Case Study: Modeling the Lateral Mobility of the Rio Grande below Cochiti Dam, New Mexico

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Abstract: The Cochiti reach of the Rio Grande served as a case study to test the hypothesis that the lateral mobility of an alluvial river decreases as the river approaches equilibrium. The lateral mobility of the river was measured using a geographic information system from digitized aerial photographs of the nonvegetated active channel between 1918 and 2001. Reach-averaged lateral mobility was quantified in terms of width change, lateral migration, and total lateral movement. By 2001, the width of the Cochiti Reach was close to the expected equilibrium width indicating that the river had adjusted to the incoming water and sediment load. An exponential equation based on deviation from equilibrium width described 95–96% of the variance in channel width, 78–90% of variance in migration rates, and 92% of the variance in total lateral movement between 1918 and 1992. For validation of the model, the 2001 width and migration rates were predicted with errors as low as 19 and 8%, respectively. The exponential width model was also applied to four other rivers that exhibited narrowing trends following dam construction and explained 82–89% of the variance in width change on those rivers.

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Introduction

The movement of alluvial rivers across their floodplains is of interest to engineers and scientists concerned with river management. Conflicting goals on many rivers in the southwestern United States have resulted in a need to quantify and understand the changes in both historic and current rates of lateral movement. Understanding how quickly a channel is adjusting would be useful in both engineering planning and ecological assessment of both regulated and nonregulated river systems.

Several studies have documented the complexity and variation in the causes and rates of lateral movement in alluvial rivers. Depending on the input conditions and planform geometry, lateral movement can take different forms including meander migration (Hooke l980; Bradley and Smith 1984; Nanson and Hickin 1986; Thorne 1991; Lawler 1993; Richardson 2002), width changes (Surian 1999; Winterbottom 2000; Buhman et al. 2002; Chitale 2003), and wandering, avulsion, and cutoffs in the case of braided rivers (Coleman 1969; Klaassen and Masselink 1992; Warburton et al. 1993; Xu 1996; Cao et al. 2002). The mechanism of lateral movement varies with planform resulting in varying rates of lateral movement (Brice 1982; Friedman et al. 1998; Wu et al. 2005) over different time scales (Church 1995). Anthropogenic interventions on river systems, such as dam construction, alter the incoming water and sediment regime and result in varying impacts on the lateral response of alluvial rivers (Williams and Wolman 1984; Johnson 1992; Xu 1996, 1997; Shields et al. 2000; Simon et al. 2002). Numerical modeling has also been applied successfully to describe lateral migration (Kassem and Chaudhry 2002 Olsen 2003; Wilson et al. 2003; Duan and Julien 2005). Future developments in lateral migration modeling depend largely on the availability of data sets with high quality data on riverbank properties like the data set of Darby (2005).

Application of the concept of an equilibrium state to the study of river channel form can help better understand and quantify how and why rivers move and change. The concept that a river will adjust its cross-sectional form, bed configuration, planform geometry, and bed slope to accommodate the water and sediment entering the channel can be applied to understand the adjustments of the Rio Grande to changes in water and sediment inputs. Lagasse (1994) suggested that by 1980 portions of the Rio Grande downstream from Cochiti Dam may have completed adjustment to the construction of the dam, suggesting a more stable condition. Crawford et al. (1993) also proposed that the Rio Grande has undergone cycles of equilibrium and disequilibrium as it adjusted to varying water and sediment inputs from both natural and anthropogenic causes.

Lateral movements of the Rio Grande in north central New Mexico (Fig. 1) resulting from changes in climate, land use, and water and sediment discharge have been documented over the last 80 years by several federal agencies. This documentation provides an excellent opportunity to explore the relationships between changes in channel processes and lateral mobility. The abundance of information collected on the Cochiti reach includes topographic and bathymetric surveys, aerial photos, sediment, and discharge measurements that trace the changing level of stability of the river since 1918.

The purpose of this paper is to examine the lateral mobility of the Cochiti reach of the Rio Grande from the perspective of de-

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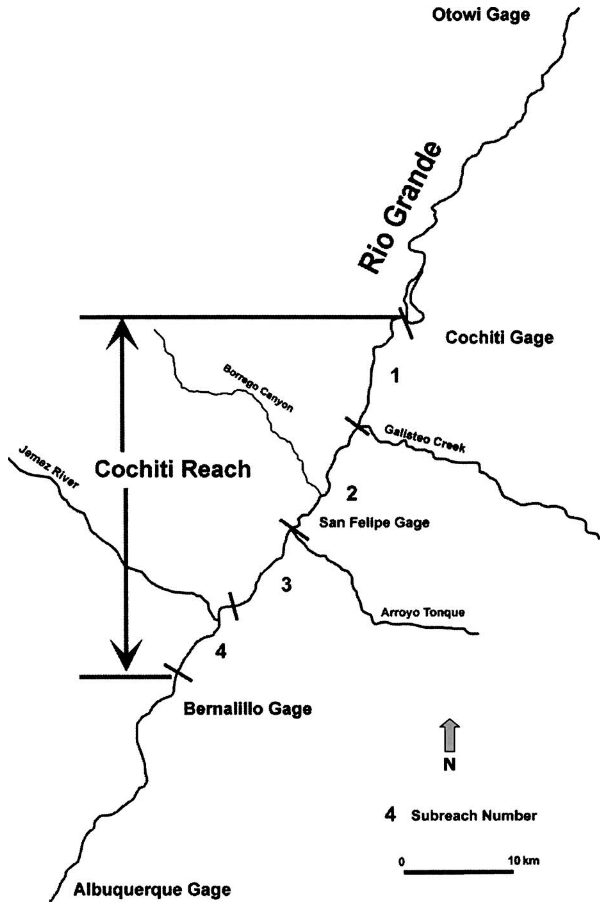


Fig. 1. Cochiti Reach, Rio Grande, N.M.

viation from an equilibrium condition predicted by downstream hydraulic geometry equations. The hypothesis to be examined is that the rate of lateral movement decreases as a river approaches an equilibrium configuration. The hypothesis is tested through examination of the historic data and changes in morphology of the Rio Grande (1918–2001), application of hydraulic geometry equations, and development of lateral mobility models in which the rate of lateral movement is expressed as a function of the deviation from an equilibrium width. The models are validated with Rio Grande data and are also applied to four other rivers.

Rio Grande Study Reach and Database

The Cochiti reach of the Rio Grande extends 45 km downstream from Cochiti Dam to the Highway 44 Bridge at Bernalillo (Fig. 1). Located 65 km upstream of the City of Albuquerque, Cochiti Dam began impounding water in November 1973 and detains runoff from a drainage area of about $37,800\ km^2$ (Bullard and Lane 1993). Cochiti Dam provides the largest flood control storage reservoir volume ($6.17 \times 10^8\ m^3$ or 500,000 acre-ft) on the main stem of the Rio Grande. The dam traps virtually the entire sediment load from upstream as well as controlling the water discharge downstream (Dewey et al. 1979, Richard 2001). Several tributaries, most of which are ephemeral arroyos, enter the Rio Grande in the Cochiti reach and contribute both water and sediment to the main stem. The two major tributaries, Galisteo Creek and the Jemez River, were dammed in 1970 and 1953, respectively, (U.S. Army Corps of Engineers 1978).

