QUANTIFICATION OF STREAMFLOWS NEEDED TO REMOVE CHANNEL VEGETATION: THE CACHE LA POUDRE RIVER

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Channel maintenance flows, as used in this paper, are streamflows needed to maintain a river channel in a healthy condition with a functioning aquatic and riparian ecosystem. This paper presents an overview of consideration the computational process of determine the channel maintenance flows for the Cache la Poudre River in Colorado (USA) when the objective is to remove unwanted vegetation from the river channel and to prevent establishment of vegetation. The removal of vegetation requires streamflow with a bed-surface dimensionless shear stress of 0.035 unless the roots of the vegetation are in sand and fines on the bed surface. If the roots are in fines and sand a much larger value of the dimensionless shear stress is needed. The discharge required at the mouth of Poudre Canyon is 147 m^3/s. Two significant reservoirs have been constructed on the North Fork of the Cache la Poudre River. These are Halligan Reservoir completed in 1910 and Milton H Seaman Reservoir completed in 1943. An index to the ability of a river to maintain its channel (the Channel Maintenance Capacity Index, CMCI) has been developed. The CMCI calculated for vegetation removal was 36.3 for the 1882-1909 period (prior to the two reservoirs), 14.6 for 1910-1942, and 4.9 for 1943-2015. This is a substantial reduction in channel maintenance capacity caused by the two reservoirs. It is important to prevent the deposition of fines and sand on gravel bars in the river otherwise plants will become rooted and difficult to remove. The dimensionless shear stress required for flushing fines and sand from the river is 0.021 and has been used as the value required to prevent deposition of the sand and fines; the discharge needed for this dimensionless shear stress is 58.3 m3/s. Thus, there are two environmental flow needs related to vegetation in the Cache la Poudre River: 1) a discharge of 147 m^3/s to remove vegetation and a discharge of 58.3 m^3/s to flush fines and sand from the river which is required to minimize the establishment of vegetation. The flushing discharge of 58.3 m^3/s should occur most years with a maximum of one year without flushing of fines and sand. The maximum interval between years of with streamflows adequate for vegetation removal is not known; also not known is the length of time the discharge should exceed 147 m^3/s. The same is also true for the time required in each year the discharge should exceeded the discharge needed to flush fines and sand.

1. INTRODUCTION

Environmental flows are streamflows needed to maintain a quality riverine ecosystem. An important component of environmental flows is streamflows that maintain the channel of the river in a desired condition. Channel maintenance flows, as used in this paper, are streamflows needed to maintain a river corridor in a healthy condition with a channel that can support a functioning aquatic and riparian ecosystem. In the past ‘channel maintenance flows’ were the streamflows required to maintain only the stream channel substrate and was called a flushing flow because the objective was to remove fines from a gravel/cobble bed. Over the years ‘channel maintenance’ has evolved to be ‘river corridor maintenance’ even though the term used is channel maintenance.

A *river corridor* has three major components: 1) stream channel, a channel with flowing water at least part of the year; 2) floodplain, a highly variable area on one or both sides of the stream channel that is inundated by floodwaters at some interval, from frequent to rare; and 3) transitional upland fringe, a portion of the upland on one or both sides of the floodplain that serves as a transitional zone or edge between the floodplain and the surrounding landscape (Federal Interagency Stream Restoration Working Group [1]). A schematic of the stream channel is shown in Figure 1. In Figure 1 this is the part of the river channel with vegetation shown on the left of the channel. In this paper the topic is limited to the management of vegetation within the stream channel and relates to the prevention of establishment of vegetation as well as the removal of vegetation once established.

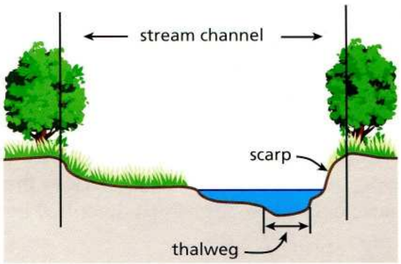

Figure 1: Cross section of a stream channel. The scarp is the sloped bank and the thalweg is the lowest part of the channel. Source: Federal Interagency Stream Restoration Working Group [1].

The objective of this paper is to present an approach to calculating the value of the streamflows needed to maintain a stream channel free of vegetation. The computational process is first presented followed by a case study of the Cache la Poudre River in Colorado (USA). There is some overlap between the two sections because information on the Poudre River is used to estimate the parameters used in the computations. The sections that follow present an outline of two other studies relating to channel maintenance flows.

