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RECOMMENDATION AND EVALUATION OF A MITIGATIVE FLUSHING FLOW REGIME BELOW A HIGH MOUNTAIN DIVERSION

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ABSTRACT: The recommendation of flushing flows as part of an overall instream flow regime is becoming more common below water development projects in the western United States. Typically, objectives of these high magnitude, short duration releases are to maintain channel capacity and fish habitat quality by preventing riparian encroachment and flushing accumulated fine sediments from the streambed. While several methods have been developed for estimating flushing requirements, little evaluation has taken place regarding the effectiveness of implemented releases. Water development-related construction activity in the headwaters of south-central Wyoming's Little Snake River during mid-1984 resulted in substantial deposition of fine and coarse sediment in the stream channel. Given the potential for severe embeddedness of Colorado cutthroat trout habitat, our study was conducted to 1) quantify the amount and composition of deposition; 2) monitor quantitative and qualitative changes in the deposition in response to varying hydrologic, hydraulic and sediment transport characteristics; 3) recommend a flushing flow regime to mitigate the sediment spill; and 4) evaluate the effectiveness of the recommended regime. Flushing flow releases were somewhat successful in meeting management objectives. Preliminary discussion of a new method for flushing flow analysis, termed "sediment transport input-output modelling", is also presented.
KEY TERMS: Flushing flow, sediment transport, instream flow, fish habitat.

INTRODUCTION

Alteration of stream flow regime and sediment loading from water development activities can result in both short- and long-term changes in channel morphology and conveyance capacity. Subsequently, the condition of the aquatic habitat can be affected. In recent years, much research and development effort has been directed toward the determination of suitable instream flows to maintain fisheries habitat in regulated streams (Stalnaker and Arnette, 1976; Wesche and Rechard, 1980). However, there are several facets of the instream flow problem which have not been adequately investigated, one involving the recommendation of flushing flows to simulate the peak runoff hydrograph characteristics of most unregulated streams (Reiser et al., 1985).

Limited research has been conducted to develop methodology for determining the magnitude, timing, and duration of flushing flows needed to maintain channel integrity

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and associated habitat characteristics through the movement of sediment deposits. Of the 15 methodologies identified by Reiser et al. (1985), a majority were not designed specifically to assess flushing flows, but rather were approaches for studying sediment transport problems. The several formal methodologies currently available (Wesche et al., 1977; Environmental Research and Technology, Inc., 1980; Rosgen, 1982) were developed in response to immediate management needs and are relatively untested in terms of accuracy and reliability.

During 1984, the Wyoming Water Research Center initiated a research project entitled, "Development of methodology to determine flushing flow requirements for channel maintenance purposes." Objectives of this project are to 1) document the rate of change of various channel characteristics resulting from aggradation/degradation processes under altered flow regimes; 2) quantify the physical and hydraulic properties needed to transport deposited sediment through natural channels; 3) test the predictive capabilities of existing sediment transport models against field data; and 4) develop methodology to predict conditions of flow needed to flush sediments to maintain given streams in prescribed hydraulic, physical and biologic conditions.

One stream selected for study in response to these objectives was the North Fork of the Little Snake River (North Fork), a steep, rough, regulated, headwater stream. Wesche et al. (1977) recommended both maintenance and flushing flow regimes for the North Fork in light of the proposed expansion of water diversion facilities in the drainage by the City of Cheyenne, Wyoming, as part of their Stage II water development program. Construction of Stage II began in 1983. During the late summer of 1984, intense rainfall in the construction area resulted in the deposition of a broad size range of sediments in that section of the North Fork where flushing recommendations had been made. At the request of the Wyoming Game and Fish Department and in cooperation with the United States Department of Agriculture Forest Service, the authors initiated a study of the North Fork. The objectives of this paper are to describe 1) the methods used to assess the extent of the 1984 sediment deposits; 2) the response of the deposited sediment to the 1985 spring runoff flow regime; 3) the mitigative flushing flow regime recommended for 1986; and 4) the effectiveness of the 1986 flushing flow recommendation.

DESCRIPTION OF STUDY AREA

The North Fork of the Little Snake River is a steep, rough, regulated tributary of the Little Snake River located in the Green River sub-basin of the Colorado River basin in southwest and southcentral Wyoming (Figure 1). The headwaters of the North Fork rise on the west slope of the Continental Divide at an elevation of 10,000 feet (ft) above mean sea level (msl) and flow southwesterly 12 miles to the confluence with the Little Snake River at an elevation of 7,000 ft. Average gradient is 4.6 percent. A United States Geological Survey (U.S.G.S.) streamflow gaging station (#09251800) located 1.5 miles below the study area was in operation from 1957 to 1965 and recorded a maximum discharge of 515 cubic feet per second (cfs) on June 7, 1957. Average discharge over the period of record was 26 cfs. Prior to initial water diversion in the mid-1960's, the North Fork hydrograph was typical of unregulated mountain streams in the central Rocky Mountain Region, with the majority of runoff occurring in the May to late-June period, as a result of the melting snowpack.

The North Fork and its tributaries support the largest known, essentially-pure, naturally-reproducing endemic population of Colorado River cutthroat trout (Salmo clarki pleuriticus Cope) (Binns, 1977). For this reason, management of the population is a high priority for the Wyoming Game and Fish Department.