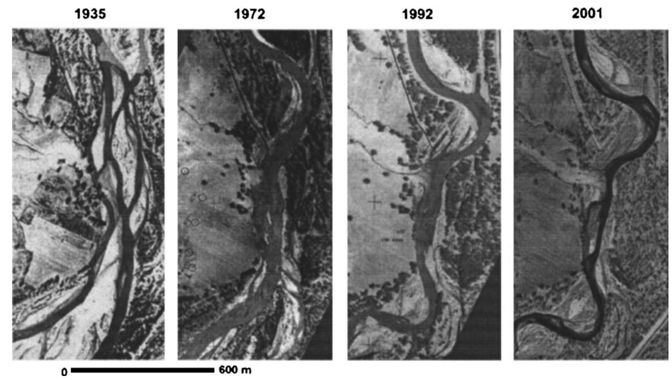


Fig. 2. Aerial photos of Rio Grande 18–20 km downstream from Cochiti Dam at confluence with Borrego Canyon

Collection of hydrologic, sediment and morphologic data on the Rio Grande began in 1895 and continues to the present, creating a comprehensive data set. In 1895, the Otowi gauging station (Fig. 1) was established by the U.S. Geological Survey (USGS) and provides the longest record of discharge and suspended sediment data used in this study. The San Felipe gage was established in 1925, Cochiti gage in 1926, Bernalillo gage in 1941, Albuquerque gage in 1941, and Jemez gage in 1936. The combination of severe flooding and sedimentation along with irrigation needs in the middle Rio Grande valley since the early 1900s prompted federal agencies including the U.S. Army Corps of Engineers (the Corps), the U.S. Bureau of Reclamation (Reclamation), the USGS, and the Soil Conservation Service (SCS), now the Natural Resources Conservation Service (NRCS) to begin more intensive surveys of the river. Cross section surveys were collected beginning in 1918, bed material sampling began in the 1930s, suspended sediment measurements were initiated in the 1940s, and aerial photography (e.g., Fig. 2) or topographic surveys are available from 1918 to 2001 (Richard 2001). The net result of these data collection efforts is a comprehensive documentation of the Cochiti reach for more than 80 years (Leon et al. 1999). A thorough discussion of the cross-section survey, bed

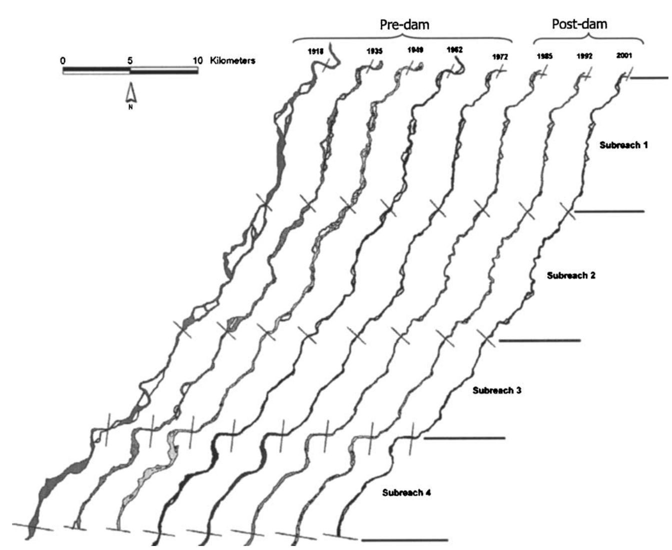


Fig. 3. Planform maps of active channel of Cochiti reach for 1918–2001

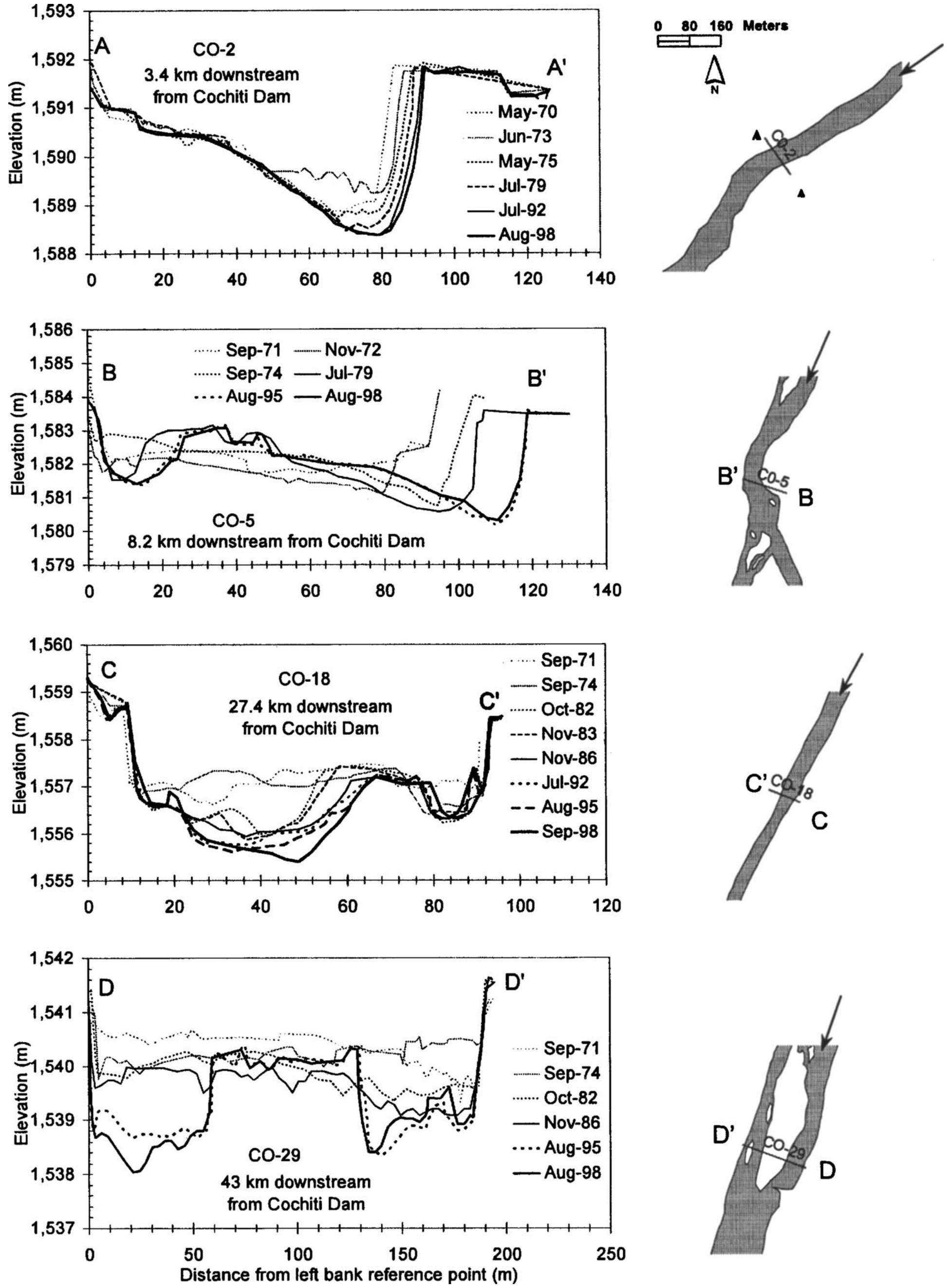


Fig. 4. Cross-section geometry (1970–1998) and planform (2001) of active channel. Arrows indicate flow direction.

elevation, and bed material data used in this study is presented in Richard (2001).