1.1 Gunnison River Study

In regulated rivers one of the impacts of changes in streamflows is an increase in the vegetation within the stream channel. Friedman and Auble [2] developed a box elder clearing model for the Black Canyon of the Gunnison River that relates streamflow to an annual fraction of the bottom land cleared of vegetation. The model relates discharge to water-surface elevations, which are then used to estimate inundation durations and shear stresses in the channel bottom. The model has a two-part clearing function: 1) an area of the channel is cleared in a year if the shear stress exceeded the critical shear stress for mobilizing sediment at that location, and 2) a location is cleared if it was inundated for more than 85 days in the growing season (1 May-1 October). Thus, the percent of Black Canyon bottom cleared of box elder as a function of annual peak discharge and discharge exceeded for 85 growing-season days is presented in Figure 2. A minimum discharge of 8.5 m^3/s has been established for the Gunnison River in the Black Canyon reach. Consequently, permanently flooded areas with inundating discharges less than 8.5 m^3/s are excluded in the analysis presented in Figure 2.

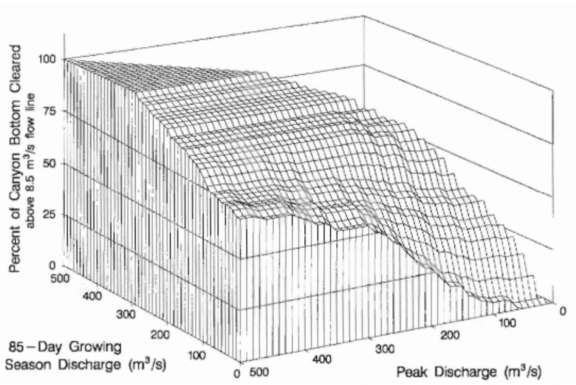

Figure 2. Percent of Black Canyon of the Gunnison River bottom cleared of box elder as a function of annual peak discharge and discharge exceeded for 85 growing-season days. From Friedman and Auble [2].

1.2 Isere River Study

Jourdain *et al.* [3] monitored three bars of the Isere River in the French Alps between April and September 2014. Coarse sediment mobility was estimated from painted plots and topographic measurements. Vegetation evolution and fine sediment deposition were monitored in 25 m² plots (between 5–10 plots per bar), using repeated vertical photographs. Streamflows in the 2014 measurement period was characterized by minor flow events, with a recurrence interval of approximately 4 months. Very high suspended sediment concentrations (up to 40 g/l) occurred occasionally and resulted in measurable sediment deposition. Very little coarse sediment mobility was observed, and as a result no established vegetation was removed. In contrast, a ten-year flood occurred in May 2015. The surface sediment layer was totally mobile (disappearance of the painted plot and significant modifications of bar topography) and vegetation was removed through burial and erosion. Their results are the following.

1. Floods must mobilize sediments in order to remove vegetation.
2 Partial surface mobility is insufficient to remove young willow and herbaceous vegetation.
3. When significant bed mobility occurs, vegetation can be removed through burial under a thick layer of coarse sediments; lateral erosion on the margins of main and secondary channels; and uprooting when the bar surface is fully mobile.
4. Minor floods (of the range of annual floods) are not able to remove vegetation from bars. A 10 year flood triggered sufficient mobility to remove young vegetation.

The Isere River study is the Ph.D. project of Camille Jourdain and very likely to result in improved knowledge about how to manage streamflows in regulated rivers to control unwanted vegetation.

2 STREAMFLOWS REQUIRED TO REMOVE VEGITATION

The following three sections present three topics:

1. streamflows required to remove vegetation from the channel by movement of the bed-material
2. duration of streamflows required to remove vegetation from the stream channel, and
3. importance of keeping sand and fines moving through the river channel.

