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# ANALYSIS OF MINIMUM STREAMFLOW AND SEDIMENT TRANSPORT IN THE YAMPA RIVER, DINOSAUR NATIONAL MONUMENT

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Yampa in equilibrium in Dinosaur Nat'l Monument (bed material, slope, Q, sediment)
Sediment storage will occur if depletions exceed 100KAF/year & Little Snake input constant
Site specific impacts would require complete water & sediment routing investigation of each reach

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## INTRODUCTION

This study will investigate minimum streamflow and sediment transport in the Yampa Canyon in northwestern Colorado. The historic sediment load will be analyzed for the period of record for the available gaging station data. A minimum streamflow hydrograph for the Yampa in Dinosaur National Monument has been previously proposed by the National Park Service (O'Brien, 1984). This study will examine that hydrograph and test possible alternative minimum stream flow hydrographs. These minimum streamflow hydrographs will be evaluated for their effect on sediment supply to the canyon and sediment transport through the canyon.

## OBJECTIVES AND SCOPE OF WORK

The comprehensive goal of this project is to investigate the potential for designing a minimum streamflow hydrograph that would preserve and maintain the natural conditions and processes vital to the biological system of the Yampa River in Dinosaur National Monument. This investigation would review and refine previous work by the U.S. Geological Survey (USGS Elliott, et al., 1984) and the National Park Service (NPS O'Brien, 1984) and would attempt to analyze adverse impacts on sediment transport from a reduced or otherwise altered seasonal discharge.

The scope of work to accomplish this objective is outlined below in four tasks.

1. Analyze the sediment supply from the Little Snake and Yampa Rivers upstream of Dinosaur National Monument for the period of record from water years 1921 to 1984. Daily sediment load records are available for approximately five years on the Little Snake (1959-1964) and twelve years on the Yampa (1952-1958) and (1976-1982).

2. Review the sediment transport analysis by the USGS (Elliott, et al., 1984) at Deerlodge Park and the NPS (O'Brien, 1984) at Mathers Hole and evaluate the relationship between this data and the upstream supply data at the USGS gaging stations.

3. Determine the nature of the sediment load passing through Dinosaur (as measured at Mathers Hole) over the period of record (1921-1984) and evaluate whether a sediment equilibrium condition is being maintained in the Monument.

4. If sediment equilibrium has been maintained, formulate a minimum daily flow hydrograph over the period of record that approximately maintains this historic sediment equilibrium at Mathers Hole.

## BACKGROUND INFORMATION

The riverine environment of the Yampa River in Dinosaur National Monument is created through a diverse blend of physical conditions and processes. These include the steep channel slope and coarse bed material in the canyon and the water and sediment supply from two tributaries upstream of the Monument boundary, the Yampa and the Little Snake Rivers. The two tributaries have a confluence approximately five miles upstream of the Monument and drain geologically different basins. On an average, the Yampa River annually contributes approximately 72 percent of the water entering Dinosaur at Deerlodge Park but only 23 percent of the annual average sediment load. Conversely, the Little Snake carries 77 percent of the total sediment load with only 28 percent of the average annual water volume (Table 1) that flows into the Yampa Canyon. The average annual sediment load for each river shown on Table 1 is computed by summing the daily measured sediment loads from each gaging station for each water year. See O'Brien (1984) for a more complete description of the watersheds and the Yampa Canyon geomorphology.

Physical attributes of the five mile river reach downstream of the confluence and upstream of the canyon in the Deerlodge Park area indicate that this alluvial reach of river is still very active. The channel has migrated nearly 40 feet at the Deerlodge campground during recent high flow years, with substantial loss of bank on one side and channel bar growth and attachment on the opposite shore. Generally, the channel is slightly incised in this reach. At the confluence of the two rivers channel shifting and abandonment has occurred. The growth and aggradation of the Little Snake delta is the cause of this local channel migration. This confluence area and the Deerlodge Park reach will be sensitive to changes in the water and sediment discharge ratio.

The Deerlodge Park reach upstream of the canyon has a mild slope and an alluvial bed of sand whereas the canyon channel is steep with a substrate consisting primarily of cobbles, boulders and bedrock. In this alluvial reach, the river will scour sand from the bed or deposit sand on the bed depending on its ability to transport the sediment (sediment transport capacity) and quantity of sediment supplied from the upstream tributaries. Essentially, the sediment transport capacity of this reach constitutes the sediment supply to the canyon. As there are no similar major areas of sand storage (alluvial channel) in the canyon upstream of Mathers Hole, the sediment load entering the canyon at Deerlodge Park is sediment load that has been transported through the canyon historically. There are reaches in the canyon, however, which respond to the sediment load with a scour and fill cycle reflecting the rising and falling nature of the seasonal hydrograph.

The unique nature of the Yampa Canyon channel morphology not only supports important habitat for endangered species of fish (USFWS, 1982) but also creates substrate conditions which are sensitive to variations in sediment load. The Colorado squawfish spawning areas in the lower Yampa Canyon are cobble bar reaches which can be effected by sediment deposition during flows with large sediment loads (O'Brien, 1984). Although spawning sites are mostly located in riffles, areas not generally associated with sediment deposition, spawning does occur in the areas of adverse bed slope which is upstream of riffles and just downstream of deep pools. These areas are sensitive to sediment deposition. It is important, therefore, to understand the nature of the sediment load in the cobble reaches of the lower Yampa Canyon.