In order to facilitate the analysis of the Cochiti reach, it was divided into four subreaches based on channel characteristics and the existence of natural or anthropogenic controls (Fig. 1). Subreach 1 begins just downstream of Cochiti Dam and extends 12 km downstream to the confluence with Galisteo Creek and was the steepest of the four subreaches. Rittenhouse (1944) noted that Galisteo Creek contributed notably coarser sediment than the main stem of the Rio Grande. Subreach 2 extends 11 km from the Galisteo Creek confluence to the mouth of the Arroyo Tonque and demonstrated the highest sinuosity of the four subreaches. Nordin and Culbertson (1961) identified a break in bed slope and noted a transition from the coarser bed of White Rock Canyon to more of a sand-bed channel in the vicinity of the mouth of the Arroyo Tonque. Prior to the construction of Cochiti Dam, the bed material upstream of Arroyo Tonque varied in size from sand to gravel, whereas the bed material downstream was primarily sand with little variation (Nordin and Culbertson 1961). Subreach 3 extends 9.4 km downstream from the Arroyo Tonque to the Angostura Diversion Dam, which was completed by 1935. Extending from Angostura Diversion Dam 9.7 km downstream to the Highway 44 Bridge in Bernalillo, Subreach 4 was the widest of the four subreaches.

Reclamation digitized the location of the active channel (Fig. 3) from topographic surveys and aerial photos for the following years: 1918, 1935, 1949, 1962, 1972, 1985, 1992, and 2001. The active channel was defined as the area encompassing the submerged channel as well as adjacent or mid-channel unvegetated or sparsely vegetated areas (U.S. Bureau of Reclamation 1998).

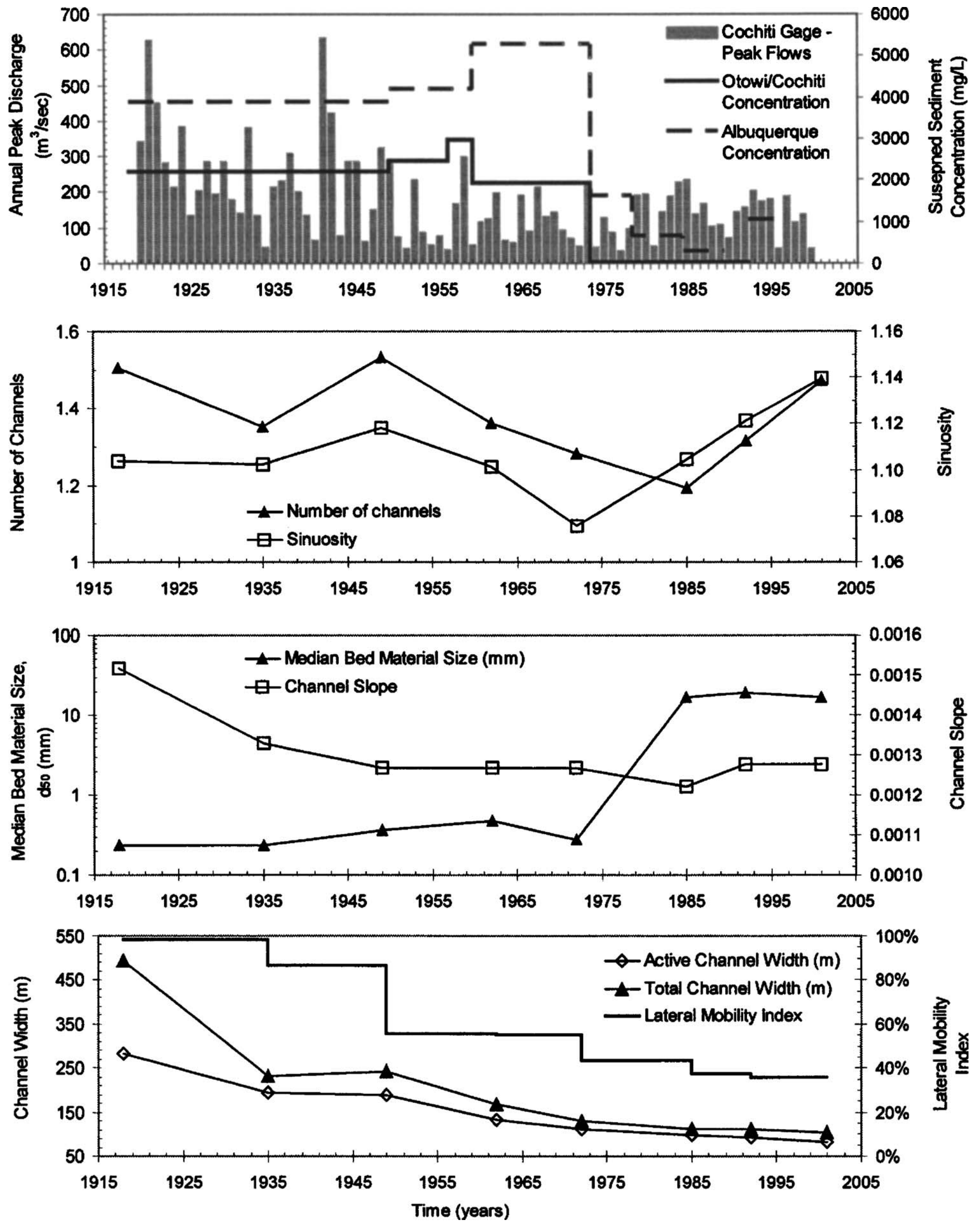


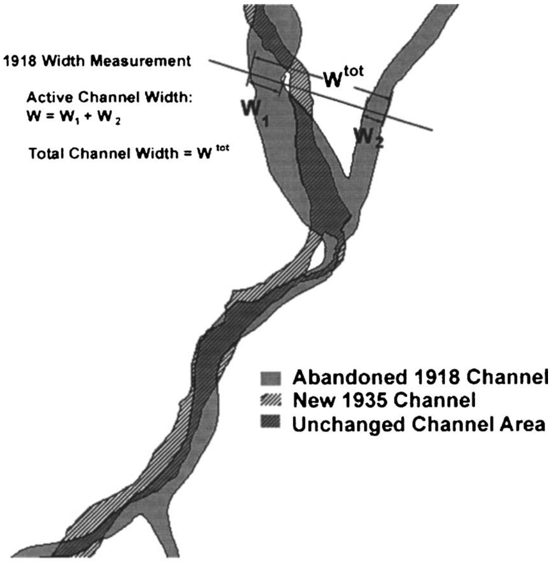
Fig. 5. Summary of changes in inputs and response of Cochiti Reach from 1918 to 1992

Measurements of planform, active channel width and lateral movements were made using a geographic information system (GIS) at 284 cross sections spaced approximately 150 m apart. The cross-section line locations were established by Reclamation in 1962 and are referred to as the aggradation/degradation (agg/deg) lines. Reclamation estimated elevations along the agg/deg lines from aerial photos in 1962, 1972, and 1992. The agg/deg lines that deviated significantly from an orthogonal orientation to the channel were redrawn.