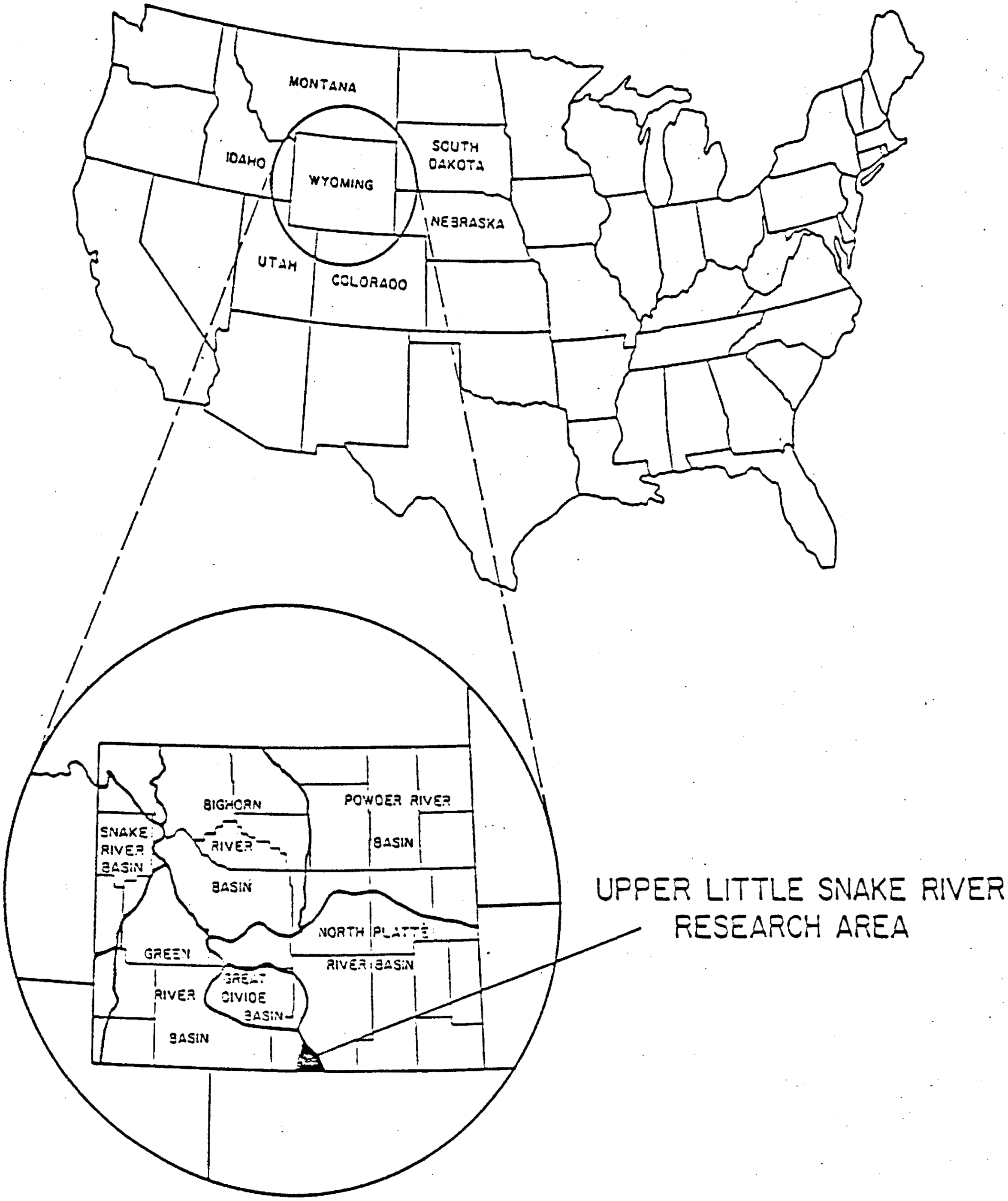


Figure. 1. Location of the Upper Little Snake River Research Area.

Transbasin diversion of water from the North Fork drainage has occurred since 1964 when the City of Cheyenne, Wyoming completed Stage I of its water development program. Approximately 8,000 acre-feet per year have been diverted (Banner Associates, Inc., 1976). During 1983, construction began on Stage II collection facilities. When completed, a total of 23,000 acre-feet per year will be conveyed from the upper Little Snake drainage to the east slope of the Continental Divide (U.S.D.A., Forest Service, 1981).

The study area on the North Fork is located in Section 27, Township 13 North, Range 85 West at an elevation of 8,580 ft, within the boundaries of Medicine Bow National Forest, 1.5 miles below the diversion structure. Within the study area boundary, a stream section 0.3 miles in length, construction of a bridge and pipeline crossing was underway in the late summer of 1984 when heavy rains precipitated the sediment spill that led to the initiation of this study. Gradient through this area is 4.4 percent while the predominant natural substrate is boulders and cobbles. Wesche et al. (1977) reported a mid-July 1976 water temperature range of 55 to 63° Fahrenheit, a total alkalinity range of 25 to 32 mg l^{-1}, a pH of 7.1, and clear water conditions for this section of the North Fork. Instream flow recommendations developed by Wesche et al. (1977) called for a minimum flow of 3.0 cfs or the natural flow, whichever is less, and a three-day annual release of 60 cfs for flushing purposes during the spring runoff period. This flushing recommendation was based upon field measurement of low bankfull discharge and the findings of Eustis and Hillen (1954).

METHODS

During the Fall of 1984, four reaches were selected for study in cooperation with personnel from the Wyoming Game and Fish Department and the U.S. Forest Service (Figure 2). Reach 1, the uppermost site below the diversion, was located just above the confluence of Second Creek, approximately 1,200 ft upstream from the North Fork bridge and pipeline crossing. Reach 1 served as the control above the construction area from which much of the sediment spill originated. Reaches 2, 3 and 4 were located in descending order below the North Fork crossing area and were within the zone of immediate deposition from the spill. Given the intensive nature of the sampling to be conducted, study reaches were kept short in length, with Reach 2 being the longest, 50 ft.

During the Fall of 1985, three additional study reaches were established. Reach 0, located above the diversion, was selected to represent unregulated hydrologic and hydraulic conditions, while Reaches 5 and 6 were added to monitor migration of the sediment spill downstream (Figure 2). This paper will focus on the analysis of data collected from Reaches 2, 4, 5 and 6.

Three recording streamflow gage stations were installed within the study area in 1985 to monitor the North Fork hydrograph (Figure 2). Each station consisted of a stilling well constructed from perforated plastic pipe, a Leopold and Stevens Type F water stage recorder, a steel platform on which the recorder was seated, and an outside staff gage for measuring stream stage. A rating curve for each gage station was developed following standard U.S.G.S. procedures (Buchanan and Somers, 1969).

Four equally spaced cross-channel transects were established within each study reach. Field data collected along these transects were used to quantify changes in response to the runoff hydrograph of 1) hydraulic characteristics, including discharge, channel width, top width, water depth, cross-sectional area, wetted perimeter, hydraulic radius, and mean water velocity; 2) bedload transport; 3) suspended sediment transport; 4) quantity and distribution of deposited sediments; and 5) quality of the deposited sediments.