The potential for water resource development in the upper basins of the Little Snake and Yampa Rivers must be carefully evaluated because of the complex interdependence of the sediment load and water discharge in both

Table 1. Historical Sediment Data

| | Yampa, Maybell | | Little Snake, Lilly | |
|---|---|---|---|---|
| Water Year | Discharge (acre-feet) | Sediment Load (tons/year) | Annual Discharge (acre-feet) | Sediment Load (tons/year) |
| 1952 | 1,447,177 | 547,740 | 727,828 | |
| 1953 | 829,208 | 247,886 | 268,721 | |
| 1954 | 522,182 | 125,025 | 178,256 | |
| 1955 | 772,587 | 401,893 | 233,164 | |
| 1956 | 1,033,298 | 397,647 | 410,900 | |
| 1957 | 1,781,336 | 607,486 | 507,000 | |
| 1958 | 882,840 | 511,717 | 425,000 | |
| 1960 | 1,010,000 | | 300,301 | 931,650 |
| 1961 | 629,300 | | 162,779 | 438,142 |
| 1962 | 1,492,000 | | 569,128 | 3,156,957 |
| 1963 | 630,200 | | 203,601 | 958,285 |
| 1964 | 865,200 | | 318,014 | 1,221,563 |
| 1976 | 826,300 | 246,508 | 382,400 | |
| 1978 | 731,628 | 500,450 | 507,000 | |
| 1979 | 660,582 | 232,540 | 417,500 | |
| 1980 | 645,121 | 651,042 | 557,400 | |
| 1981 | 279,388 | 187,247 | 248,300 | |
| 1982 | 692,174 | 618,903 | 570,100 | |
| Average* | 854,140 | 407,237 | 310,765 | 1,341,319 |

*Average is calculated only for those years with corresponding sediment loads.

The Little Snake measured daily sediment load data is presented in graphical form in Appendix D-1.

The Yampa River measured daily sediment load data (only 2500 data points) is presented graphically in Appendix D-2.

The Little Snake and Yampa Rivers water discharge hydrographs for the period from Oct. 1, 1959 to Sept. 30, 1964 are presented graphically in Appendicies D-3 and D-4 respectively.

The Little Snake measured sediment data is presented as a function of time (similar to a hydrograph) in Appendix D-5.

A simulated Yampa sediment hydrograph for the same period (1959-64) is presented in Appendix D-6.

rivers. While less sediment load is beneficial to maintaining substrate conditions for viable spawning, an adequate sediment supply must be maintained for beach replenishment and riparian vegetation in the canyon. Important to the canyon ecology is the relationship of endemic phreatophytes (willows and cottonwoods) and their confrontation with invading tamarisks over available sandy beaches for seed germination. The cottonwoods in the riparian zone require moist, sandy substrate during seed deposition and high flows to scour yearling growth of tamarisks. The substrate must be relatively free of alien vegetation for cottonwood seed germination and growth. Further, the beaches are important to the aesthetic and recreational resource values in the canyon. The interaction of all the biological and physical processes occurring in the canyon require thorough understanding before peak flows and annual water volumes are reduced in the upstream tributary systems.

The effect of reducing the discharge in the Little Snake will be to reduce the sediment load to the canyon. Concomitantly, reducing the water supply in the Yampa River upstream of the confluence with the Little Snake River will have the effect of limiting the river's ability to transport the sediment load in the canyon. The possible options for water development must be evaluated in terms of quantifying how the equilibrium of the hydrologic system is disrupted.

## PROCEDURE

To initiate the project, the daily flow discharge and sediment load data base was reviewed, this included reviewing data from the reports by the NPS (O'Brien, 1982 Flug, O'Brien, et al., 1983 O'Brien, 1984) and the USGS (Elliott, et al., 1984), and reviewing the USGS gaging station data in computer files. It was discovered during this review that there were missing data in the USGS daily flow records, that the most recent years (exceedingly wet years) had not yet been processed into the files, and that the sediment discharge relationships required further evaluation. The following tasks were performed to remedy these problems.

1. Seventy-two random blocks of eight day, daily Little Snake water discharges were missing from the computer data base. Most of missing data were extracted from the published USGS water supply records in the library and added to computer files. Several blocks of missing data from the period 1928 to 1934 had to be obtained from the Colorado State records as the USGS relinquished responsibility for taking the Little Snake discharge measurements during this period.

2. The water years of 1983 and 1984 were added to the computer files completing the current published USGS database (64 years dating from 1921). These years constitute very high volume water years with 1983 the highest volume water year on record.

3. All three databases (USGS gaging station USGS, Elliott data and the NPS O'Brien data) had water-sediment discharge regressed relationships based log-log data transformation using a mathematical least squares best fit to the data. This regression method underestimates predicted sediment loads and the

underestimated value increases with the degree of scatter about the rating curve and can reach as high as fifty percent (Ferguson, 1986). The statistical regression model for the sediment load $Q_s$ (tons/day) is:

$$Q_s = a\,Q^b \tag{1}$$

where a = regression coefficient
b = regression exponent
Q = water discharge (cfs)

This model can be improved by applying an unbiased correction factor:

$$C = e^{(2.65s^2)} \tag{2}$$

$$\text{where } s^2 = \sum_{i=1}^{n} (\log Q_{s_m} - \log Q_{s_c})/(n-2) \tag{3}$$

and

$Q_{s_m}$ = measured sediment load
$Q_{s_c}$ = calculated sediment load (predicted from eq. (1))
n = number of data points

The bias correction is made by multiplying the regression coefficient a by the correction factor C. This simple correlation based on statistical considerations removes most of the bias when the log-log rating plot is approximately linear with normally distributed scatter. It improves the accuracy of the sediment load estimate. When the average of the measured sediment load for all three databases are compared with predicted values, further corrections can be made by adjusting the coefficient a.

With updated and revised databases it was possible to determine a base flow for both the Little Snake and Yampa Rivers separately. The water year was divided into a base flow period (September 1 to February 28) and high flow period (March 1 to August 31). The mean flow for this fall and winter period for each river was determined using the entire period of record. This mean flow was designated as a base flow for this analysis.

To analyze potential impacts of flow reduction in a method that retains the shape of the seasonal hydrograph, exceedance probability hydrographs were developed. The exceedance hydrographs were computed from the daily discharge record for each river, Yampa at Maybell and Little Snake at Lily gaging stations, based on Wiebull probability distribution. An exceedance probability hydrograph implies that for the given percentage exceedance the flow will be equal to or greater than that corresponding discharge (e.g. 75 percent exceedance probability means that three out of every four years the flow will be equal to or greater than the indicated flow for that day). To determine a particular exceedance hydrograph the daily flows for every day of the year in the historical record must be ranked according to the flow magnitude from the lowest to the highest discharge. A probability for that day based on the total number of years is then assigned to each discharge. Using that probability, the flow that is exceeded (say 50 percent of the time) can be determined on a daily basis to calculate the 50 percent exceedance hydrograph. This was accomplished for 50, 75, 84, 90 and 95 percent exceedance hydrographs for each river. A 50 percent exceedance hydrograph is equivalent to the median hydrograph for the flow period. Smaller exceedance hydrographs are represented by the larger exceedance percentages, 75, 84, 90 and 95. A 95 percent exceedance hydrograph is a much smaller hydrograph with substantial volume depletion. Examples of exceedance hydrographs are shown in Figure 1. The hydrographs in this figure are based on lognormal exceedance probabilities which would generate slightly different hydrographs than a Wiebull distribution. The hydrographs shown in Figure 1 are very similar to those employed in this study.