Changes in River Morphology

Changes in both the hydrology and channel morphology (e.g., Fig. 4) of the Middle Rio Grande during the last 80 years have been documented in numerous other studies including Richard (2001), Lagasse (1980, 1981, 1994), Scurlock (1998), Leon (1998), and Bauer (1999). Richard (2001) identified a decline in the peak annual flows at the Cochiti gage since 1918 (Fig. 5). Peak discharges also declined at the Otowi gage upstream of Cochiti Dam indicating that the decline is not solely a result of the dam. The channel responded to the decline in peak discharge by continued narrowing and variation in number of channels (Figs. 2 and 3). In 1918 the Cochiti reach averaged 133–284 m in active channel width and exhibited characteristics of braiding with up to four channels at some cross sections (Figs. 3 and 5) (Sanchez and Baird 1997; Lagasse 1980; Richard 2001). By 2001, the active channel had narrowed to average widths of 65–95 m (Fig. 5).

Construction of the dam resulted in significant impacts on the channel downstream (Lagasse 1980; Leon 1998; Bauer 1999; Richard 2001). Cochiti Dam was designed for flood control and as such generally passes the natural hydrograph, typically only detaining flood peaks that exceed 140 m^3/s. Prior to the construction of Cochiti Dam, the average suspended sediment concentration entering the Cochiti reach remained above 700 mg/L and the mean annual flood was 223 m^3/s. The postdam average sus-



$$LMI = \frac{\text{Abandoned 1918 Channel Area} + \text{New 1935 Channel Area}}{\text{1918 Channel Area}}$$

Fig. 6. Measurement of active and total channel widths (W and W^{tot} and lateral mobility index from superposed geographic information system coverages of active channel

pended sediment concentration at the Cochiti gage was 38 mg/L and the postdam mean annual flood was 136 m^3/s (Richard 2001). Prior to the dam construction, the bed material was primarily sand-sized and the river bed exhibited a net aggradational trend through 1972 (Graf 1994; Richard 2001). After 1973, the riverbed in the first few miles downstream of the dam coarsened to a gravel/cobble bed (Leon 1998) and by 1985 the entire Cochiti reach had a median bed material size greater than 5 mm (Fig. 5). Degradation of the channel bed following closure of the dam was documented as far as 200 km downstream from the dam (Sanchez and Baird 1997) with the greatest degradation (up to 2 m) occurring at the downstream end of the reach. The sinuosity of the Cochiti reach also increased following dam construction (Figs. 3 and 5). Incision of the channel bed following dam construction isolated some of the mid-channel bars in Subreach 4 from flood waters allowing vegetation to encroach. As a result, the average number of channels increased after 1985 (Fig. 5).

Table 1. Input Data and Results from Application of Julien and Wargadalam (1995) Hydraulic Geometry Equations.

						Julien–Wargadalam	
	Reach number	Slope	d_{50}(mm)	Q(m^3/s)	Measured W (m)	Predicted W (m)	% error (%)
1918	1	0.0018	0.20	487	309	117	−62
	2	0.0014	0.24	487	288	123	−57
	3	0.0017	0.25	487	189	119	−37
	4	0.0011	0.26	487	347	129	−63
1935	1	0.0019	0.20	382	182	105	−42
	2	0.0012	0.24	382	249	115	−54
	3	0.0010	0.25	374	124	119	−4
	4	0.0011	0.26	374	213	116	−45
1949	1	0.0016	0.40	328	183	102	−44
	2	0.0012	0.40	328	182	108	−41
	3	0.0011	0.31	331	110	111	1
	4	0.0011	0.31	376	286	117	−59
1962	1	0.0016	0.59	300	128	98	−23
	2	0.0012	0.59	300	115	104	−9
	3	0.0010	0.35	286	92	106	16
	4	0.0012	0.34	334	208	109	−48
1972	1	0.0017	0.31	145	102	73	−29
	2	0.0011	0.31	145	95	79	−17
	3	0.0011	0.24	143	79	79	0
	4	0.0011	0.22	183	176	87	−50
1985	1	0.0017	11.77	235	90	86	−5
	2	0.0010	24.05	235	87	95	9
	3	0.0012	24.25	229	73	90	24
	4	0.0009	5.95	245	151	100	−34
1992	1	0.0017	31.91	158	78	72	−7
	2	0.0012	13.82	158	93	78	−16
	3	0.0012	19.85	165	80	79	−1
	4	0.0009	8.67	167	124	85	−31
2001	1	0.0017	22.83	187	77	78	0
	2	0.0012	20.44	187	95	83	−12
	3	0.0012	9.98	198	65	86	32
	4	0.0009	11.20	169	89	86	−4

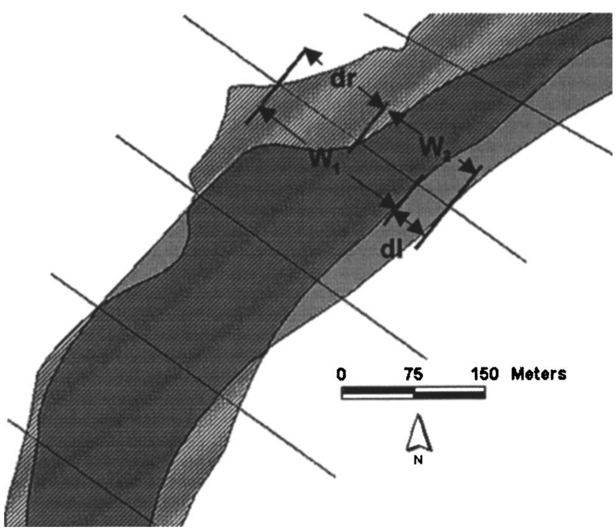


Fig. 7. Measurement of bankline changes and channel width at cross-section 145 between 1918 and 1935

The cross section surveys from 1970 to 1998 reveal channel degradation, planform shift, and bank erosion following construction of Cochiti dam (Fig. 4). The four cross sections shown in Fig. 4 demonstrate the type of changes that the river has undergone since dam construction. Cross-section line CO-2 (Subreach 1) is located just upstream of a mild bend in the river and demonstrates how erosion of the outerbank occurred while the shape of the cross section was maintained. CO-5 (Subreach 1) is also located in a meander and demonstrates how the channel geometry shifted from wide and shallow to two deeper and more narrow channels. A scour hole developed at the outerbank and the outerbank eroded almost 30 m laterally. Further downstream at CO-18 (Subreach 3) and CO-29 (Subreach 4) the predam wide and shallow geometry is evident as well as increased degradation (up to 2 m). At CO-29, the isolation of a mid-channel bar resulting from adjacent bed degradation is noticeable.