2.1 Move bed-material

Both the Gunnison and Isere River studies found that the bed-material had to be mobilized to remove vegetation from the river channel. An analysis of streamflows in the river presented in Milhous [4] also indicated the bed material must be move in order to remove the vegetation. The work in [4] indicated the dimensionless bed shear stress (τ^*) adequate to move the sediment and the vegetation growing on the sediment was 0.035. In their work in the Black Canyon Friedman and Auble used 0.031 as the τ^* required for adequate movement of the substrate. A bed-material transport study of Oak Creek in Oregon, Milhous, [5], τ^* was found to be 0.030. This value was obtained subjectively based on measured bed-material loads and is the value at the critical discharge for the bed surface material. The critical discharge was the discharge at which a sudden increase in the rate of bed-material transport occurred. The range in τ^* at the discharge adequately to move the bed-surface material is 0.030-0.035. The preferred value of τ^* is 0.035. Gessler, [6], develop a probability distribution for the probability particles not moving during an experimental study. This relation was used to estimate the probability of movement for the τ^* for adequate movement; the range of probability of movement is 6-14%.

The bed-material transport study of Oak Creek in Oregon found that the minimum value of τ^* for movement of the surface material in a gravel/cobble river is 0. 017 but that the probability of a particle moving is quite low (approaches zero based on Gessler's relation). The Oak Creek study also found that at 0.025 there lower practical limit on the τ^* required for movement of the surface bed-material. The Gessler probability of movement is 1.2%.

A major flood in September 2013 removed vegetation from bars in the Poudre River. Pictures of two of the bars are shown as Figure 3. Prior to a flood in 2013 both bars were covered by vegetation. Following the flood some of the vegetation had been removed and some striped of leaves. The maximum τ^* was 0.049 and the time the τ^* was above 0.035 was about 26 hours (40 hours above 0.030). These values were adequate to remove much of the vegetation. A longer flood or a larger flood may have move additional vegetation. The observations of the Poudre River suggest the use of a range of 0.035-0.030 (with 0.035 preferred) as needed to remove vegetation is reasonable.

Figure 3. Left photo was taken from the Risk Canyon Road Bridge across the Cache la Poudre River. Right photo was taken about 3 km downstream at a bicycle trail crossing of the river. Both pictures were taken on 28 September 2013 following a major flood on 13 September 2013.

2.2 Duration of streamflows

The duration of streamflows required to remove vegetation from the river channel is not known at this time. If the streamflows do reach the critical discharge for the bed material for a short period of time there would only be partial movement of the surface bed material which Jourdain *et al.* [3] say is insufficient to remove young willow and herbaceous vegetation. If the time was longer the total surface would be moved (but not all at the same time) and the bed would be mobilized adequately to remove vegetation.

The best we can do is to analysis the duration of streamflows adequate to remove in the past to help estimate the impact of proposed water management changes in the streamflows on vegetation in the future. The approach suggested is to use an index that includes some elements of time. A channel maintenance capacity index has been developed (see Milhous [4]). The Channel Maintenance Capacity Index equation used in this paper is based on the load calculated from concentration form with a reference discharge to make the index dimensionless. The equation is:

$$cmci(i) = \frac{\{[QD(i) - Q_{crt}]^{(\beta-1)}\}QD(i)}{\{Q_{ref}\}^{\beta}} \qquad (1)$$

The annual CMCI is the sum of the daily cmci(i) for all days where the discharge is larger than the critical discharge. For details on the logic and computational process see Milhous [4] and [7].

Daily streamflows are used because shorter period data is not usually available. A concern in computation of the CMCI is the determination of the critical discharge for vegetation removal. One approach is given in the case study that follows. In all cases the critical discharge should have a τ^* of at least 0.025 at the critical discharge.

2.3 Keep sand moving

Friedman and Auble [2] report that as particle size decreases, the relative contribution of plant roots to sediment stability increases greatly and the shear stress needed to remove the vegetation by movement of the substrate. They report that the two box elders that survived shear stresses much more than the critical value were both rooted in relatively fine sediments. This means it is probable stress criteria given in the previous section (τ^* of 0.035) significantly underestimates the shear needed when fines are present and the plants are rooted in the fines. The conclusion of this is that the sand and fines should be kept from depositing on the river bars and if they are deposited removed quickly before plants root structure in them.

Subjective analysis of data for Oak Creek indicated there must be some disturbance of the surface bed sediment for fines and sand to be flushed from the surface. The assumption made here is that adequate for keeping sand and fines moving through the river. The criteria for flushing flows is that the τ^* must be at least 0.021. The value of 0.021 would keep the bars free of sand and fines if the sand and fines were removed prior to establishment of vegetation.