To expand sediment budget analysis to years without measured sediment load data or to analyze various altered hydrographs, the modified sediment regression relationships were applied to the given daily discharge to predict daily sediment loads. The computed sediment load associated with each day was summed for each gaging station and Mathers Hole to determine the mean annual sediment for each exceedance hydrograph. An array of water volumes and sediment loads was generated. In this analysis, the specified exceedance hydrographs were analyzed as minimum streamflow hydrographs with the volumes of water in excess of minimum streamflow criteria assumed to be withdrawn from the system and unavailable for sediment transport.

Variations on the NPS minimum streamflow hydrograph were analyzed by incorporating additional peak flows from the Yampa River (Maybell) in excess of the proposed NPS minimum streamflow hydrograph. These peak flows were added to the NPS minimum streamflow hydrograph in increasingly larger percentages. The Little Snake River peak flows were not altered in the NPS minimum streamflow analyses. For example, discharges above 90 percent of the actual peak flow in any year were added to the Yampa River flows in one set of runs those flows above 75 percent of the actual peak were added in another. In this manner, the effects of decreasing the number of high flow discharge days in the Yampa River could be evaluated.

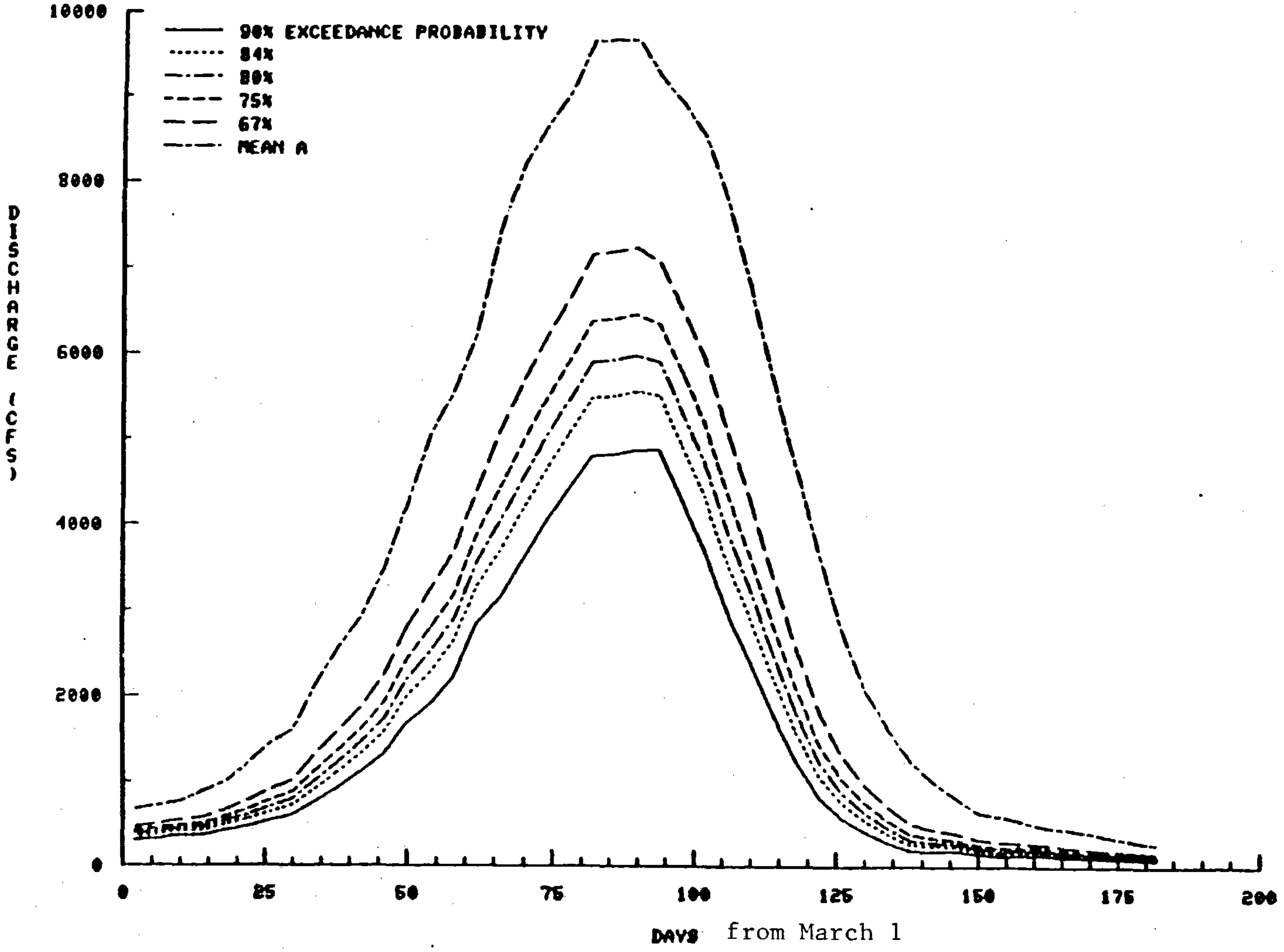
## RESULTS

The volume of the mean annual hydrograph of the Yampa River in Dinosaur was increased from 1,510,000 AF to 1,540,000 AF as a result of adding two very high volume years, 1983 and 1984, to the water discharge database (Table 2). Additionally, the mean flow for the period of September 1 to February 28 was determined using the expanded database:

| | |
|---|---|
| Little Snake: | 98 cfs |
| Yampa: | 297 cfs |
| Combined: | 395 cfs |

This compares with 367 cfs combined mean flow in O'Brien's 1984 report. These historic mean flows constitute the minimum base flow for the indicated period.