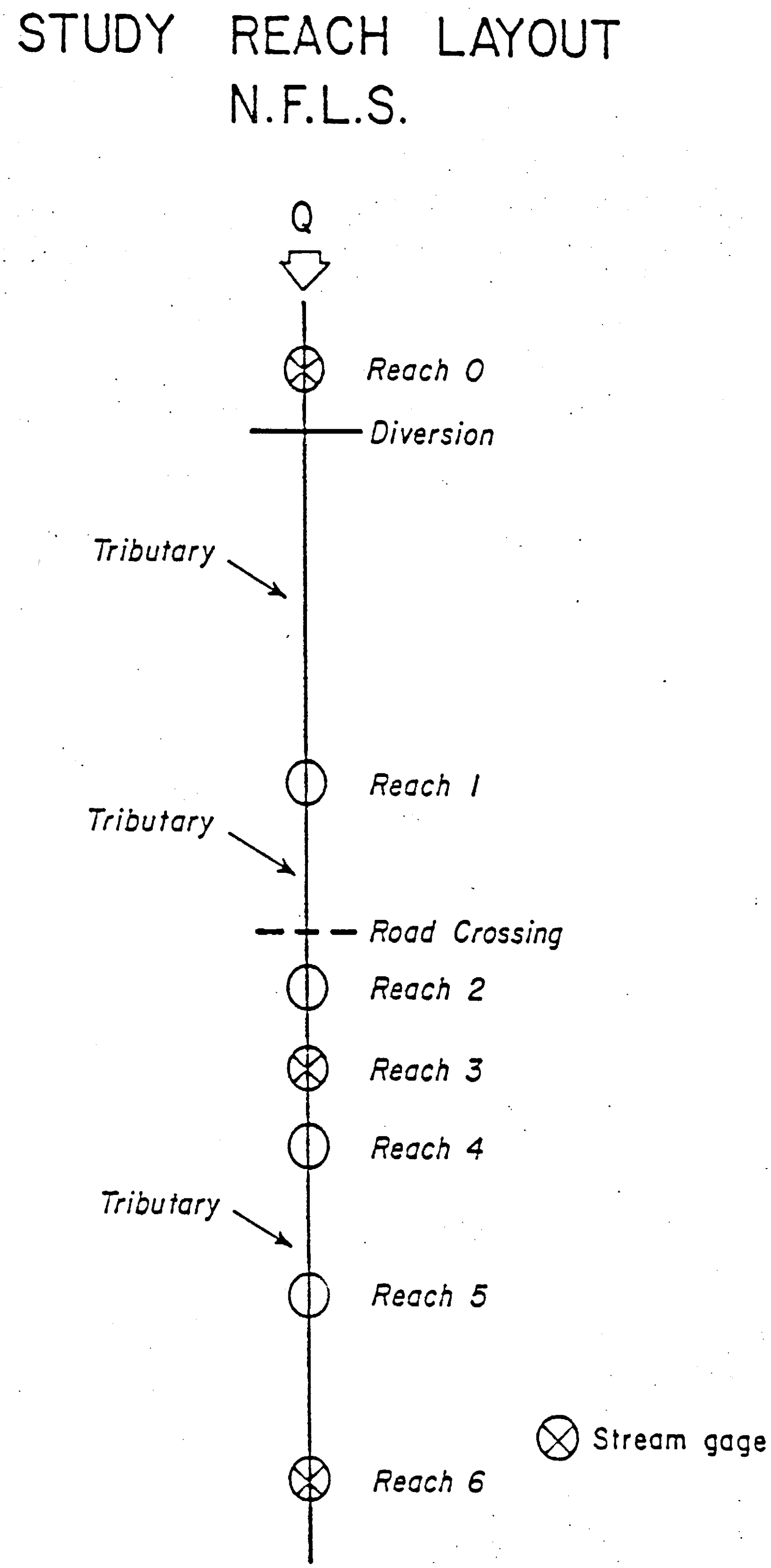


Figure. 2. Study reach layout on the North Fork of the Little Snake River.

Field sampling began in late October, 1984, was then discontinued over the winter months, and was reinitiated in early May, 1985 as spring runoff began. Sampling continued throughout the open water period. This sampling pattern was repeated during 1986 and 1987.

Suspended sediment samples were taken with a USDH-48 sampler using the Equal Transit Rate technique described by Guy and Norman (1970). Bedload transport was measured using a Helley-Smith sampler as described by Emmett (1980).

The quantity of deposited sediment within each study reach at each sampling time was determined by multiplying the volume of material by its mean density and dividing this product by the surface area. Volume was calculated as the product of mean depth of deposition (measured at approximately 80 locations within the reach using a round steel depth rod), reach length, and reach width. Mean density determinations were based upon the analysis of core samples collected from each reach using a McNeil-Ahnell sampler (McNeil and Ahnell, 1964). All cores were oven dried for at least 24 hours at 140°F to standardize weight measurements. Volume of each core was determined by water displacement.

The composition and quality of the deposited material within each reach over time was assessed by:

Collecting 12 core samples periodically at each study reach over the period of study.

Particle size distribution by weight within each core sample was determined by dry-sieve analysis at the University of Wyoming's Department of Range Management Watershed Laboratory.

The mean particle size distribution for each reach at each sampling time was determined by averaging the results from the 12 individual core samples. Distribution plots of particle size versus percentage (by weight) finer than the given sieve sizes were then developed.

Deposition quality by reach over time was then assessed by calculating the geometric mean particle size (d_g), as follows:

$$d_g = (d_1^{w_1} \times d_2^{w_2} \times \ldots d_n^{w_n}), \qquad (1)$$

where d_n is the midpoint diameter of particles retained by the nth sieve and w_n is the decimal fraction by weight of particles retained on the nth sieve (Platts et al., 1983).

RESULTS

Development of Flushing Recommendation

The sediment spill on the North Fork occurred in the late summer of 1984. As streamflow during this season was near baseflow and water storage capabilities did not exist to allow trial flushing flow releases, study of the response of the deposited material to the runoff hydrograph could not begin until the spring of 1985. Based upon the 1985 investigation, the recommended mitigative flushing flow regime would then be implemented in 1986.

A summary of selected hydraulic characteristics by study reach is presented in Figure 3. Reach 2, representative of the steep gradient, boulder strewn, riffle-cascade habitat common on the North Fork, had water surface slopes exceeding 4.0 percent. Water velocities were higher and depths shallower at Reach 2 than at other study reaches. Reach 4 was characterized by lower gradient (less than 1.0 percent), deeper water and slower velocities, and typified the pool habitat, formed by woody debris, that serves as important rearing areas for Colorado River cutthroat trout. Reaches 5 and 6 were similar in character to Reach 4. Reaches 1 and 3, not shown in Figure 3, were similar in hydraulic characteristic and represented more moderate conditions. For the purpose of mitigative flushing flow regime development, analysis has focused on Reaches 2 and 4.

Spring runoff hydrographs for 1985, 1986 and 1987 at the Reach 3 streamgage are presented in Figure 4. Also shown is the magnitude of the maintenance flushing flow recommended by Wesche et al. (1977) for the North Fork in the vicinity of Reaches 2, 3 and 4. This recommendation, 60 cfs for a duration of three days, was not intended for mitigative purposes in response to a sizeable sediment spill, but rather for routine channel flushing and maintenance under normal operating conditions.