3 CACHE LA POUDRE CASE STUDY

The Cache la Poudre River is located in north central Colorado (USA) with part of the watershed in the Southern Rocky Mountains, the lower part in the Great Plains and a transition area between the mountains and plains. The case study presented in this paper relates to the lower part and mostly concerns the river as the river transitions from the confinement of Poudre Canyon to an unconfined alluvial channel. In the upper Poudre River watershed (above the canyon mouth), the majority of the river flow is from snowmelt, with additional streamflow from overland storm runoff during summer and some ground water inflow. Tributary inflows to the Poudre River downstream of the canyon are minimal except during storm events. Most years the annul peak discharge is caused by snowmelt but there are some years where the peak is from major rainfall in the transition area that may coincides with snowmelt but often does not. Natural flows are augmented by nine transbasin diversions that deliver water into the upper Poudre River. The river has 21 major diversions at multiple locations primarily for municipal water supply and agricultural use (one slightly above the canyon mouth). These diversions occasionally dry-up the river in short reaches along the river during winter and summer. The river is recharged downstream of the dry-up points by surface water discharges and ground water inflows. Water is returned to the river through a variety of point and non-point discharges. For additional information on the river see U.S. Army Corps of Engineers, [8].

The objective of this case study is to investigate impacts of reservoirs on the North Fork of the Poudre on the ability of the Poudre River to keep river bars free of vegetation. In 1910 North Poudre Irrigation Company completed Halligan Reservoir with a capacity of 6,400 acre-feet (7.9 hm^3). In 1943, the city of Greeley completed construction of the Milton Seaman Dam creating a reservoir of 5,000 acre-foot (6.2 hm^3).

3.1 Move bed-material

The first task at hand is to determine the streamflows that cause a bed dimensionless shear stress (τ^*) of 0.035 and 0.030 (the range expected to remove vegetation from the river). There are two approached that could be used. The first is to do an analysis of all cells (locations) in the channel and determine the streamflows needed to remove vegetation from all cells where vegetation is established on the river bars. This approach insures that each cell is cleared of vegetation (this is a hydraulic approach). The second approach is to use average cross-sectional parameters and insure the river streamflows, on average, are adequate to remove the vegetation. This is more of a hydrological approach. The approach use in this paper is the hydrological approach. The relation between the average τ^* and the streamflow was determined using gaging station data and is presented in Milhous,[9]. The equation for discharge, Q_t, as related to the dimensionless shear stress, τ^*, is $Q_t = 65990(\tau^*)^{1.82}$. The target dimensionless shear stress is 0.035 which yields a discharge of 147 m^3/s and 0.030 yields 112 m^3/s as the discharges required to move the substrate supporting the vegetation. The 112 m^3/s is taken as the lower bound on the discharge required for vegetation removal.

The annual peak discharges in the Poudre River measured at the mouth of Poudre Canyon are presented in Figure 4. The preferred discharge for removal of the vegetation is 147 m^3/s.

The return periods for each of the three periods with different amounts of storage on the North Fork were analyzed using a log-Pearson Type III analysis. The results are presented in Table 1.

3.2 Duration of streamflows

The time required to remove vegetation is not known. An index to the variation in the times above the discharge was calculated using the approach presented in Milhous, [4]. The critical discharge used in the calculation was 97 m^3/s and is 66% of the critical discharge required to remove vegetation. The 66% is based on the ratio of the maximum daily discharge and peak discharge in a year. The dimensionless shear stress at 97 m^3/s is 0.028 with 3% probability of movement. The value of ß was 2.0. The Channel Maintenance Capacity Index (CMCI) for each year is presented in Figure 5 with a summary for each period in Table 2.

The conclusion is that the reservoirs have had a significant impact on the ability of the Poudre River to remove vegetation from bars in the Fort Collins Reach of the Poudre River.