FIGURE 1.



YAMPA RIVER -- FLOWS OF VARIOUS EXCEEDANCE PROBABILITY (Lognormal)

Hydrology?

Table 2. Historical Hydrograph Volumes

| Water Year | Annual Volume (acre-feet) | Water Year | Annual Volume (acre-feet) |
|---|---|---|---|
| 1921 | 1584567. | 1953 | 700438. |
| 1922 | 1838252. | 1954 | 1005751. |
| 1923 | 1347465. | 1955 | 1443543. |
| 1924 | 1408446. | 1956 | 2289240. |
| 1925 | 1691386. | 1957 | 1693288. |
| 1926 | 1887604. | 1958 | 1029978. |
| 1927 | 2106429. | 1959 | 1310152. |
| 1928 | 2902553. | 1960 | 792112. |
| 1929 | 1359346. | 1961 | 2060738. |
| 1930 | 1265287. | 1962 | 833860. |
| 1931 | 2144967. | 1963 | 1184427. |
| 1932 | 1599209. | 1964 | 1793325. |
| 1933 | 454095. | 1965 | 1008993. |
| 1934 | 1120021. | 1966 | 1253888. |
| 1935 | 1508971. | 1967 | 1622582. |
| 1936 | 1426433. | 1968 | 1508031. |
| 1937 | 1708732. | 1969 | 1869818. |
| 1938 | 1233386. | 1970 | 2112790. |
| 1939 | 1106580. | 1971 | 1266828. |
| 1940 | 1384672. | 1972 | 1751740. |
| 1941 | 1649526. | 1973 | 1956125. |
| 1942 | 1244955. | 1974 | 1639329. |
| 1943 | 1241415. | 1975 | 1207034. |
| 1944 | 1722819. | 1976 | 448427. |
| 1945 | 1179419. | 1977 | 1958202. |
| 1946 | 1777476. | 1978 | 1727802. |
| 1947 | 1466055. | 1979 | 1835731. |
| 1948 | 1857943. | 1980 | 802459. |
| 1949 | 1393951. | 1981 | 1943124. |
| 1950 | 1310703. | 1982 | 2246512. |
| 1951 | 2175005. | 1983 | 3103573. |
| 1952 | 1097929. | 1984 | 2192989. |
|  |  | Average | 1543543. |

The original regression coefficients and exponents for the suspended sediment load as determined in the 1984 NPS study are shown in Table 3 along with the revised values based on the statistical correction. The original regression relationships were based on five years of USGS daily water and sediment discharge data from the Little Snake gaging station at Lily, twelve years of USGS water and sediment discharge data from the Yampa River at Maybell, fifty-two water and sediment discharge measurements made at Mathers Hole by the NPS (O'Brien, 1984) in 1982 and 1983, and thirty-three water and sediment discharge measurements at Deerlodge by the USGS (Elliott, et al., 1984) in 1983. The correction factor C is presented in the right hand column. This factor is a combination of the statistical bias correction factor described in the Procedure Section and an additional modification to reproduce the average value of the measured data for all sampling stations. The corrected coefficients and exponents shown in Table 3 were used in all the sediment budget computations.

Calculations of the annual sediment load based on the modified regression relationships predicted identical annual loads for the Deerlodge and Mathers sampling sites (only 6 percent difference was determined). This confirms the conclusions in O'Brien's report that the suspended sediment load from the Deerlodge Park reach is being transported through the Yampa Canyon. The sediment load in Deerlodge Park is limited by the river's transport capacity because this is an alluvial reach of river. The river tries to transport as much sediment as possible, but the sediment transport is constrained by the flow conditions. The sediment load at Deerlodge, therefore, constitutes the sediment supply to the canyon and Mathers Hole. The Mathers Hole site probably has greater transport capacity than Deerlodge because of its steeper slope, however, the sediment load is limited by the available supply at Deerlodge. There are no major sources of sediment in the canyon, therefore, the river cannot transport any more suspended sediment load at Mathers than passes into the canyon from the Deerlodge Park reach. Mathers regression relationship predicts a slightly greater load than Deerlodge (6 percent greater) so the Mathers relationship is employed in this analysis to compare with the load predicted from the upstream gaging station data at Maybell and Lily.

Suspended sediment load data are used in the sediment budget analysis because all the sediment records for the Yampa at Maybell (12 years) and the Little Snake at Lily (5 years) consisted only of suspended load measurements. The bed material in cobble bed reaches of the lower canyon is coarse. Its viability as spawning substrate for the Colorado squawfish is dependent upon keeping the cobble interstices free of sand and gravel size sediment which is transported principally as bedload. (See O'Brien, 1984, for definitions of bedload, bed material, and suspended load). Although the bedload is critical to the maintenance of the sand free cobble substrate, it represents less than one percent of the total load. The unmeasured sand load was estimated at two percent of the annual total load (O'Brien, 1984). This three percent (bedload plus unmeasured sand load) of the average annual total load should be relatively constant over the period of record and its variation can be reflected by the variation in the suspended load. The analysis of the suspended load data, therefore, should be interpreted as reflecting the total historic load in the system.

The summation of the Yampa (Maybell) and Little Snake (Lily) predicted suspended sediment load was assumed to constitute the upstream sediment

Table 3. Suspended Sediment Regressed Relationships, $Q_s = a Q^b$.

| | Original | | Corrected | | Correction Factor |
|---|---|---|---|---|---|
| | a | b | a | b | C |
| Little Snake | 0.330 | 1.35 | 0.949 | 1.35 | 2.88 |
| Yampa | 0.00129 | 1.69 | 0.00254 | 1.69 | 1.97 |
| Mathers | 0.0855 | 1.39 | 0.121 | 1.39 | 1.42 |
| Deerlodge* | 0.125 | 1.35 | 0.166 | 1.35 | 1.33 |

*Determined by USGS (Elliott, et al., 1984) supply to the Deerlodge Park reach and to the Yampa Canyon. This combined suspended sediment supply was compared to the predicted suspended sediment load that could be transported (capacity) at Mathers Hole using the revised regression relationships applied to the daily discharges for the entire period of record (64 years). All the sediment discharge calculations were made employing the revised regression relationships in Table 3. The summation of the upstream daily water discharges was assumed to equal the daily discharge at Mathers Hole for that day. The predicted difference between the upstream sediment supply and the sediment transport capacity in the canyon results in a surplus (+), storage or deposition of sediment from the canyon or scour (-), the removal of sediment in the canyon. It may be more appropriate to state that a negative value indicates a potential to scour.