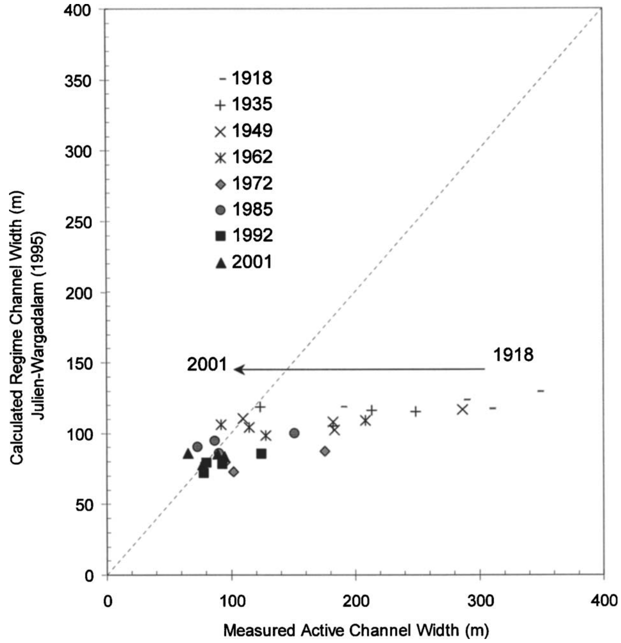


Fig. 8. Comparison of channel width calculated from Julien and Wargadalam (1995) equations with measured active channel width of Cochiti reach, Rio Grande from 1918 to 2001

Measuring Lateral Mobility

In order to quantify the changing degree of mobility of the channel with time to determine if the regulated river is more stable, a lateral mobility index (LMI) was developed. The digitized planform maps of (Fig. 3) of the active channel were analyzed in a GIS. The superposition of successive GIS coverages provided information on the changes in active channel areas. The percentage of the active channel that was either abandoned or newly occupied was measured. The lateral mobility index is the ratio of the area of the channel that is no longer in the same place to the previous channel area (Fig. 6)

$$\text{lateral mobility index} = \frac{\text{changed active channel area}}{\text{previous active channel area}} \times 100$$

A value close to 100% indicates high channel mobility where the channel has avulsed to another location. Smaller values of the lateral mobility index indicate channel activity through width change and lateral migration. The river channel has become less mobile since 1918 (Fig. 5) as the lateral mobility index declined from nearly 100% between 1918 and 1935 to less than 40% between 1992 and 2001.

To measure the lateral mobility of the Rio Grande in the Cochiti reach, the successive sets of digitized maps of the active channel were superposed over the following time periods: 1918–1935, 1935–1949, 1949–1962, 1962–1972, 1972–1985, 1985–1992, and 1992–2001. Four descriptors of lateral mobility were extracted from the digitized coverages of the active channel: the total bankline change per year L; the rate of change in active channel width dW/dt; the rate of change in total channel width dW^{tot}/dt; and the lateral migration rate M. The four lateral mobility descriptors were computed from changes in the bankline location at each of the 284 cross-section lines. Subreach-averaged values were computed using 1/2 of the distance to the next upstream and downstream lines as weighting factors. The change in position of the right and left banks was measured separately at each of the 284 cross-section lines. Two different descriptors of channel width were measured at each cross-section line: the active channel width (W) and the total channel width (W^{tot}). The active channel width is the nonvegetated or sparsely vegetated portion of the channel and does not include vegetated midchannel bars or islands. The active channel width is considered to be representative of the channel formed by the prevailing water and sediment regime. The total channel width includes vegetated midchannel bars and islands. (see Fig. 7).

The lateral movement rate of the channel banks, L, incorporates width change and lateral migration of the channel and provides insight into when and where the river is most mobile without taking into account how it is moving. The lateral movements of the outermost left bank dl, and right bank dr were summed at each cross-section line and divided by the length of the time period

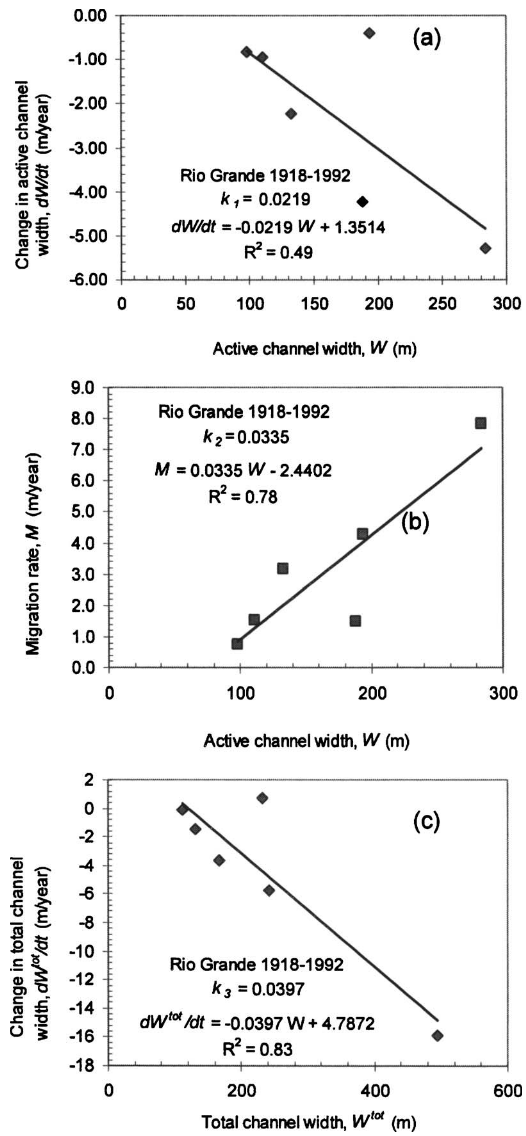


Fig. 9. Testing model hypothesis with Rio Grande data from 1918 to 1992: (a) change in active channel width, dW/dt (m/year) versus measured active channel width (m); (b) lateral migration rates M (m/year) versus measured active channel width (m) of Rio Grande from 1918 to 1992; and (c) change in total channel width dW^{tot}/dt (m/year) versus measured total channel width W^{tot} (m)