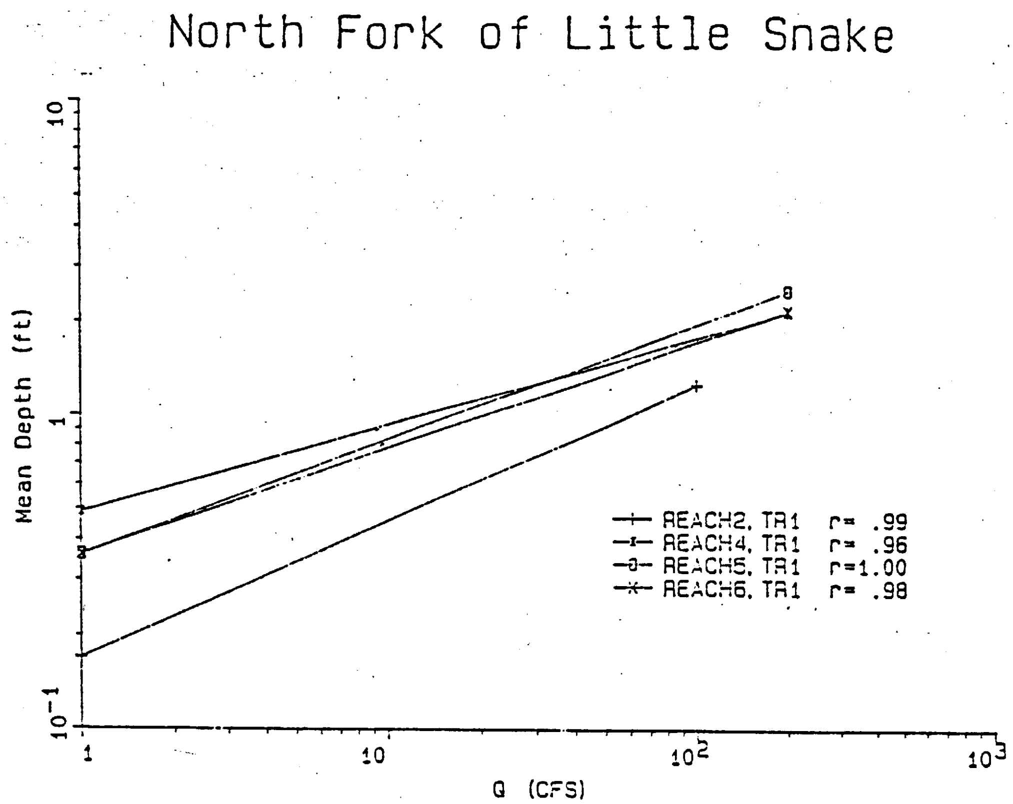
Three major runoff peaks occurred during 1985 which equalled or exceeded the magnitude and duration of the 1977 flushing flow recommendation (Figure 4). Each peak had a maximum instantaneous discharge of 105 cfs while the maximum mean daily peaks ranged from 73 to 80 cfs. Based upon maximum instantaneous discharge, the earliest peak lasted three days (May 10 to 12), the second peak extended over eight days (May 23 to 30), and the third peak exceeded the recommended discharge on five consecutive days (June 6 to 10). A fourth peak occurred in late June during which the maximum flow approached the 60 cfs level, but only for a portion of one day.

A time series plot of the quantity of deposited material within the study reaches is presented in Figure 5, while the quality of the deposition, expressed as geometric mean particle size, is plotted over time in Figure 6. Reach 4, the low gradient pool section, was found to have the greatest magnitude and variation in terms of deposition quantity as well as the lowest deposition quality throughout 1985. Based upon these results and the assumption that the maintenance of pool quantity and quality is essential to the well-being of the Colorado River cutthroat trout population in the North Fork, Reach 4 became the focus of our mitigative flushing flow regime development study.

Five factors needed to be considered in the development of the mitigative flushing flow regime for the North Fork. These included 1) the number of flushing events needed; 2) the magnitude of each event; 3) the duration of each event; 4) the desired rate of hydrograph rise; and 5) the timing of the releases. Figure 7 presents the relationship of the 1985 instantaneous hydrographs for the four runoff events to the quantity of deposited sediments in Reach 4. These results formed the basis for our 1986 recommendation.

Number of Flushing Events.--Analysis of Figure 7 indicates that the latter three flushing events were successful in reducing sediment deposition from 82 to 51 lbs per ft^2 over the period from May 21 to July 1. The first flushing event, May 10-12, resulted in the import of 50 lbs/ft^2 into Reach 4 (32 lbs/ft^2 in October, 1984; 82 lbs/ft^2 on May 15, 1985), 60 percent of which was removed by the latter three flushes.

The 1985 data indicated that three flushing events would be necessary in 1986. The first event would concentrate any additional surplus sediments from the upstream steep and moderate gradient reaches in the pools, while the second and third events would reduce the aggraded material. On the average, the latter three 1985 flushes each



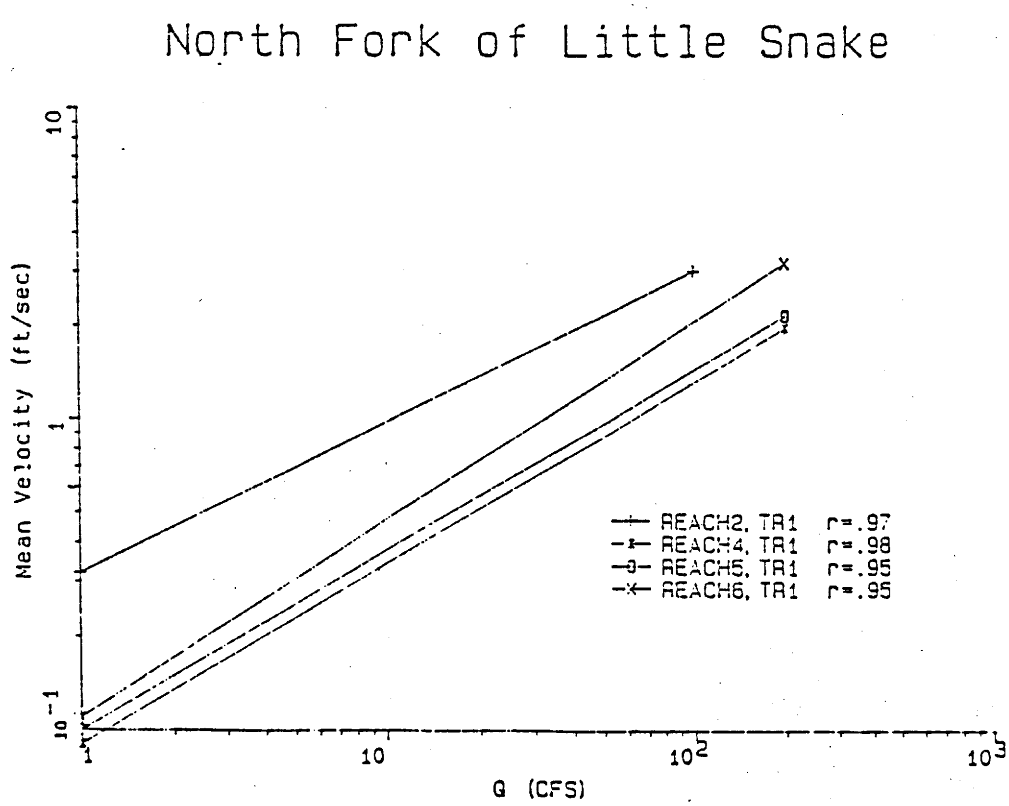


Figure. 3. Relationships of water depth and velocity with discharge at four North Fork of Little Snake study reaches.