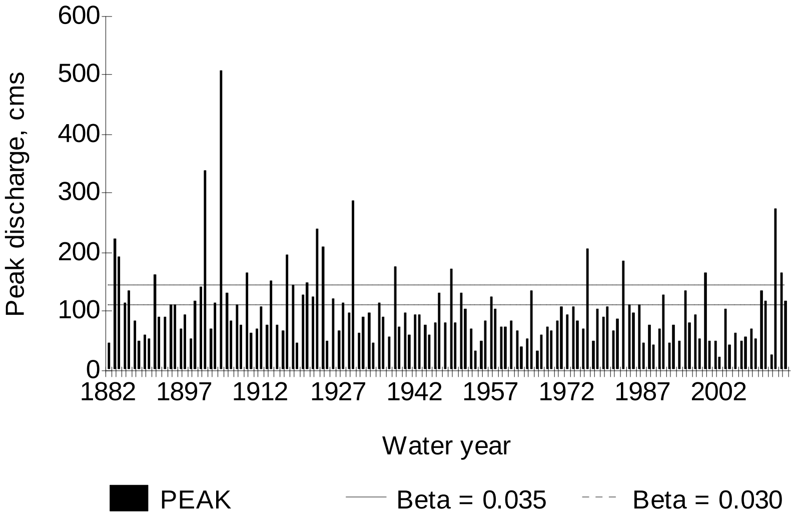

Figure 4. Peak Annual discharge of Cache la Poudre River at Mouth of Canyon (USGS Station Number 06752000). The horizontal line is for a discharge of 147 m^3/s and the lower line for 112 m^3/s (Beta is the dimensionless shear stress.)

Table1. Return period of the streamflow, 147 m^3/s, required to remove vegetation from bars in the Cache la Poudre River in the Fort Collins area. The return period of the lower bound discharge of 112 m^3/s is also shown.

Period	Return period, in years	
	147 m^3/s	112 m^3/s
1882-1909	3.7	2.3
1910-1942	5.1	2.7
1943-2015	10.5	4.2

3.3 Keep sand moving.

The effective dimensionless shear stress is the difference between the target (0.021) and the actual value. In this paper the annual dimensionless shear stress (τ^*) is the calculated using the maximum daily discharge in a year. The effective dimensionless shear stress at the canyon mouth of the river for the period of the record at the gage is presented in Figure 6. The discharge at a τ^* of 0.021 is 58.3 m^3/s with a 0.1 percent probability of movement of the surface bed material.

Prior to completion of Milton H Seaman Reservoir there was only one period (1888-1890) with more than one year in a row where there was a deficit in the shear stress needed to remove fines and sand; and I n that three year period the deficits were small. Contrast this to the 2000-2007 period with much large deficits and only one year without a deficit (2003). In 2013 and 2014 there was adequate discharge to remove vegetation by transport of the substrate but not all of the vegetation on the bars. The observation that there was one three year period and a four year period between 2000 and 2007 without adequate flushing flows suggests the deposition of fines and sand may have contributed to the lack of complete vegetation removal in 2013 and 2014.

4. DISCUSSION

Channel maintenance flows, as used in this paper, are streamflows needed to maintain a river channel in a healthy condition by removing vegetation in the river channel and preventing the conditions needed for vegetation establishment.

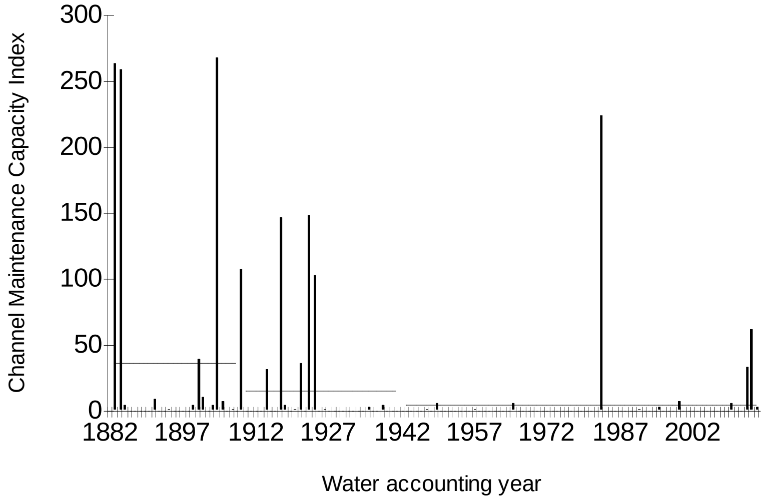

Figure 5. Annual Channel Maintenance Capacity Index of Cache la Poudre River at Mouth of Canyon (USGS Station Number 06752000). The horizontal lines are the average value for each of the three periods defined by the years a major reservoir was completed on the North Fork. Halligan Reservoir was completed in 1910 and Milton H Seaman Reservoir was completed in 1943.

