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Climate change and changes in sediment transport capacity in the Colorado Plateau, USA

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Abstract Information is presented on changes in the sediment transport capacity of streams of the Colorado Plateau region of the United States. The changes in transport capacity may be due to changes in climate. Changes in the ability of three rivers in the Colorado Plateau to transport sediment were investigated (Paria River at Lees Ferry, Arizona; Sevier River at Hatch, Utah; and Little Colorado at Woodruff, Arizona) using an index to sediment transport potential (or capacity) of the rivers. The index is called a Sediment Transport Capacity Index (STCI). The parameters in the index are calibrated to measured sediment concentrations. Other investigators have postulated that there have been three climate regimes in the Colorado Plateau during the 20th century: 1905–1941, 1942–1977 and 1978–1998. Time series analyses of the STCI showed reasonably clearly that there was a change in the climate about 1941 and a high probability of a change about 1923–1929. The STCI time series for the Sevier River had the expected pattern because the STCI increased in the years following 1997 nearly to the pre-1942 values from lower 1942–1977 values. The Little Colorado River showed a similar pattern, but not nearly to the magnitude suggested by the change in precipitation. The STCI for the Paria River essentially did not change. Changes in sediment transport also are investigated in the lower San Juan River where alterations in the sediment balance of the river may be due to variations in the character of summer precipitation.

Key words climate change; Colorado Plateau, USA; sediment transport

INTRODUCTION

The Colorado Plateau is a relatively dry physiographic province in the western United States (Fig. 1). The plateau is characterized by a semiarid to arid landscape of sedimentary rocks with volcanic intrusions (Baars, 1972). Large rivers cross from the southern Rocky Mountains into the plateau (Green, Upper Colorado and San Juan rivers). These three join in the plateau to form the lower Colorado River.

Hereford *et al.* (2002) have investigated variations in the patterns of precipitation in the Colorado Plateau during the 20th century. They found that three multidecadal precipitation regimes are apparent in the precipitation history: (a) a wet period from 1905 to 1941 with an annual precipitation on the plateau of about 370 mm; (b) a dry period from 1941 to 1977 (320 mm); and (c) another wet period 1978–1998 (380 mm). Analysis of the precipitation in the mountain and plateau region of southwestern Wyoming and western Colorado exhibited a similar pattern except the last year of the wet period was 1952, and the period after 1987 tended to be either dry, or near the average for the period-of-record.

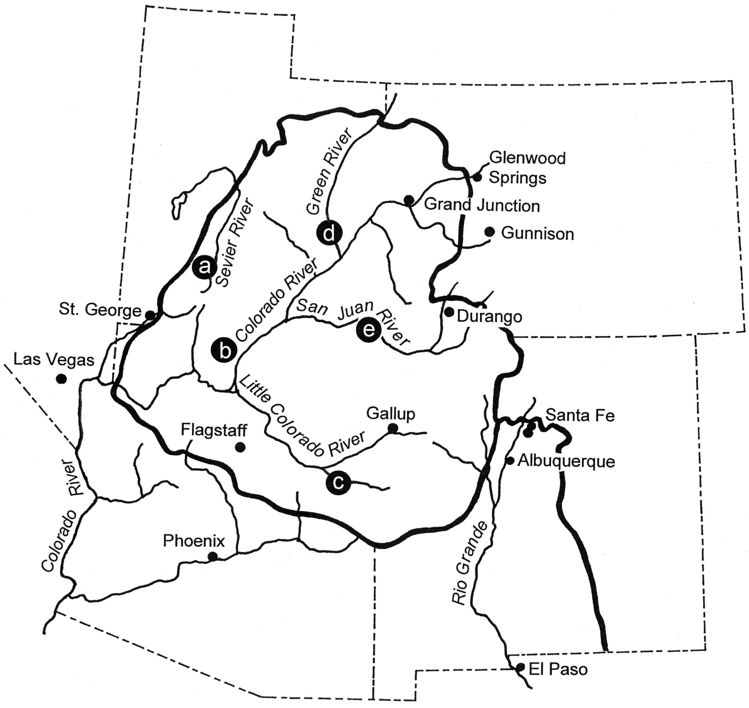

Fig. 1 Map of the Colorado Plateau showing the major rivers and the location of the most useful gauging stations. The locations considered in this paper are: (a) Sevier River near Hatch, Utah; (b) Paria River at Lees Ferry, Arizona; (c) Little Colorado River at Woodruff, Arizona; (d) Green River at Green River, Utah; and (e) San Juan River at Shiprock, Utah.