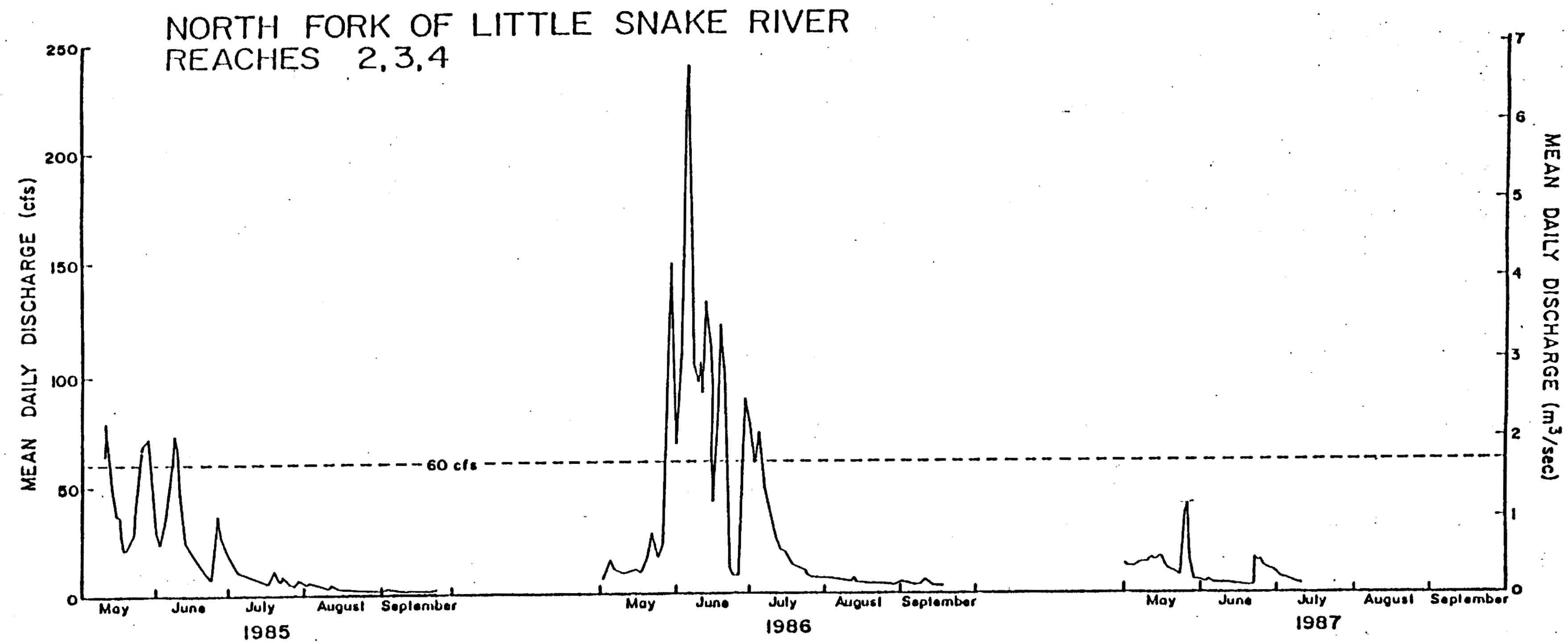


Figure. 4. Hydrographs for 1985, 1986 and 1987 at Reach 3, North Fork of Little Snake River.

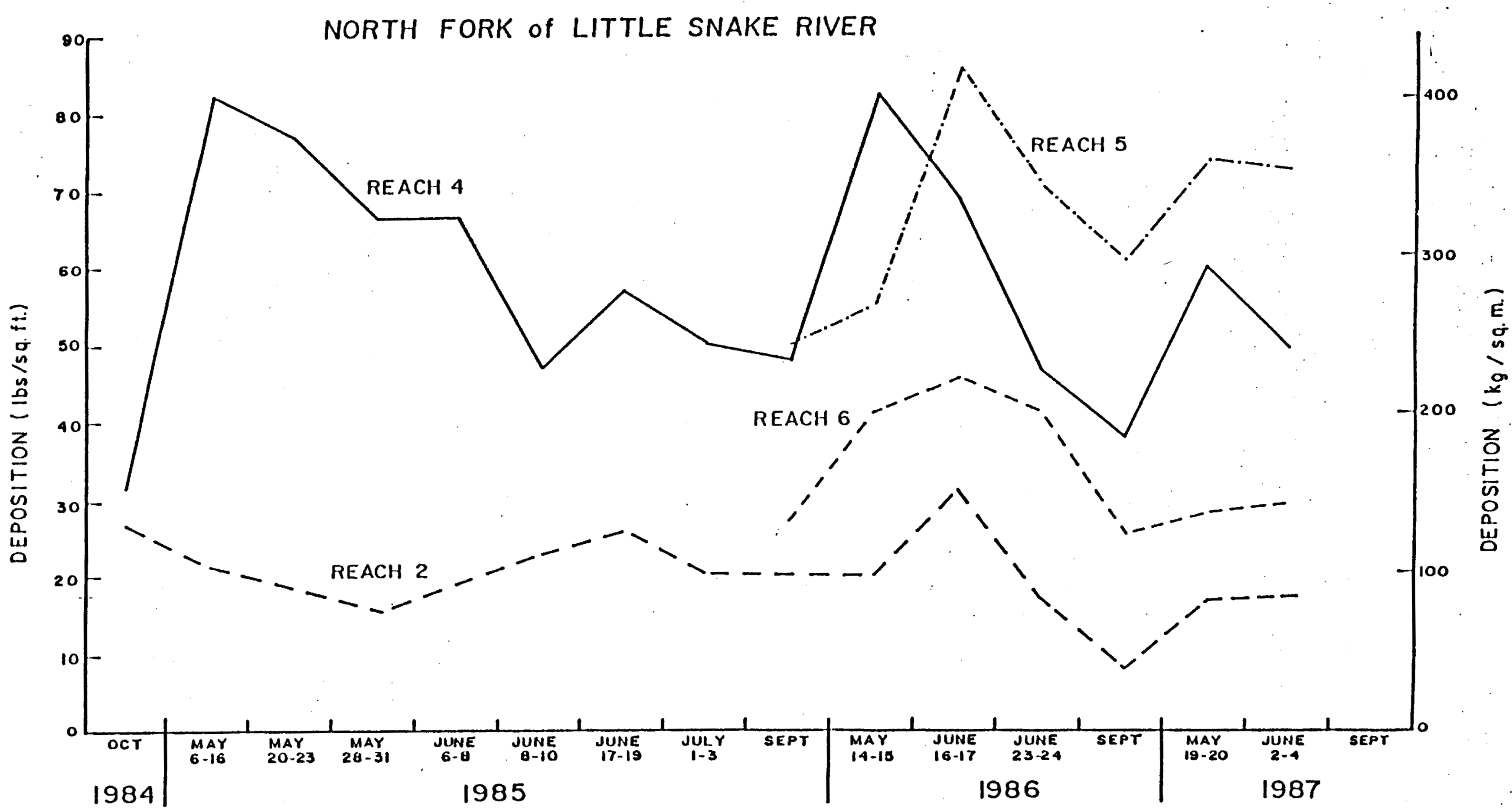


Figure. 5. Quantity of sediment deposition over time at the North Fork of Little Snake River study reaches.