Table 2. Return period of the streamflow, 147 m^3/s, required to remove vegetation from bars in the Cache la Poudre River in the Fort Collins area. Channel Maintenance Capacity Index (CMCI) calculated using a critical discharge of 97.02 m^3/s. The time periods are defined by the years a major reservoir was completed on the North Fork.

Period	return period, in years, of annual peak discharge of 147 m^3/s	Average CMCI	CMCI with 25% of annual CMCI larger	% zero CMCI
1882-1909	3.7	36.3	8.86	48.1
1910-1942	5.1	14.6	2.44	69.7
1943-2015	10.5	4.9	0.00	78.1

The remove of vegetation requires a dimensionless shear stress (τ^*) of 0.030-0.035 unless the roots of the vegetation are in sand and fines on the bed surface. If the roots are in fines and sand a much large value of τ^* is needed. The discharge required for a τ^* of 0.035 at the mouth of Poudre Canyon is 147 m^3/s. It is also important to prevent the deposition of fines and sand on bars in the river otherwise plants will become rooted and difficult to remove. The dimensionless shear stress required to flush fines and sand from the river is 0.021 and has been used as the prevent deposition of the sand and fines; the discharge at a τ^* of 0.021 is 58.3 m^3/s. Thus, there are two environmental flow needs related to vegetation in the Cache la Poudre River: 1) a discharge of 147 m^3/s is required to remove vegetation and a discharge of 58.3 m^3/s is the streamflow required to flush fines and sand from the river in order to minimize the establishment of vegetation. The flushing discharge of 58.3 m^3/s should occur most years with a maximum of one year in a row without flushing of fines and sand. The maximum interval between years of vegetation removal is not known. The duration of time the discharge must exceed 147 m^3/s in one event in order for there to be adequate removal of vegetation from the river is also not known. The same is also true for the time required to flush fines and sand.

There is an inconsistency in this paper. That inconsistency is the use of peak flows for the magnitude of discharge and then the use of daily discharges for duration analysis. Once the impact of time on the vegetation removal process is understood the inconsistency will be eliminated.

The analysis used is this paper is more of a hydrologic approach and average cross-sectional parameters were used in the analysis. A better approach is to use a hydraulic approach of calculation the stress on the streambed on a location (cell) basis and consider the percent of the river channel keep clean of vegetation.

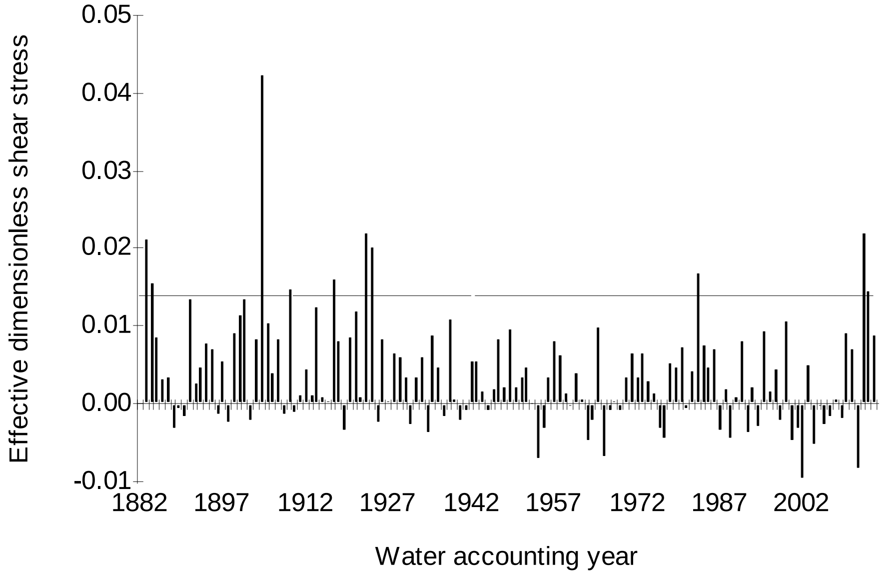

Figure 6. Effective dimensionless shear stress for flushing of sand and fines from the Cache la Poudre River at Mouth of Canyon (USGS Station Number 06752000). The horizontal lines show the three periods defined by the years a major reservoir was completed. The lines are at a value of 0.014 and all years with effective dimensionless shear stress above the line have a dimensionless shear stress of at least 0.035.

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