Graf *et al.* (1991) showed that a decrease in the magnitude and frequency of floods has resulted in considerable storage of sediment in the Paria River by formation of a flood plain. Prior to 1940, a significant flood plain did not exist. Beginning about 1940, a flood plain was formed by the river as a result of sediment deposition within the pre-1940 channel. Prior to 1940, the sediment was flushed through the channel without deposition. After 1980, deposition ceased because floods have not been above bank-full for the new channel. Graf *et al.* also suggest that changes in the characteristics of summer and winter storms (mostly thunderstorms) may be important factors in affecting changes in sediment movement.

Changes in the quantity of precipitation may not be the only impact of climate change, there may also be changes in the intensity and seasonality of precipitation that cause changes in annual streamflows, or the ability of the river to transport sediment. For instance, the same precipitation amounts may occur as a low- or high-intensity storm. A lower intensity could result in streamflows with less potential to move sediment and less sediment delivered to a river, than a high intensity storm. Also, a series of small runoff events are expected to carry less sediment than one large event with the same volume of water.

The objective of this paper is to investigate the changes in the sediment transport capacity of three streams, and changes in the delivery of sediment to one stream. A Sediment Transport Capacity Index (STCI) is used to investigate variations in the ability of a stream to move sediment, and a sediment budget is used to investigate changes in the sediment yield to a river.

THE SEDIMENT TRANSPORT CAPACITY INDEX

In the absence of actual suspended sediment concentration measurements, it is possible to estimate the load (flux) of suspended sediment by using a power relation (regression) between load and discharge (Vanoni, 1975). One of the more complicated relations is:

$$SL = a(Q - Q_{crt})^{(b-1)} \times Q$$

where Q is the discharge; Q_{crt} is a critical discharge below which the sediment load (SL) is either zero or related to discharge by some other relation; and a and b are empirical coefficients.

The transformation of the sediment load equation to an index of sediment transport capacity is explained in Milhous (1999a). The result is a sediment transport capacity index (STCI) calculated using the following equation:

$$STCI = \sum_{i=1,n} Q(\mathrm{i}) \left[(Q(\mathrm{i}) - Q_{crt})^{b-1} \right] / Q_{ref}{}^{b}$$

where the terms are as above except Q_{crt} is a critical discharge associated with the size of the sediment particles in the substrate. The summation is over n measurement intervals (usually days). Summing over a year of daily discharges, n is either 365 or 366.

The best practice is to determine the value of the b coefficient from a relation determined from either measured sediment load or concentration, and discharge. If measured sediment concentration or load data are not available for known discharges, the value of b often is in the region of 2.0. The use of 2.0 is based on a review of a number of the discharge versus sediment load relations. The range in the b coefficient is considerable depending on the characteristics of the sediment load used in its determination. For relations based on total suspended sediment load, the value of b will be different from the b determined using the suspended sand load.

The assumptions are: (a) a change in the index can help an analyst better understand the possibility of change in the sediment regime; and (b) the sediment transport capacity index is a better predictor of sediment yield than either annual discharge or peak annual discharge.

THE SEDIMENT TRANSPORT CAPACITY INDEX OF THREE RIVERS

A summary of the time series of the annual STCI for three rivers is presented in Table 1. If data are available, the average sediment transport capacity and annual discharges for each of the three rivers (Sevier River in Utah, Paria River in Arizona and Little Colorado River in Arizona), and for each of the periods used by Hereford *et al.* (2002), are calculated and presented in the following discussions. Additional details of the analysis of the three rivers are presented in Milhous (2003), along with an analysis of the Rio Puerco (New Mexico). The reference discharge is selected by the analyst in order to scale the STCI. The reference discharge used in the calculation of the STCI was 2.83 m^3 s^{-1} for all three rivers.