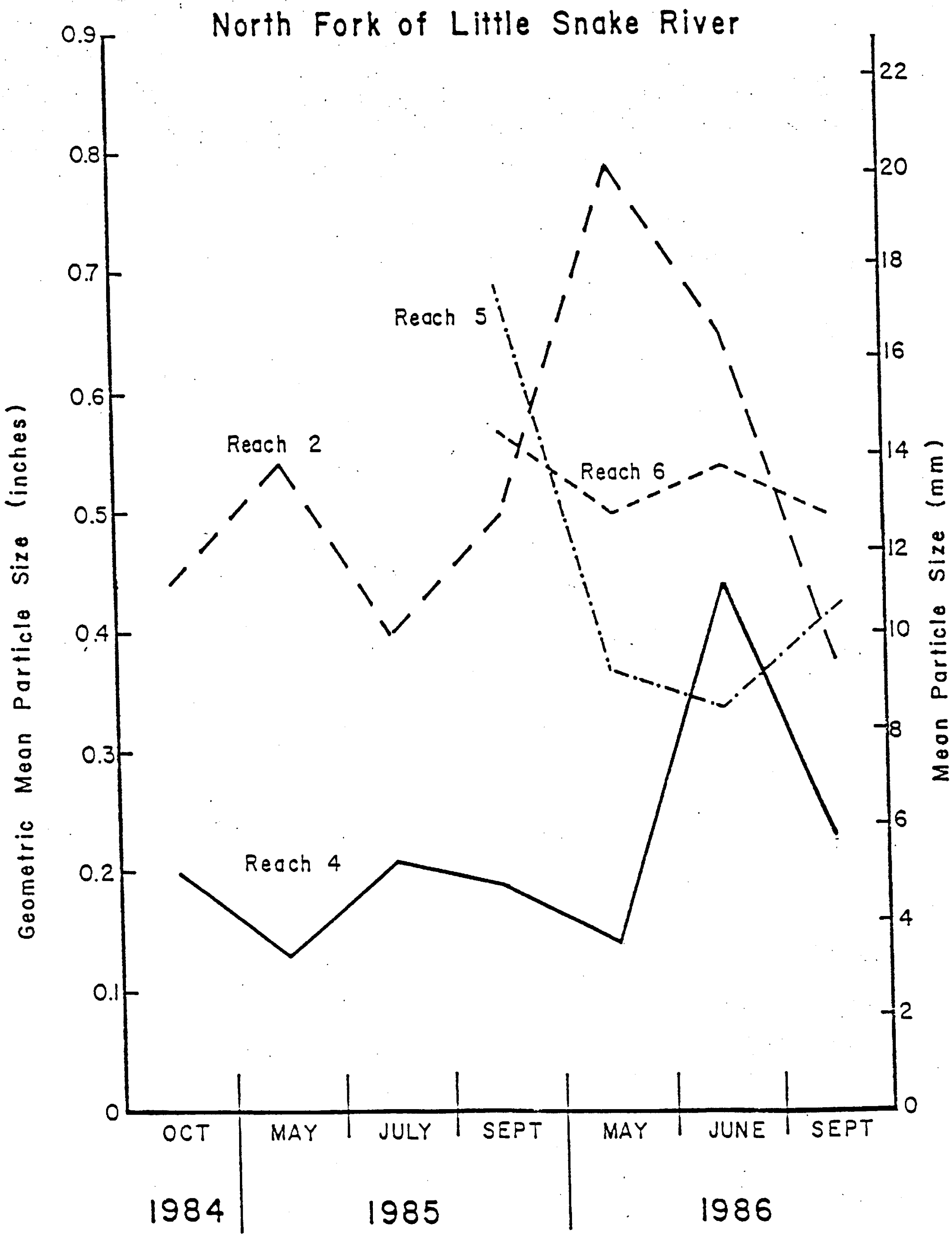


Figure 6. Quality of Deposited Sediments Over Time at the North Fork of Little Snake River Study Reaches.