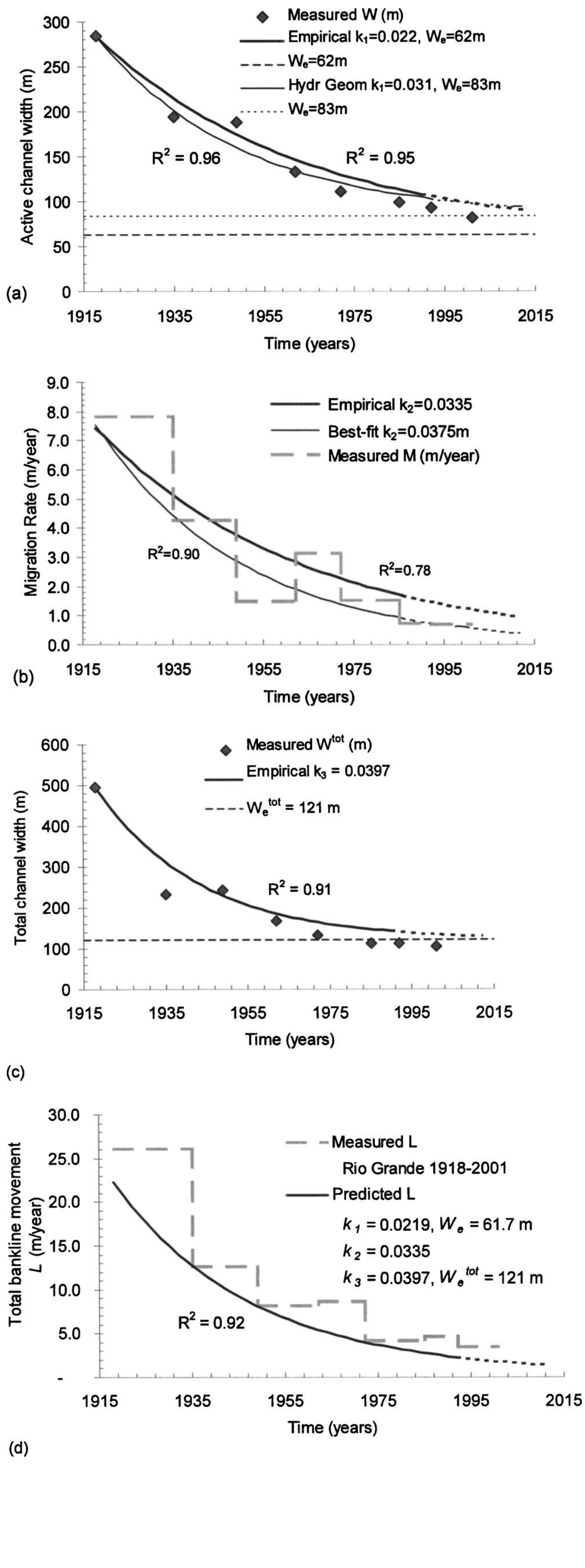


Fig. 10. Model results: (a) active channel width W; (b) migration rate M; (c) total channel width W^{tot}; and (d) lateral movement rate L (dashed portion of curves indicates model validation/prediction)

Table 2. Model Validation Results. Prediction Number 1 Utilizes Model Parameters Estimated Empirically from Analysis Shown in Fig. 9. Prediction Number 2 Utilizes Expected Hydraulic Geometry Width from Julien and Wargadalam (1995) Hydraulic Geometry Equation to Estimate Model Parameters

Variable	Measured from Cochiti reach, Rio Grande, N.M.	Prediction number 1	Prediction number 2
2001 active channel width (m)	81.9	97.8	98.1
(% error) (%)	—	(19)	(20)
1992–2001 migration rate (m/year)	0.7	1.5	0.8
(% error) (%)	—	(111)	(8)
2001 total channel width (m)	104	134	—
(% error) (%)	—	8	—
1992–2001 total lateral movement rate (m/year)	3.6	2.3	—
(% error) (%)	—	(−34)	—

$$L = \frac{dr + dl}{t_2 - t_1} \tag{1}$$

Note that dr and dl are always positive and represent the magnitude rather than the direction of the right and left bank displacement.

The annual rate of change in active channel width dW/dt at each cross section was computed by subtracting the width at the beginning of the time period from the width at the end and dividing by the length of the time period in years

$$\frac{dW}{dt} = \frac{W - W_o}{t - t_o} \text{ (m/year)} \tag{2}$$

The value of dW/dt is negative when the channel narrows and is positive when the channel widens.

Similarly, the annual rate of change in total channel width, dW^{tot}/dt, which includes mid-channel bars and islands, was computed as the difference between the total width at the beginning of the time period and the total width at the end of the time period, divided by the length of the time period in years

$$\frac{dW^{tot}}{dt} = \frac{W^{tot} - W_o^{tot}}{t - t_o} \text{ (m/year)} \tag{3}$$

A negative value of dW^{tot}/dt indicates a total channel narrowing and a positive value indicates total channel widening. Changes in total width could result from changes in active channel width and/or changes in size and number of mid-channel bars or islands as a result of avulsion or incision.

The lateral movement rate, L, describes the total bankline change, which includes narrowing or widening of the channel as well as migration. The lateral migration rate, M, was computed by removing the total width change from the lateral movement rate measurement

$$M = L - \left| \frac{dW^{tot}}{dt} \right| = \frac{dr + dl}{t - t_o} - \frac{|W^{tot} - W_o^{tot}|}{t - t_o} \text{ (m/year)} \tag{4}$$

The absolute value of the rate of change in total width was subtracted because it does not include changes in size of mid-channel bars and islands.

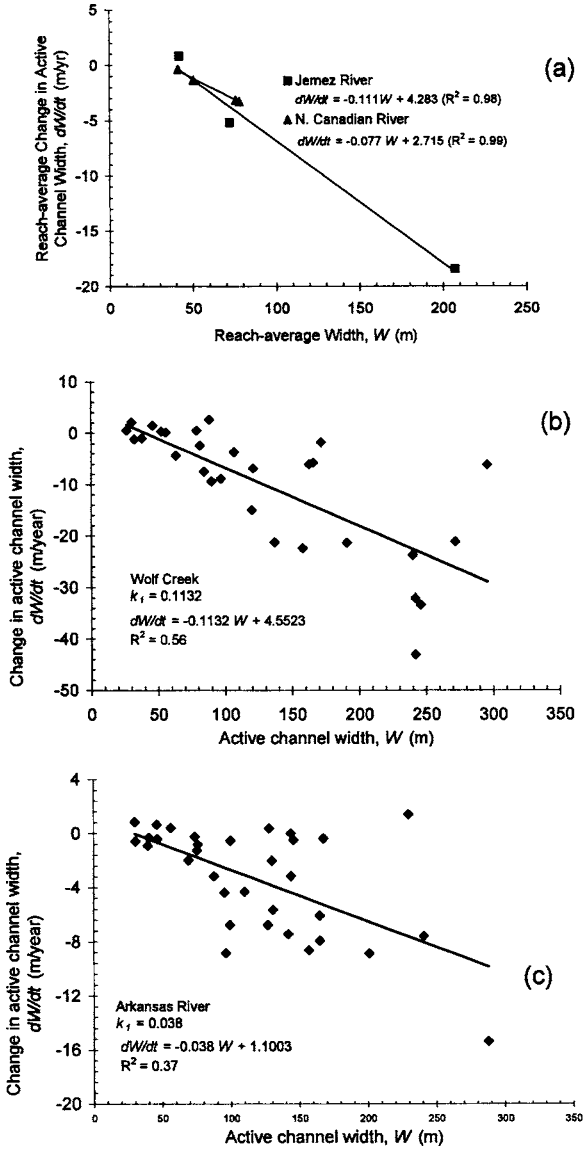


Fig. 11. Annual change in width dW/dt versus active channel width W (a) Jemez River and N. Canadian River reach-averaged data, (b) Wolf Creek cross-section data, and (c) Arkansas River cross-section data