There are several important assumptions inherent in this analysis:

1. The sediment regression relationship (Table 3) used as a predictor for the measured load is only a function of discharge.

2. The regression relationships used in this study will reflect only long term trends and not the short periods of severe overloading. The actual measured load (especially for the Little Snake) will greatly fluctuate diurnally and will display different regression relationships for the rising and falling limbs as shown in O'Brien's (1984) report.

3. There is some lag time between the arrival of the annual peak water discharge and peak sediment load at Mathers Hole. The daily loads are additive and, therefore, this impact of lag time should be negated in the long term analysis.

4. The actual storage and/or scour of sediment in the canyon is subject to localized physical conditions and processes. Sediment often tends to move in waves. Sediment transport, deposition or scour is a function of numerous variables including slope and sediment size distribution. Sediment transport is a selective process according to size fraction and localized armoring of the bed may inhibit further transport of the finer sediment sizes. These variables may cause sediment storage in a pool during a time when the canyon is experiencing general scour. Sometimes sediment being stored may itself induce the local processes to increase or decrease the sediment transport thereby changing the regression relationships. The results should only be interpreted as indicating a general or long term trend and not necessarily the exact local conditions that would have occurred in the canyon based on the computational criteria.

5. The concept of scour (negative storage) in the canyon is a vague one because once the fine sediment is removed from the bed and the bed is armored, no further sediment can be removed. These values should indicate only a potential to scour.

The historical sediment budget is shown in Table 4. This information is summarized below for 1921 to 1984 water years*.

Average Annual Volume (AF):

| | |
|---|---|
| Little Snake | 428,000 |
| Yampa | 1,120,000 |
| Combined Rivers | 1,548,000 |

Average Annual Sediment Load (tons):

| | |
|---|---|
| Little Snake | 2,020,000 |
| Yampa | 389,000 |
| Combined Rivers (supply) | 2,409,000 |
| Mathers (capacity) | 2,290,000 |
| Difference (supply - capacity)** | 119,000 |

* These values compare with Table 4 average values rounded off to three significant digits.

**This represents an historic 5 percent difference compared to the sediment load at Mathers Hole.

The summary shows that the sediment transported through the canyon is in approximate long-term equilibrium with the upstream supply an obvious result considering the long-term adjustment of this river to the geologic and climatic conditions (O'Brien, 1984) and the essentially unregulated nature of the flows in the river system. The 5 percent difference between the upstream sediment supply and the load transported at Mathers Hole is within the range of error in the discharge measurements made by O'Brien (1984).

The slight propensity for sediment storage revealed in Table 4 must be analyzed by reviewing the historical sediment data for the Little Snake and Yampa Rivers on which the predictive regression relationships are based. From Table 1 the sediment data was collected for years that on the average were only 77 percent of mean volume for the Yampa and 73 percent for the Little Snake. This data was collected on the average during dry periods. This is difficult to interpret, because in Table 1 it is noted that the measured sediment load in the wet years was from 5 to 8 times the measured sediment load in the drier years. These drier years may have helped produce more sediment load in the wet years. More sediment data is necessary to conclude that the system is aggrading or degrading over the long term and the best interpretation is that barring any dramatic climate changes relative equilibrium has been established.

Exceedance flows for a range of probabilities were calculated as discussed in the Procedure and are presented in Appendix A. These exceedance hydrographs were input as minimum streamflow hydrographs together