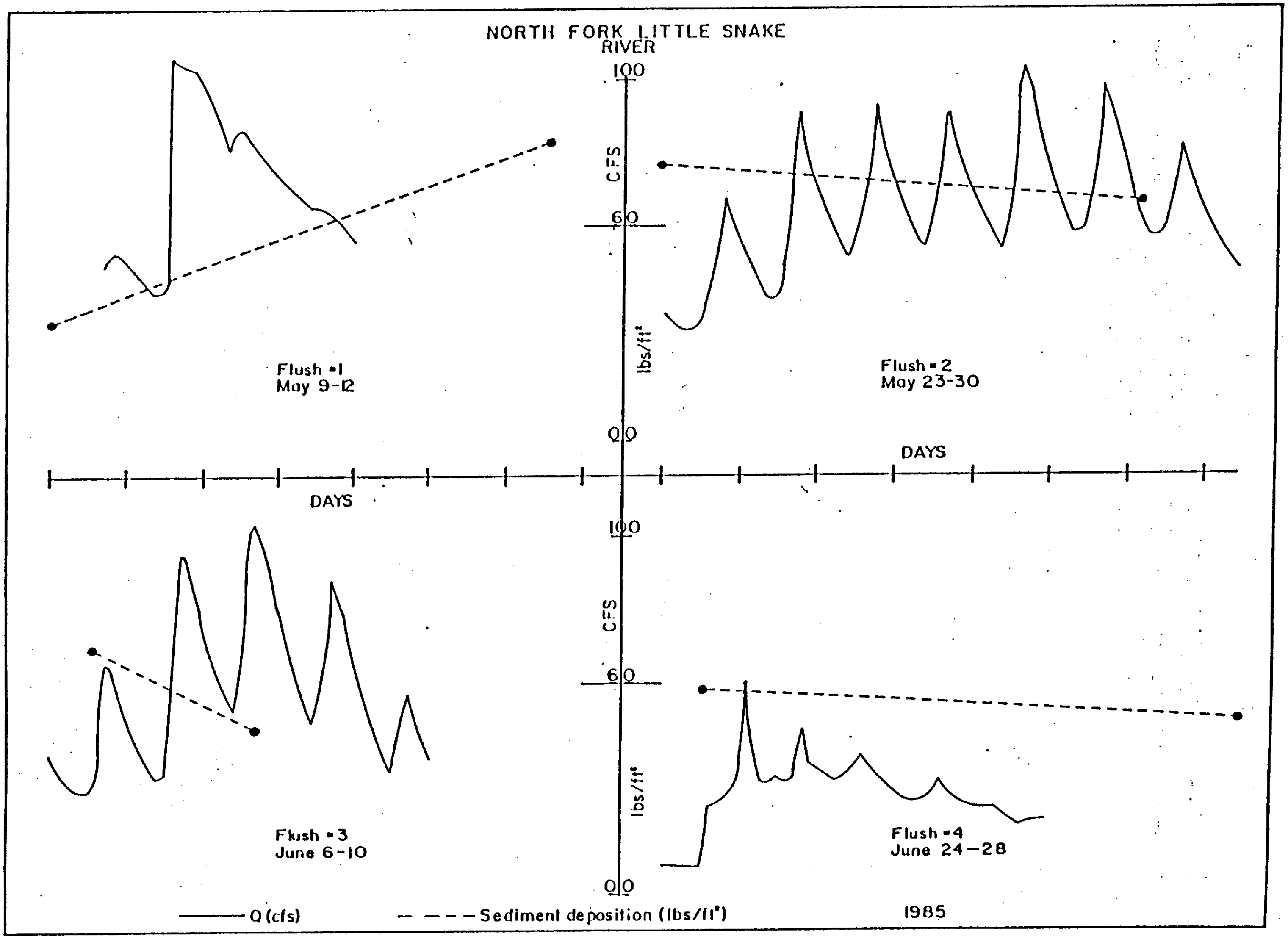


Figure 7. Relationship of the 1985 Instantaneous Hydrographs for the Four Runoff Events to Deposition Quantity at Reach 4, North Fork of Little Snake River.

removed 10 lbs/ft^2 of aggraded material. If the assumption was made that the target deposition level in Reach 4 would be approximately 30 lbs/ft^2 (the October 1984 level), and that material from the 1984 sediment spill had not reached this study section to any great extent prior to our October 1984 sampling, then the result of the latter two 1986 flushes would approach our target level.

Magnitude.--The 1985 flushing events were somewhat successful in removing deposited sediments and increasing mean grain size of bed material. The peak instantaneous flow during each of the four flushes equaled or exceeded 60 cfs, while for Flushes 1, 2 and 3, 60 cfs approximated the median flow, based upon flow duration analysis. Inspection of cross-section plots indicated that a discharge of 60 cfs covered the active low flow channel in both steep and low gradient sections, paralleling the results reported by Wesche et al. (1977), who recommended 60 cfs as the flushing flow for this portion of the North Fork. Analysis of 1985 bedload composition data indicated that the majority of the material being transported at flows greater than or equal to 60 cfs was less than 0.5 inches in diameter. Thus, we would not expect severe disruption of quality spawning gravels given flushing flows of this magnitude.

Duration.--Analysis of Figure 7 indicated that Flush #1 (three-day duration) and the first three days of Flush #3 were the most successful for moving bed material. In contrast, deposition measurements taken after six consecutive days on which peak daily flows had exceeded 60 cfs indicated that Flush #2 was not as effective. Thus, each flush was recommended for three days.

Rate of Hydrograph Rise.--Clearly, magnitude and duration of events were not the only variables determining flushing success.

Inspection of Figure 7 indicated that the flushes which moved the most bed material, #1 and #3, also had the steepest slopes on the ascending limbs of the hydrographs. Flush #1 had a rate of rise of 16.4 cfs/hour while Flush #3 rose 10.2 cfs/hour. Flush #4, the smallest event in terms of magnitude and duration, resulted in a net export of 7 lbs/ft^2 from Reach 4, only 30 percent less than that exported by Flush #2. However, the rate of hydrograph rise for #4 exceeded 13 cfs/hour for the main portion of the ascending limb compared to less than 7 cfs/hour for the steepest portions of the hydrograph for Flush #2. Thus a rate of rise of at least 10 cfs/hour was recommended.

Timing.--As water storage was not possible on the North Fork, flushing flow events had to be timed in accordance with the spring snowmelt runoff period. Inspection of the 1985 hydrograph and the discharge records from USGS gage station No. 09251800 indicated that the probability of having sufficient streamflow available for the three flushing events was greatest from mid-May to mid-June. As cutthroat spawning activity begins on the North Fork during the latter part of June (Quinlan, 1980), all flushing should be completed prior to that time to prevent egg deposition in areas soon to be dewatered.

The trend of the 1985 sediment deposition data indicated that moderate pool filling occurred between flushing events, but that the peak amount of deposition between successive non-flushing periods decreased over time. Because of this and also to attempt to coordinate flushing events with normal work week patterns, we recommended a ten-day non-flushing period between each successive flush.

To achieve the recommended rate of hydrograph rise, flushing events were to be initiated during mid-afternoon. Inspection of the 1985 instantaneous hydrographs indicated the most rapid rise in the hydrograph occurred at that time due to snowmelt runoff.

Evaluation of Flushing Recommendation

During the winter of 1985-86, negotiations were conducted between the involved parties and the mitigative flushing flow recommendations presented above were approved for implementation during the spring of 1986. Thus, we were provided the rather unique opportunity to evaluate the success (or failure) of our recommendation.

Snowpack in the North Fork watershed was well above normal during the winter of 1985-86. This, coupled with the agreement to pass all flow during the required three flushing periods, resulted in flushing releases well in excess of the required 60 cfs. As shown in Figure 4, peak mean daily discharges approached 250 cfs. Due to needed maintenance on the diversion system, additional flushes were also released in late June and early July.