Downstream Hydraulic Geometry

Downstream hydraulic geometry defines the width, depth and velocity of alluvial channels in equilibrium to convey the incoming water and sediment loads. In the early 1900s the "regime theory" defined stable configurations that were non-silting and nonscouring under the design discharge (e.g., Lacey 1929). Applying regime theory to natural channels, Leopold and Maddock (1953) developed a set of empirical equations in which channel geometry varies with changing discharge. From logarithmic plots of width against discharge, changes in width were described by $W=aQ^b$, where a and b are empirically derived constants with $b\sim 0.5$. Since Leopold and Maddock's (1953) seminal paper, many other equations have been developed to describe the downstream hydraulic geometry state of alluvial channels. Some recent studies expand on Leopold and Maddock's original premise and include other variables such as bed and bank material (Simons and Albertson 1963), sediment supply (Parker 1979; Julien 2002), and bank vegetation (Hey and Thorne 1986).

Julien and Wargadalam's (1995) hydraulic geometry equations are based on four fundamental hydraulic relationships of continuity, resistance, sediment mobility, and secondary flow. The equations were tested with 835 channels from around the world. The equations were calibrated, validated, and verified on rivers with different alluvial conditions varying from natural sand-bed channels, gravel/boulder-bed channels, and small-scale laboratory channels. The following equations are the simplified form that use discharge, Q (m^3/s) bed material size, d_s (m) and slope, S, as the independent variables to calculate the expected channel width, W_e (m), and mean flow depth, D_e (m), as a function of a roughness exponent $m=1/\ln(12.2D/d_s)$

$$W_e = 1.330Q^{[(4m+2)/(6m+5)]}d_s^{-[4m/(6m+5)]}S^{-[(2m+1)/(6m+5)]} \quad (5a)$$

$$D_e = 0.200Q^{[2/(6m+5)]}d_s^{[6m/(6m+5)]}S^{-[1/(6m+5)]} \quad (5b)$$

The hydraulic geometry relations of Julien and Wargadalam (1995) were applied to the four subreaches of the Rio Grande for each of the study years using the input data in Table 1. The discharge used in the hydraulic geometry calculations was the peak mean daily discharge for the 5 year period prior to the date of the aerial photo. The 5 year peak discharge was assumed to be the discharge that cleared vegetation and maintained the shape and form of the nonvegetated active channel for that time period. If an area was not flooded for about 5 years, that area would have developed enough vegetation that it would be excluded from the nonvegetated active channel during the digitization process. The median bed material and slope were determined by averaging the available data for each study period by subreach.

From 1985 to 2001, the measured active channel width varied from the predicted hydraulic geometry width by 1–34% (Fig. 8). Prior to dam construction, deviation from the predicted hydraulic geometry width ranged from 1 to 63%. With time, the measured active channel width of the Cochiti reach has moved closer to the expected equilibrium width as predicted by the hydraulic geometry equations. Comparisons with other downstream hydraulic geometry relationships gave similar results and the details are described in Richard (2001).

Lateral Mobility Models

The hypothesis to be tested is that a relationship exists between the lateral mobility descriptors (dW/dt, M, dW^{tot}/dt, and L) and the deviation from an expected equilibrium condition. Describing the deviation of the channel from the expected channel width as $(W-W_e)$ and $(W^{tot}-W_e^{tot})$, the assumed relationships take the following linear from:

$$\frac{dW}{dt} = -k_1(W-W_e) \quad (6)$$

$$M = k_2(W-W_e) \quad (7)$$

$$\frac{dW^{tot}}{dt} = -k_3(W^{tot}-W_e^{tot}) \quad (8)$$

The proposed relationships between channel width and lateral movement rates [Eqs. (6)–(8)] were tested with the Cochiti reach data (Fig. 9). The results indicate that migration rate and rate of change in active and total channel width decrease as the channel

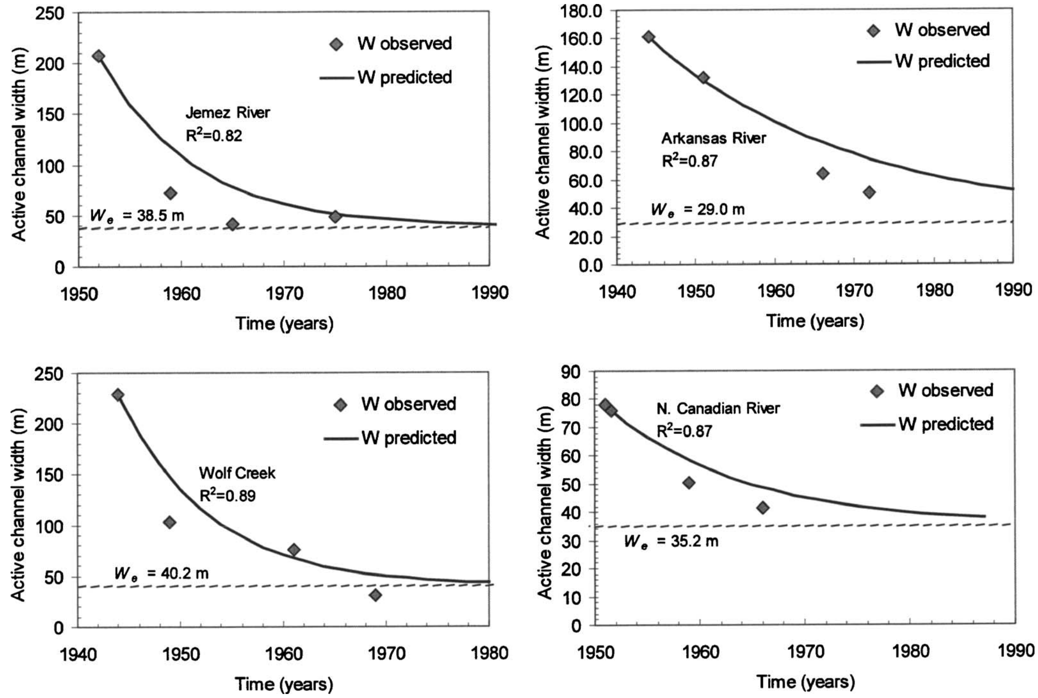


Fig. 12. Application of exponential model to four other rivers

narrows. If we consider that the channel is narrowing toward an expected or regime width in adjustment to altered flow regime, then a model of the time change in channel width can be developed by rearranging and integrating Eq. (6)

$$\int_{W_o}^{W} \frac{dW}{(W - W_e)} = \int_0^t - k_1 \, dt \tag{9a}$$

$$\ln(W - W_e)\big|_{W_0}^{W} = -k_1 t\big|_0^t \tag{9b}$$

$$\ln\left(\frac{W - W_e}{W_o - W_e}\right) = -k_1 t \tag{9c}$$

The result is an exponential function to describe the active channel width as a function of time

$$W(t) = W_e + (W_o - W_e) \cdot e^{-k_1 t} \tag{10}$$

Similarly, the total channel width can be modeled by

$$W^{\text{tot}}(t) = W_e^{\text{tot}} + (W_o^{\text{tot}} - W_e^{\text{tot}}) \cdot e^{-k_3 t} \tag{11}$$

