sharma *et al.* (1994) used this relationship in generating flow hydrographs from the estimated runoff volumes.

The integrating effect of basin size is prominant for all arid regions. Fig. 5 presents hydrographs for the Luni River at five locations showing a downstream decline in both the peak flow and runoff volume due to transmission losses into alluvium in the beds and banks of streams. Large transmission losses have also been reported in southwest United States of America (Renard and Keppel, 1966), southern Spain (Butcher and Thornes, 1978), Australia (Stewart and Boughton, 1983), Saudi Arabia (Walters, 1990) and northwest India (Sharma and Murthy, 1994). It is likely that the transmission losses occur in all arid zone streams (Pilgrim *et al.*, 1988).

Sediment transport

Arid regions have a potential for generating and transporting large quantities of sediment (Jones, 1981; Reid and Frostick, 1987) due to the torrential rainfall, excessive weathering, sparse vegetative cover, aeolian superficial deposits and biotic interference (Sharma *et al.*, 1992). Sediment degrade the water quality, and affects the physical and biological conditions in the receiving systems. Absolute values of sediment concentration in the Divisadero Largo and Luni Basin varies between 0.2 and 28.9 g L^{-1}. These values are higher than the sediment concentrations of 1.0 - 12.0 g L^{-1} in central Australian rivers and 5.0 g L^{-1} throughout the western United States of America (Mabbutt, 1977).

Based on about 500 data sets recorded over a period of sixteen years between 1979 and 1994, Sharma *et al.* (1995) derived a physically based sediment delivery model for the arid regions, where the initial potential sediment load is always in excess of the transport capacity (Foster *et al.*, 1980), as:

$$\ln (T_c - q_s) = - G X + \ln C \quad ...(1)$$

where,

T_c is sediment transport capacity calcuated using a simplified transport equation of the form (Nearing *et al.*, 1989):

$$T_c = k_t T_s^{3/2} \quad ...(2)$$

where,

T_s is hydraulic shear stress acting on the soil, and k_t is a transport coefficient,
q_s is sediment delivery rate,
G is a first order reaction coefficient,
X is downslope distance, and
C is a constant of integration and is equal to $T_c - q_s$ at $X = 0$.

Fitting a least squares technique to the observed sediment delivery data in both the regions, the parameter G was found to be 0.036 m^{-1} in the Divisadero Largo Basin and 0.0034 m^{-1} in the Luni Basin. A decrease in G indicates that sediment particles travel further before they deposit (Foster, 1982). For the G values greater than unity most of the resulting sediment concentrations are negligible (Laguna and Giraldez, 1993).

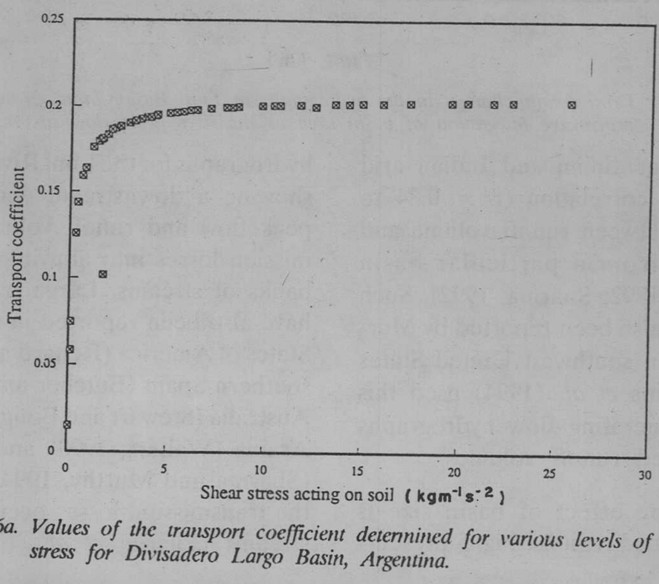

Fig. 6a. Values of the transport coefficient determined for various levels of shear stress for Divisadero Largo Basin, Argentina.