## TABLE 4. Historical Sediment Budget

| YEAR | ANNUAL VOLUME (AF) | LITTLE SNAKE SEDIMENT LOAD (TONS) | YAMPA SEDIMENT LOAD (TONS) | MATHERS SEDIMENT LOAD (TONS) | UPSTREAM SEDIMENT LOAD (TONS) | SEDIMENT BUDGET (TONS) |
|---|---|---|---|---|---|---|
| 1921 | 1584567. | 2307491. | 385399. | 2385427. | 2692890. | 307463. |
| 1922 | 1938252. | 2172914. | 518113. | 2827029. | 2691027. | -136002. |
| 1923 | 1347465. | 1780136. | 278502. | 1832021. | 2058638. | 226617. |
| 1924 | 1408446. | 1641589. | 251524. | 1750245. | 1893113. | 142868. |
| 1925 | 1891386. | 2703132. | 358799. | 2456348. | 3061931. | 605583. |
| 1926 | 1887604. | 2707362. | 493069. | 2920997. | 3200431. | 279434. |
| 1927 | 2106429. | 2966047. | 591838. | 3329891. | 3557886. | 227995. |
| 1928 | 2902553. | 4923381. | 903119. | 5084688. | 5826500. | 741812. |
| 1929 | [illegible] | 1080081. | 286711. | 1689500. | 1366792. | -322709. |
| 1930 | 1265287. | 1894021. | 179539. | 1521308. | 2073560. | 552251. |
| 1931 | 2144767. | 3943836. | 516132. | 3397641. | 4459968. | 1062327. |
| 1932 | [illegible] | 2781006. | 383621. | 2489784. | 3164627. | 674842. |
| 1933 | 454079. | 208665. | 59155. | 407766. | 267820. | -139946. |
| 1934 | 1120221. | 975708. | 272347. | 1505555. | 1248055. | -257500. |
| 1935 | 1505969. | 1661234. | 432739. | 2299095. | 2093973. | -205122. |
| 1936 | 1426430. | 2353130. | 296219. | 2062400. | 2649349. | 586949. |
| 1937 | [illegible] | 2357453. | 436918. | 2596560. | 2794371. | 197811. |
| 1938 | 1233389. | 1195899. | 267489. | 1611027. | 1463388. | -147639. |
| 1939 | 1106081. | 1094776. | 257702. | 1504960. | 1352478. | -152482. |
| 1940 | 1388672. | 1736565. | 319689. | 1935679. | 2056255. | 120575. |
| 1941 | 1649520. | 2092351. | 355411. | 2352286. | 2447762. | 95475. |
| 1942 | 1244953. | 1517739. | 241509. | 1631793. | 1759248. | 127456. |
| 1943 | 1241414. | 1929145. | 286421. | 1855296. | 2215565. | 360269. |
| 1944 | 1722819. | 2292243. | 442946. | 2616436. | 2735189. | 118753. |
| 1945 | 1179418. | 1307563. | 215982. | 1468395. | 1523544. | 55149. |
| 1946 | 1777477. | 2142665. | 457705. | 2634986. | 2600371. | -34616. |
| 1947 | 1466054. | 1193977. | 386065. | 2037897. | 1580042. | -457855. |
| 1948 | 1057933. | 2721165. | 483152. | 2906983. | 3204317. | 297334. |
| 1949 | 1373955. | 2034735. | 274635. | 1918335. | 2309370. | 391035. |
| 1950 | 1310702. | 1168394. | 301138. | 1730898. | 1469532. | -261366. |
| 1951 | 2775005. | 4273251. | 633607. | 3814938. | 4906858. | 1091920. |
| 1952 | 1097932. | 1081580. | 256954. | 1473965. | 1338534. | -135431. |
| 1953 | 792435. | 580512. | 97383. | 714475. | 677895. | -36580. |
| 1954 | 1005751. | 840801. | 196675. | 1215848. | 1037476. | -178372. |
| 1955 | 1457036. | 1889342. | 353897. | 2092829. | 2243239. | 150411. |
| 1956 | 2289240. | 2528581. | 835775. | 3950276. | 3364356. | -585920. |
| 1957 | 1693285. | 2087273. | 501728. | 2686764. | 2589001. | -97763. |
| 1958 | 1029978. | 725413. | 215060. | 1235946. | 940473. | -295473. |
| 1959 | 1310150. | 1198698. | 292551. | 1727632. | 1491249. | -236383. |
| 1960 | 792112. | 530843. | 145061. | 884008. | 675904. | -208104. |
| 1961 | [illegible] | 2799984. | 557094. | 3175325. | 3357078. | 181753. |
| 1962 | 833852. | 713836. | 134878. | 923741. | 848714. | -75027. |
| 1963 | [illegible] | 1463326. | 279291. | 1695941. | 1742617. | 46676. |
| 1964 | 1793326. | 2220671. | 476006. | 2700082. | 2696677. | -3405. |
| 1965 | [illegible] | 1173205. | 142679. | 1132979. | 1315884. | 182905. |
| 1966 | 1253887. | 1453966. | 251597. | 1642383. | 1705563. | 63181. |
| 1967 | 1622582. | 2351674. | 404991. | 2468418. | 2756665. | 288247. |
| 1968 | 1508031. | 1750575. | 336216. | 2076095. | 2086791. | 10696. |
| 1969 | 1869518. | 2616916. | 535933. | 3002008. | 3152848. | 150840. |
| 1970 | 2112790. | 3268433. | 537415. | 3320331. | 3805847. | 485517. |
| 1971 | 1268820. | 1395687. | 240217. | 1584498. | 1635904. | 51406. |
| 1972 | 1751740. | 2552581. | 442686. | 2682755. | 2995266. | 312511. |
| 1973 | 1956129. | 2798703. | 608073. | 3284719. | 3406776. | 122058. |
| 1974 | 1639329. | 2056541. | 436001. | 2486017. | 2492542. | 6525. |
| 1975 | 1207036. | 1547249. | 206968. | 1503452. | 1754217. | 250765. |
| 1976 | 448429. | 264511. | 48429. | 378544. | 312941. | -65603. |
| 1977 | 1955205. | 2406870. | 574048. | 3100962. | 2980917. | -120045. |
| 1978 | 1727802. | 1964045. | 523576. | 2734480. | 2487621. | -246858. |
| 1979 | 1835731. | 2839179. | 505636. | 2965064. | 3344815. | 379751. |
| 1980 | 802459. | 928812. | 123062. | 918087. | 1051874. | 133788. |
| 1981 | 1943124. | 2721471. | 485676. | 2948712. | 3207147. | 258435. |
| 1982 | 2246512. | 3574818. | 633379. | 3701367. | 4208197. | 506830. |
| 1983 | 3103573. | 5476615. | 1258737. | 6121612. | 6735352. | 613740. |
| 1984 | 2192989. | 2547749. | 658169. | 3457926. | 3205918. | -252008. |
| AVERAGE | 1543543. | 2023080. | 388954. | 2290038. | 2412034. | 121996. |

Yampa River Average Annual Volume 1,115,136 AF

Little Snake Average Annual Volume 428,406 AF with base flows of 98 cfs for the Little Snake and 297 cfs for the Yampa into the same sediment budget program which produced the historical data in Table 4. The summary results are shown in Table 5 and all the results are presented in Appendix B.

The exceedance hydrographs for each tributary are evaluated one at time with the prescribed base flow (base flow or exceedance discharge whichever is greater is used for that daily discharge) and these constitute the minimum streamflow hydrograph in this analysis. A comparison is made between the minimum streamflow hydrograph and the historic discharge on a daily basis for each year on record and the smaller value is used in the analysis. This comparison is made for the discharge at Mathers Hole (the combined flow for the Little Snake and Yampa Rivers). The sediment load predictions are then performed based on the final discharge values at Maybell, Lily, and Mathers Hole.

The sediment budget array in Table 5 demonstrates that a sediment balance or equilibrium in the canyon will only be maintained if the streamflows in each tributary are reduced by equal proportions. This table also shows that if the Little Snake River flow remains essentially undepleted, the flows in the Yampa should not be reduced if the sediment equilibrium is to be maintained. Within the range of error in the measurements and the error introduced in this analysis some minor depletion of the Yampa River as discussed later would not adversely effect the system.