A model describing the channel migration rate M as a function of time can also be obtained by combining Eqs. (10) and (7), as

$$M(t) = k_2((W_o - W_e) \cdot e^{-k_1 t}) \tag{12}$$

A fourth model describing the total lateral movement rate of channel is also obtained by combining Eqs. (4), (8), and (12)

$$L(t) = M + \left| \frac{dW^{\text{tot}}}{dt} \right| \tag{13a}$$

$$L(t) = k_2[(W_o - W_e) \cdot e^{-k_1 t}] + k_3(W^{\text{tot}} - W_e^{\text{tot}}) \tag{13b}$$

$$L(t) = k_2[(W_o - W_e) \cdot e^{-k_1 t}] + k_3[(W_o^{\text{tot}} - W_e^{\text{tot}}) \cdot e^{-k_3 t}] \tag{13c}$$

In order to apply the four models [Eqs. (10)–(12) and (13*c*)] to the Cochiti reach data, the model parameters k_1, k_2, k_3, W_e, and W_e^{tot} were first estimated empirically from plots of the lateral mobility descriptors dW/dt, M, and dW^{tot}/dt for 1918–1992 against the channel width of the Cochiti reach (Fig. 9). The 2001 data were reserved for validation of the model. The constants k_1, k_2, and k_3 are the slopes of simple least squares linear regressions between the channel width and the lateral mobility descriptors. The expected channel width or regime widths W_e and W_e^{tot} were estimated by dividing the intercepts ($k_1 W_e$) and ($k_3 W_e^{\text{tot}}$) by the slopes (k_1 and k_3) of the resulting regression lines.

A second application of the models utilized the expected hydraulic geometry width, W_e, from the Julien and Wargadalam hydraulic geometry equations to estimate W_e instead of the empirical derivation described above. The k_1 value was determined by varying it to produce a "best-fit" equation that minimized the sum-squared error (SSE) between the predicted and observed active widths from 1918 to 1992. The k_2 value was determined by minimizing the SSE between the predicted and observed migration rates between 1918 and 1992.

Application of the four exponential models to predict W, M, W^{tot}, and L using the two different methods of parameter estimation fit the historic data well, and explain up to 96% of the variance in width change rate and 78% of the variance in lateral migration rate. Changes in active channel width are better predicted than the channel migration rate.

The model was then applied to the 1992–2001 Cochiti reach data in order to validate the models. The use of the models in this predictive capacity is illustrated in Fig. 10 by the dashed portions of the model results curves. Errors in prediction of the 2001 width varied from 8 to 20% and errors in prediction of the 1992–2001 migration rate varied from 8 to 111% (Table 2).

To further explore the relationship between deviation from equilibrium, dam construction, and lateral mobility, the exponential model [Eq. (10)] was applied to other rivers exhibiting narrowing trends after dam closure, specifically the Jemez River downstream from Jemez Dam, N.M., Wolf Creek downstream from Fort Supply Dam, Okla., the Arkansas River downstream from John Martin Dam, Colo., and the North Canadian River downstream from Canton Dam, Okla. using data compiled by Williams and Wolman (1984). The values of k_1 and W_e were determined empirically from reach-averaged and cross-section data for each year that the rivers narrowed using the empirical least-squares method of parameter estimation described above. It should be noted that a simple least squares regression is based on the assumption that the variance of the error terms is constant. Both the Wolf Creek and Arkansas River data increase in deviation from the best-fit trend line as the active channel width increases. Future research may include a rigorous analysis of residuals and perhaps a weighted least squares analysis. Additionally, reach averaging of the Arkansas River and Wolf Creek data resulted in too few data points for a reasonable estimation of k_1. As a result, the crosssection data were used to estimate k_1 for the Arkansas River and Wolf Creek. (See Fig. 11).

As a result, parameter estimates were fairly similar with k_1 values for the four rivers varying from 0.038 to 0.11 and expected channel widths from 29.0 to 40.2 m. The exponential models [Eq. (10)] were applied to the reach-averaged widths for each river. The model results are in good agreement ($0.82 < R^2 < 0.89$) with the field measurements on these four rivers (Fig. 12).

Summary and Conclusions

The changes in width and lateral mobility of the Cochiti Reach of the Rio Grande were measured from the GIS maps of the active channel from 1918 to 2001. The measured active channel width decreased from 280 m in 1918 to 82 m in 2001. The active channel width is currently very close to the expected equilibrium width predicted by Julien and Wargadalam (1995) hydraulic geometry equations. Besides narrowing, the lateral movement L, the lateral migration M, and the total channel width W^{tot} of the Rio Grande decreased with time, supporting the hypothesis that lateral mobility decreases as the channel approaches equilibrium.

An exponential function was used to model changes in active channel width and lateral migration rates with time. The model parameters were determined from the relationship between lateral mobility and active channel width. In Fig. 10, the exponential model explained 96% of the temporal variance in width W, up to 90% of the temporal variance in migration rates M, and 92% of the temporal variance in total lateral movement rates L. The exponential model supports the hypothesis that lateral channel changes are proportional to the deviation from regime conditions. The validation of the models on the Rio Grande with the 1998–2001 lateral movement measurements, and the successful applications to four other regulated rivers, demonstrate the utility of the model to describe changes in mobility rates with time. It is acknowledged that major channel changes will take place during floods, however, the continuous exponential function reflects longterm changes very well.

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Notation

The following symbols are used in this paper:

a and b = empirically determined constants;
D_e = expected channel depth from Eq. (5) (m);
dl = lateral movement of outermost left bankline (m);
dr = lateral movement of outermost right bankline (m);
d_s = representative bed material sediment size [mm or m in Eq. (5)];
dt = length of time period (years);
dW/dt = rate of change in active channel width (m/year);
dW^{tot}/dt = rate of change in total channel width (m/year);
k_1 = rate constant for active channel width model;
k_2 = rate constant for migration model;
k_3 = rate constant for total width model;
L = total lateral movement rate (m/year);
M = migration rate (m/year);
m = exponent of resistance equation;
Q = dominant discharge (m^3/s);
S = channel slope (m/m);
t = time (years);
t_0 = beginning of time period (years);
W = nonvegetated active channel width (m);
W_e = expected active channel width from Eq. (5) (m);
W_e^{tot} = expected total channel width (m);
W_o = active channel width at onset of narrowing, or beginning of study period, t_o, (m);
W^{tot} = total channel width including vegetated bars and islands (m); and
W_o^{tot} = total channel width at onset of narrowing, or beginning of study period, t_0, (m).

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