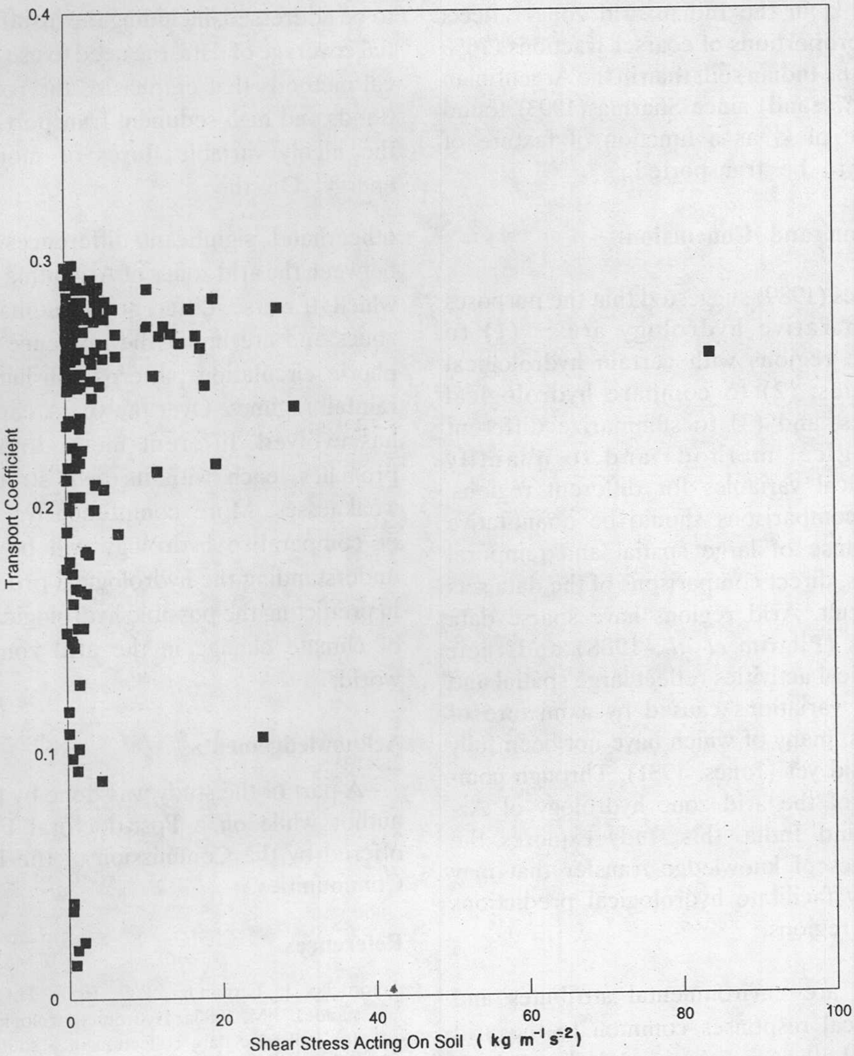

Fig. 6b. Values of the transport coefficient determined for various levels of shear stress for Luni River Basin, India.

Fig. 6 a and b depicts k_t as a function of T_s for the study basins. At higher values of T_s, k_t becomes relatively constant. However, k_t rapidly approaches zero when T_s is small. Therefore, the value of T_s must be carefully selected to be representative of the entire basin, as well as the areas of greatest potential for erosion or deposition. Further, Finkner *et al.* (1989) reported that the threshold shear stress below which detachment by flow did not occur was generally greater than 1 kg s^{-2} m^{-1}. For T_s = 1 kg s^{-2} m^{-1}, k_t could be identified for the Divisadero Largo Basin as 0.18 and for the Luni Basin as 0.26 (Fig. 6 a, b). These values are six and nine times higher than 0.029 as reported for the silt loam soils in the United States of America (Finkner *et al.*, 1989). The nine times higher value of k_t in the Indian arid zone reflects greater proportions of coarser fractions (76% sand) in the Indian soils than in the Argentinian soils (42% sand) since Sharma (1993) found the value of k_t as a function of texture of the soil to be transported.

Discussion and Conclusion

Kovacs (1989) suggested that the purposes of comparative hydrology are : (1) to delineate regions with certain hydrological similarities, (2) to compare hydrological processes, and (3) to summarize different hydrological methods and to quantify hydrological variables for different regions. All the comparisons should be quantitative but, because of large spatial and temporal variations, direct comparisons of the data sets are difficult. Arid regions have sparse data networks (Pilgrim *et al.*, 1988) and their hydrological activities reflect large spatial and temporal variations caused by a mixture of processes, many of which have not been fully understood yet (Jones, 1981). Through comparisons of the arid zone hydrology of Argentina and India, this study explores the possibilities of knowledge transfer that may eventually facilitate hydrological predictions for arid regions.

There are environmental attributes and hydrological responses common to the arid zones of both Argentina and India. Runoff producing rainfall events are infrequent and of short duration, so that a long period of observation and a high sampling rate during storms are required. As the vegetation is scarce, and the rainfall and runoff periods are short, evapotranspiration is of little importance for the modelling of runoff and sediment transport. Fast hydrological responses and similar hydrological processes integrated over small areas occur in both the regions. Also, there are common hydrological problems to be addressed, including the insufficient spatial coverage of data, the need to use hydrological methods that emphasize the role of flash floods and high sediment transport rates, and the highly variable fluxes of moisture and energy. On the other hand, significant differences also exist between the arid zones of Argentina and India, which traverse different latitudinal climatic zones and are under the influence of atmospheric circulation patterns causing different rainfall regimes. Over the years, each country has evolved different methodological approaches, each with its own strengths and weaknesses. More comprehensive treatment of comparative hydrology will be useful in understanding the hydrological processes and in predicting the possible hydrological impacts of climate change in the arid zones of the world.

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