To progress further with the sediment budget analysis, the NPS minimum streamflow hydrograph (O'Brien, 1984) is tested assuming that the flows in the Little Snake River are depleted according to criteria derived from Table 4 of the USFWS Stagecoach Biological Opinion (1986). This criteria postulates monthly target flows for wet, dry and average years and results in a minor depletion of the average annual volume of the Little Snake of 29,000 AF (6 percent). The concepts of a dry or drought year and a wet year in the hydrologic record of a given river is subject to interpretation. To quantify these delineations for application of the FWS flow targets for the Little Snake, the annual volume for the period of record was statistically analyzed for the combined flows of the Yampa and Little Snake Rivers. Based on the statistics, flows were divided into three categories using one-half the standard deviation to identify wet, average and dry years:

| | |
|---|---|
| Wet Years (18) | > 1,800,000 AF |
| Average Years (25) | 1,300,000 AF < Volume < 1,800,000 AF |
| Dry Years (21) | < 1,300,000 AF |

After the minor depletions are subtracted from the Little Snake historic flows, a comparison of the NPS minimum streamflow (with an alternative 340 cfs base flow) and historic flow is made on a daily basis and whichever discharge is less is assigned as the minimum hydrograph for Mathers Hole. If this Mathers Hole minimum hydrograph is less than the historic hydrograph, the difference is charged as a depletion from the Yampa river at Maybell, subject to a 297 cfs base flow at Maybell.

Table 5. Exceedance Hydrograph* Array of Water Volume (AF) and Sediment Budget.

| | | | | Annual Flow Volumes (AF) Little Snake Exceedance Flows | | | | |
|---|---|---|---|---|---|---|---|---|
| Yampa Exceedance Flows | | Percent Probability | Historic Flows | 50 | 75 | 84 | 90 | 95 |
| Percent Probability | Volume (AF) | | 428406 | 299723 | 219895 | 182159 | 157997 | 122284 |
| 50 | 853349 | | 1281756 | 1153072 | 1073244 | 1035508 | 1011347 | 975633 |
| 75 | 679646 | | 1108052 | 979369 | 899541 | 861805 | 837643 | 801930 |
| 84 | 586555 | | 1014962 | 886278 | 806451 | 768715 | 744553 | 708839 |
| 90 | 510186 | | 938593 | 804409 | 730081 | 692345 | 688183 | 632470 |
| 95 | 414443 | | 842849 | 714166 | 634338 | 596602 | 572440 | 536727 |
| | | | | Sediment Budget (tons) | | | | |
| 50 | 853349 | | 524899 | -37231 | -323875 | -437755 | -504844 | -593580 |
| 75 | 679646 | | 782856 | 202697 | -97407 | -217214 | -287918 | -381647 |
| 84 | 586555 | | 917005 | 328178 | 20669 | -102928 | -175906 | -272916 |
| 90 | 510186 | | 1028063 | 432320 | 118434 | -8496 | -83635 | -183919 |
| 95 | 414443 | | 1165565 | 561049 | 238961 | 107556 | 29472 | -75913 |

*Discharge equals or exceeds this hydrograph of daily discharges a given percentage of time. The historic hydrograph or the exceedance discharge whichever is less is used in this analysis, together with the base flows prescribed in Appendix A.

Table 6 shows the impacts of so reducing flows in the Yampa River on the sediment balance in the Yampa Canyon. The initial trial indicates that the sediment budget is excellent employing the historic flows of the Yampa and the slight depletions from the Little Snake. The remainder of the tests employ the NPS minimum streamflow hydrograph or an altered form of it for the daily discharges. In all cases, the reductions in daily flow are considered as depletions from the Yampa River. The second test in Table 6 with the NPS minimum streamflow hydrograph represents a storage of sediment in the canyon of approximately 38 percent of the sediment load predicted at Mathers Hole.

To restore some of the sediment balance to the analysis where the NPS minimum streamflow is used, flows greater than 95 percent of actual peak for each year of record are added to the hydrograph. These higher flows are added to the hydrograph by increasing only the Yampa River (Maybell) discharge. Subsequent tests (5-7) are performed adding more of the peak flows until flows greater than 50 percent of peak flow for that year are included in the hydrograph. This results in a sediment budget in which the sediment storage in the canyon is only 9 percent of the sediment load at Mathers. Adding peak flow days to the minimum streamflow hydrograph has the advantage of keeping the cobble bed mobile with bankfull discharges. This physical process is important to keeping the channel morphology active and the cobble bed conditions ideal for Colorado squawfish spawning (O'Brien, 1984).

Table 7 is similar in concept to Table 6 except that the minimum streamflow hydrograph is altered to attempt to deplete additional water from the Yampa and still maintain the sediment balance. This is accomplished by decreasing the minimum streamflow hydrograph on the rising and recession limbs and increasing the number of peak flow days. All the computer runs involving flow reductions in the Yampa are displayed in Appendix C. In these tests, minimum base flow for the Yampa at Maybell is 297 cfs or the historic flow, whichever is less. The minimum streamflow hydrographs for the runs in Table 7 are presented and compared with the NPS minimum streamflow hydrograph in Table 8. These depletions from the Yampa River are made when the historical water discharge has been above the minimum streamflow and peak flow criteria. No assumptions are made on how the water may be allocated or at what rate it may be consumptively used.

The minimum streamflow hydrograph is reduced in runs 1 through 3 in Table 7 while the peak flow criteria is reduced from 50 percent to 35 percent increasing the number of high flow days (and discharge) in the analysis. In the remaining runs 4 through 7, only the peak flow criteria is changed from 35 percent to 20 percent. Increasing the number of peak flow days results in a computed hydrograph that is closer to the historic flow condition. When the peak flow criteria is 35 percent or less, reducing the minimum streamflow hydrograph has little effect on the amount of flow depletion from the Yampa or the sediment budget. Increasing the number of high flow days with discharges in excess of 35 percent of the peak flow has the result of negating most of the minimum streamflow hydrograph. Enough high flow days are incorporated in the analysis to override the minimum streamflow criteria greater than 1260 cfs. The same minimum streamflow hydrograph is used for runs 4 through 7 in Table 7.

Table 6. Effects of Flow Reduction on the Sediment Budget in Yampa Canyon.