Table 1 The average Sediment Transport Capacity Index (STCI) and average annual discharge of the Sevier River based on the streamflow record available for the three wet and dry periods from Hereford *et al.* (2002). For the Sevier River the STCI values are also shown for sub-divisions of the pre-1941 period based on analysis of the STCI in the Green River.

	Annual: Period	STCI	Discharge ($m^3 s^{-1}$)
Sevier River at Hatch, Utah drainage area: 870 km^2	1915–1941	971	3.96
	1942–1977	555	2.80
	1978–1998	904	3.60
	1915–1923	1745	5.78
	1924–1941	584	3.06
Paria River at Lees Ferry, Arizona drainage area: 3600 km^2	1924–1941	307	1.03
	1942–1977	117	0.72
	1977–1998	115	0.80
Little Colorado River at Woodruff, Arizona drainage area: 20 590 km^2	1930–1941	3550	2.15
	1942–1977	1839	1.16
	1978–1998	2148	1.38

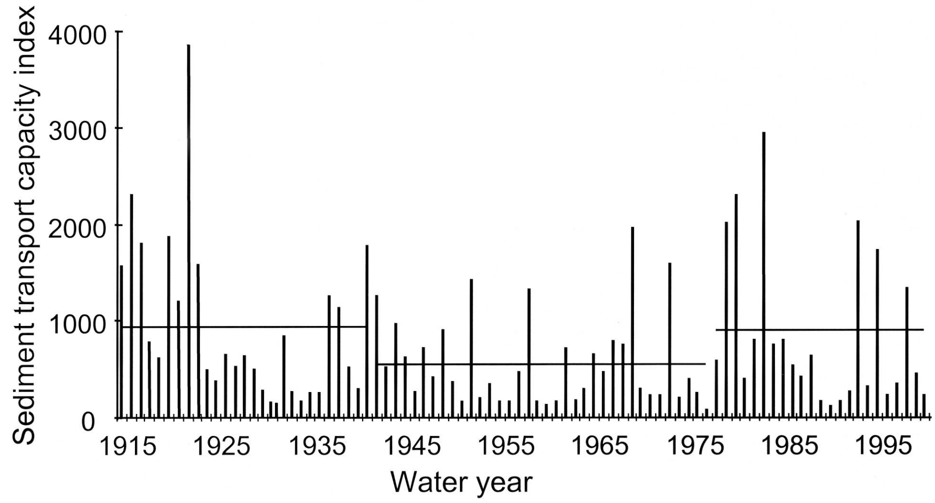

Fig. 2 The annual sediment transport capacity of the Sevier River at Hatch between 1915 and 2000. The equation used was STCI = (*Qd*/2.83)**1.67 where *Qd* is the daily discharge in $m^3 s^{-1}$. The three horizontal solid lines are the average STCI for 1915–1941, 1942–1977, and 1978–2000.

The annual STCI time series for the Sevier River at Hatch, Utah is presented in Fig. 2. The power coefficient (1.67) was determined using the total load, and a critical discharge of zero. Streamflow data for 1929–1939 were not available for the gauge at Hatch. The STCI for this period was estimated using data from the next downstream gauge. The average STCI and annual discharge for the three periods in Hereford *et al.* (2002) are presented in Table 1. The 1915 period also has been subdivided based on analysis of the STCI in the Green River (Milhous, 1999b; see Discussion). Data are missing for 1905–1914.

For the Paria River calculations, the power coefficient (2.3) used in the calculations was developed from the relation between sand load and discharge. The critical discharge was zero. Data are missing for 1905–1924. The power coefficient used to calculate the STCI for the Little Colorado River was 2.0 and the critical discharge was zero. Data are missing for 1905, 1907–1929 and 1934–1935.

SEDIMENT BALANCE FOR THE SAN JUAN RIVER

A second investigation herein is to determine if the changes in sediment yield to the lower San Juan River also agree with the three precipitation regimes. The cumulative change in sediment load between two gauges on the San Juan River is presented in Fig. 3 for two periods. In the Colorado Plateau section (segment) of the San Juan watershed, most (60% prior to 1973) of the suspended sediment transport occurs during summer and early autumn (16 July–15 November). The upper San Juan watershed is located in the San Juan Mountains; as a result, spring runoff is large compared to streamflows in the other months. The two gauging stations are at Shiprock, New Mexico and at Medicine Hat near Bluff, Utah. The drainage area of the San Juan River at Shiprock is 32 910 km^2 and the average annual discharge, 59.9 m^3 s^{-1}.

There is a change in the slope of the lines on Fig. 3 for both periods in 1961 which is probably caused by the completion of Navaho Dam upstream of Shiprock. Storage in the reservoir reduced the sediment transport capacity but because the actual load was below the capacity to move sediment the load per STCI unit increased. After 1972, the change in suspended sediment load in the summer and autumn (–0.07 Mt year^{-1}) was

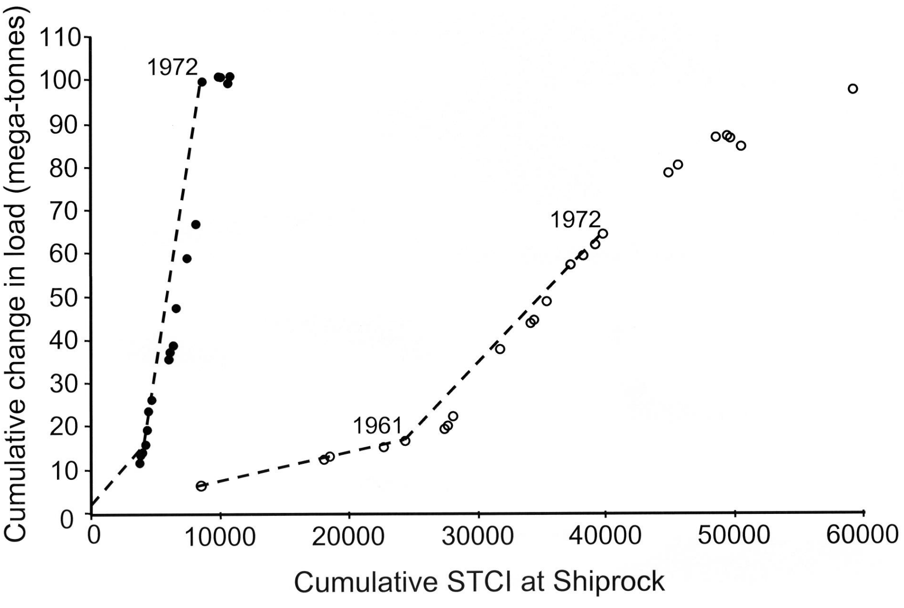

Fig. 3 The cumulative Sediment Transport Capacity Index (STCI) *vs* the cumulative measured change in suspended load between the gauging station at Shiprock, New Mexico and the station near Bluff, on the San Juan River. The power coefficient was 2.0, critical discharge zero, and the reference discharge 28.3 m^3 s^{-1}. The lines break at 1961 and end with 1972.

significantly less than the 1962–1972 period (7.2 Mt year^{-1}). The STCI at Shiprock averaged 393 for 1962–1972 and 377 for 1973–1979. There is a clear change in the relation after 1972. A similar change did not occur in the winter and spring. There may have been a change in 1977 in the winter-spring relation, but this is not clear because a major winter drought occurred in 1977 and there are only two years of record following 1977.

Analysis of the relation between change in annual discharge and change in suspended sediment load indicated there was a difference between the 1952–1969 and 1970–1980 periods. Review of the hydrographs suggested this could be a change in the sediment delivered to the San Juan River by tributary streams in the summer and autumn.