Little Snake Average Annual Flow, 399,000 AF
(6 percent reduction of Historic Flows)

| Yampa River Flows | Flow Available for Depletion in Yampa (AF) | Sediment Storage (Percentage of Sediment Load at Mathers Hole) |
|---|---|---|
| 1) Historic Flows, 1,120,000 AF | 0 | 1.1% |
| 2) NPS Minimum Streamflow Hydrograph, 774,000 AF | 346,000 | 38.0% |
| 3) NPS Minimum Streamflow Hydrograph Plus Historic Flows >95% of Peak Flows, 816,000 AF | 300,000 | 27.0% |
| 4) NPS Minimum Streamflow Hydrograph Plus Historic Flows >90% of Peak Flows, 833,000 AF | 282,000 | 24.0% |
| 5) NPS Minimum Streamflow Hydrograph Plus Historic Flows >75% of Peak Flows, 885,000 AF | 230,000 | 17.0% |
| 6) NPS Minimum Streamflow Hydrograph Plus Historic Flows >50% of Peak Flows, 963,000 AF | 152,000 | 9.0% |

Table 7. Effects of Flow Reduction on Sediment Budget in the Yampa Canyon using a Reduced Minimum Streamflow Hydrograph.

Little Snake Average Annual Flow, 399,000 AF

| Yampa River Flows | Flow Available for Depletion in Yampa (AF) | Sediment Storage (Percentage of Sediment Load at Mathers Hole) |
|---|---|---|
| 1) Q>50% of Peak Flows Plus Reduced MSH, 943,000 AF | 172,000 | 11.0% |
| 2) Q>45% of Peak Flows Reduced MSH, 948,000 AF | 168,000 | 10.5% |
| 3) Q>40% of Peak Flows Reduced MSH, 955,000 AF | 160,138 | 9.9% |
| 4) Q>35% of Peak Flows Reduced MSH, 967,000 AF | 148,000 | 8.9% |
| 5) Q>30% of Peak Flows Reduced MSH, 993,000 AF | 123,000 | 7.1% |
| 6) Q>25% of Peak Flows Reduced MSH, 1,017,000 AF | 98,000 | 5.5% |
| 7) Q>20% of Peak Flows Reduced MSH, 1,039,000 AF | 77,000 | 4.3% |

* MSH, minimum streamflow hydrograph

Table 8. NPS Minimum Stream Flow Hydrograph Compared with Those Applied in Table 7

| | | NPS | Run 1 | Run 2 | Run 3 | Runs 4-7 |
|---|---|---|---|---|---|---|
| Aug 16 | Mar 21 | 367 | 340 | 340 | 340 | 340 |
| Mar 22 | Mar 28 | 1,500 | 340 | 340 | 340 | 340 |
| Mar 29 | Mar 31 | 2,000 | 340 | 340 | 340 | 340 |
| April 1 | April 11 | 2,000 | 1,000 | 750 | 750 | 750 |
| April 12 | April 18 | 2,000 | 1,000 | 1,000 | 1,000 | 1,000 |
| April 19 | April 25 | 4,000 | 2,000 | 2,000 | 2,000 | 2,000 |
| April 26 | May 2 | 5,000 | 4,000 | 4,000 | 4,000 | 3,000 |
| May 3 | May 9 | 5,000 | 5,000 | 5,000 | 5,000 | 5,000 |
| May 10 | May 23 | 8,500 | 7,500 | 7,500 | 7,500 | 7,500 |
| May 24 | June 6 | 11,500 | 11,500 | 11,500 | 11,500 | 11,500 |
| June 7 | June 13 | 11,500 | 11,500 | 11,500 | 7,500 | 9,000 |
| June 14 | June 20 | 11,500 | 11,500 | 7,500 | 3,500 | 5,000 |
| June 21 | June 27 | 9,000 | 9,000 | 5,000 | 3,500 | 2,500 |
| June 28 | June 30 | 6,500 | 6,500 | 5,000 | 3,500 | 2,500 |
| July 1 | July 4 | 6,500 | 1,260 | 1,260 | 1,260 | 1,260 |
| July 5 | July 11 | 3,500 | 1,260 | 1,260 | 1,260 | 1,260 |
| July 12 | July 18 | 700 | 1,260 | 1,260 | 1,260 | 1,260 |
| July 18 | July 31 | 700 | 1,260 | 1,260 | 1,260 | 1,260 |
| Aug 1 | Aug 15 | 700 | 340 | 340 | 340 | 340 |

When the minimum streamflow hydrograph criteria is combined with discharges in excess of 20 percent of the peak flow for that year, a sediment balance results that exceeds the sediment load that could be transported at Mathers Hole by only 4 percent. The average annual depletion from the Yampa (Maybell) is 77,000 AF for this run. Within the accuracy of this analysis it would probably be feasible to deplete up to 100,000 AF from the Yampa River on an average annual basis. Larger depletions from the Yampa without equivalent depletions from the Little Snake would probably result in some sediment storage in the canyon over the long term. It should be noted that including a percentage of the peak flows in the minimum streamflow hydrograph is sufficient for this type of analysis of historical flows, but would not be easily administered for future water resource management. An acceptable method would be to identify the upcoming wet, dry or average year and assign a peak flow condition that would replicate the forementioned flow criteria.

## CONCLUSIONS

The Yampa River channel in Dinosaur National Monument exists in a tenuous morphological balance between the bed material, channel slope and the water discharge and sediment it conveys. This equilibrium exists because the large sediment load carried by the Little Snake is assisted in transport through the canyon by the larger discharges flowing in the Yampa River. The steep slope is the key physical attribute which insures sediment transport in the canyon under historic flow conditions. Reductions in the streamflow as a consequence of water regulation with upstream water management, storage or diversion will have an impact on the riverine environment in the Yampa Canyon. From the results presented in this study, sediment storage will occur in the Yampa Canyon if the average annual depletion from the Yampa River exceeds 100,000 AF while the Little Snake remains essentially undiminished. The effect of this storage may limit the viability of critical habitat of the endangered fish species which use the cobble bed reaches of the canyon for spawning.

This report clearly demonstrates concepts that previously had only been inferred. The sediment load investigation reveals some of the consequences and long term impacts of flow depletion from the Little Snake and Yampa Rivers. To definitively address site specific impacts would require a complete water and sediment routing investigation of each reach. The Yampa River has adjusted to basin conditions to be able to transport the sediment yield from the watershed. Both too little and too much sediment load in the canyon is construed as a negative impact when it varies from historic conditions.

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