DISCUSSION

The first objective of the paper is to determine if the climate periods identified by sediment transport potential coincide with the periods based on precipitation identified by Hereford *et al.* (2002). There was a change in the sediment transport capacity for the Sevier, Paria and Little Colorado rivers about 1941 (Table 2). This is in agreement with Hereford *et al.* An analysis of Green River streamflows (Milhous, 1999b) used three periods to calculate average values of the annual STCI. The first two are subdivisions of the period prior to storage in Flaming Gorge Reservoir and the third is the period following storage. The Green River analysis showed a change in sediment yield occurred in the Green River basin about 1944, similar to the beginning of flood plain storage in the Paria River (Graf *et al.*, 1991) and lagging by three years the change in precipitation postulated by Hereford *et al.* (2002).

The Green River analysis also showed a change in sediment transport capacity in the 1923–1929 period where the STCI, on average, was much less in the years following 1923–1929 than for the 23 previous years. This may indicate a climate change in the Rocky Mountains to the north and east of the Colorado Plateau because the Green River receives most of its water from this area. The STCI time series for the Sevier River shows a similar change (Table 1). The period-of-records for the other two rivers (Paria and Little Colorado) are not long enough to determine if there was a similar change in these rivers. The conclusion for the Sevier River, and the previous Green River analysis, is that a change may have occurred in the sediment transport potential of streams in the Colorado Plateau in 1923–1929 that is not reflected in the analysis of annual precipitation.

Table 2 The average Sediment Transport Capacity Index in each of the three rivers based on the streamflow record available for the three wet and dry periods from Hereford *et al.* (2002).

Period	Sediment Transport Capacity Index:			Ratio to 1977–1998:		
	Paria	Sevier	Little Colorado	Paria	Sevier	Little Colorado
pre-1942	307	971	3550	2.67	1.07	1.65
1942–1977	117	555	1839	1.02	0.61	0.86
1977–1998	115	904	2148	1.00	1.00	1.00

* The pre-1942 period of record used in the analysis was 1924–1941 for the Paria River, 1915–1941 for the Sevier River, and 1930–1941 for the Little Colorado River.

The evidence for a change in sediment transport capacity in 1977, similar to the change in precipitation, is not clear. There seem to be changes between the dry 1942–1977 and the wet 1978–1998 periods, but the changes are not consistent among each of the three basins. The Sevier River had the expected pattern because the STCI increased to just about the pre-1942 values. In contrast, the STCI for the Little Colorado River did increase, but not nearly as much as was expected based on the change in precipitation. The STCI for the Paria River essentially did not change. The observed changes in both annual discharge and STCI for the Little Colorado and Paria rivers is significantly different from what is expected based on the changes for the Sevier River (a return to just about pre-1942 levels). A possible cause could be the increase in tamarisk (*Tamarix ramosissims*) that occurred along most of the streams of the Colorado Plateau over the period-of-record for all the gauges. An increase did occur along the Little Colorado and Paria rivers above the gauges but did not occur to the same degree above the gauge on the Sevier River. This change is worth investigating. Other possible causes range from changes in upland vegetation, flood plain vegetation (other than tamarisk), and the pattern of rainfall.

The second objective is to determine if a change has occurred in the characteristics of summer and autumn storms and if any changes may agree with the changes in overall Colorado Plateau precipitation. The analysis for the lower San Juan River suggests an important change is the reduction of sediment yield of summer–autumn storms in the 1972–1980 period. There are two possible reasons for this. One is that there has been a change in the summer and autumn storm intensity and the second is that an invasive plant (Tamarisk) has caused the river to store sediment in the reach. The data for 16 November–15 July suggest sediment storage is probably not the case because there was not a similar reduction in the winter and spring changes in sediment yield between the gauges. The most probable cause is change in the delivery of sediment to the reach in summer and autumn.

CONCLUSIONS

The first conclusion is that there were changes in the ability of the rivers to transport sediment in 1941–1944 similar to the changes identified from precipitation but that there was also a change in 1923–1929 that was not shown to occur in the precipitation analysis.

The second conclusion is that there was a change in the 1970s decade but the characteristics of the change are not as simple as the change shown for 1941. The 1970s change included a possibility there were changes in the characteristics of the summer and autumn storms after 1972 because there was not a major change in STCI, but there was a major change in sediment yield.

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