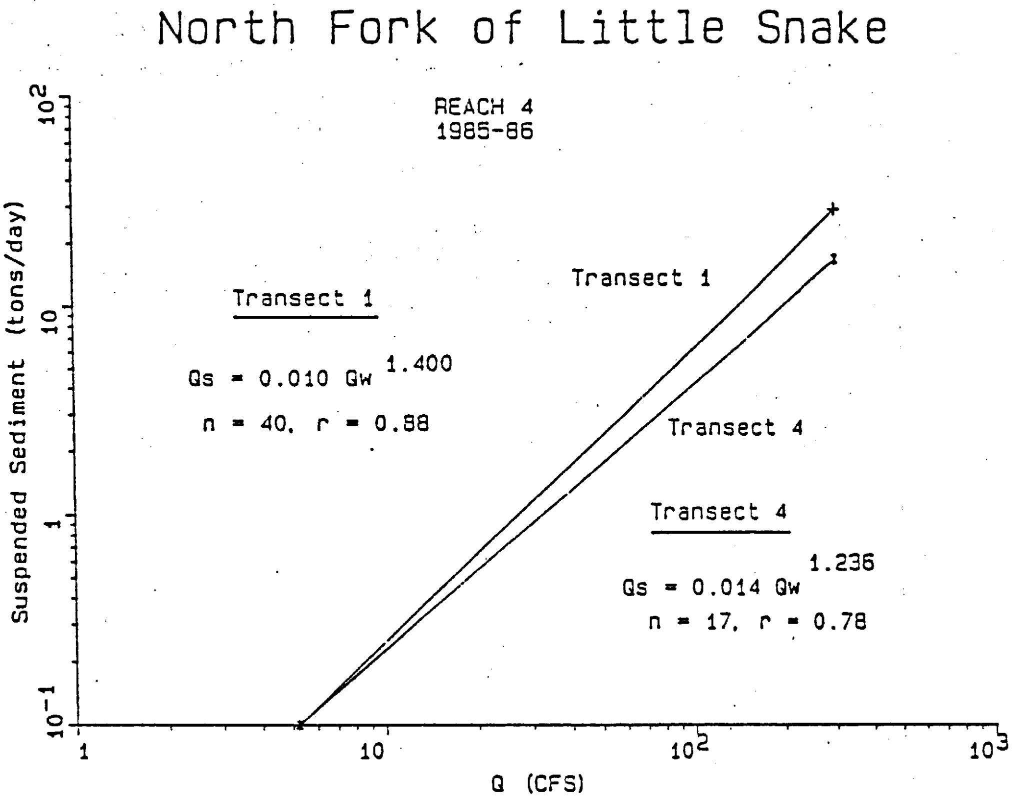
While excess water was available for release in 1986, additional sediment deposition had occurred in Reach 4 between September, 1985 and mid-May 1986 (Figure 5). Stored material increased from 48 to 82 pounds per square foot over the winter, approximately the same quantity of deposition measured in May, 1985. Also, deposition quality had declined, just as it had the previous year (Figure 6).

Overall, the flushing regime released on the North Fork during 1986 was quite successful at Reach 4 (Figures 5 and 6). Deposition quantity was reduced from 82 to 46 pounds per square foot by June 23 and to 38 pounds per square foot by September. Geometric mean particle size increased to 0.44 in. by late June, but declined by September to 0.23 in. These trends, evident at Reach 2 as well, would indicate that deposition quantity had been even further reduced by mid-July immediately following flushing releases and that fine sediments transported by lower flows had begun to redeposit. Unfortunately, no sampling was conducted between late June and September to verify this.

The migration of sediment downstream from the zone of greatest impact from the spill can be charted by comparing Reaches 4, 5 and 6 on Figures 5 and 6. The first several flushing cycles of 1986 moved material from Reach 4 and transported much of it 900 feet downstream to Reach 5. Reach 6, located approximately 3,000 feet below Reach 5, also showed increasing sediment storage through the first three flushes, but not of the magnitude observed at Reach 5. Deposition quality remained stable at Reach 6, indicating little deposition of the finer fractions being transported.

Therefore our analysis of the North Fork database has been limited primarily to gross comparisons of deposition quantity and quality both spatially and temporally. Over the next 12 to 24 months, analysis will increasingly focus on the processes of sediment transport in steep, rough tributary channels such as the North Fork, the role of woody debris in controlling such processes, the testing of the several flushing flow and sediment transport models currently available, and the development of new models.

One flushing flow method we currently have begun testing can be termed a "sediment transport input-output" model. For streams such as the North Fork, where discrete critical habitat types such as debris jam pools can be readily identified, measured, and managed in terms of flushing flow requirements, such a model would require development of sediment transport-discharge relations immediately above and below the critical habitat type. The minimum flushing flow requirement would be that discharge at which sediment output from a pool exceeded sediment input. For example, suspended load and bedload transport curves for Transects 1 and 4 at Reach 4 are presented in Figure 8. Transect 4 is located at the pool entrance while Transect 1 is at the pool exit. Combining bedload and suspended load transport curves for each transect gives an estimation of total transport into and out of the pool, as shown on Figure 9. Below approximately 110 cfs,



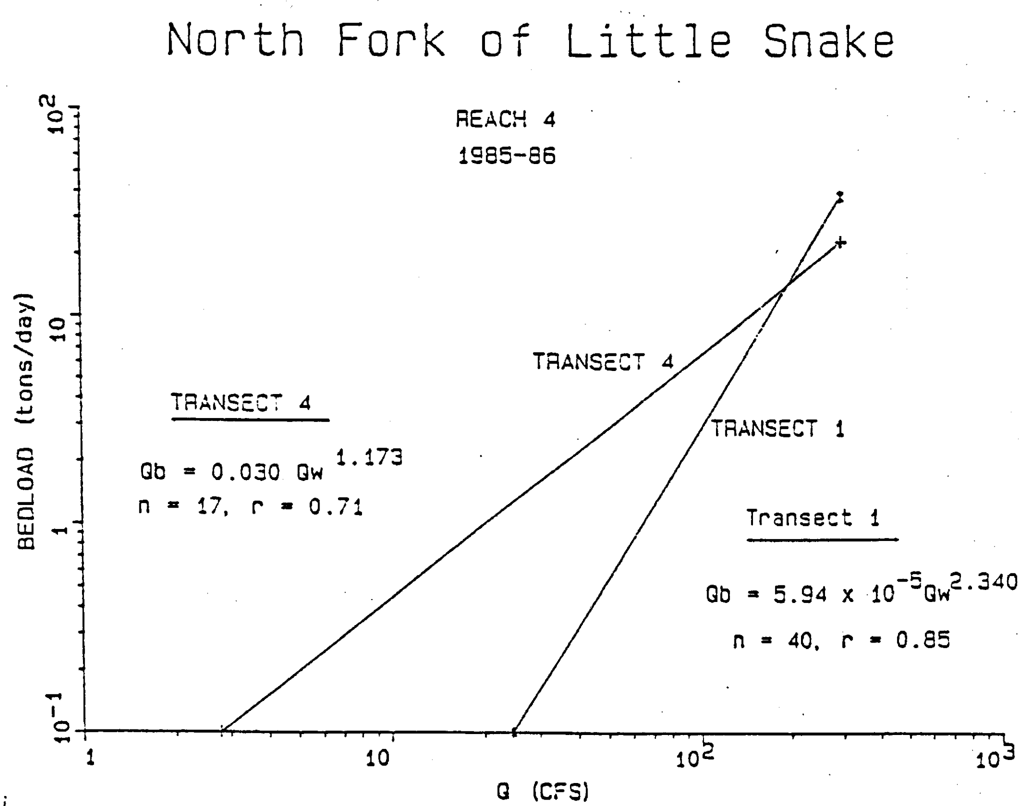


Figure. 8. Suspended and bedload transport relations at Transects 1 and 4, Reach 4, North Fork of Little Snake River.

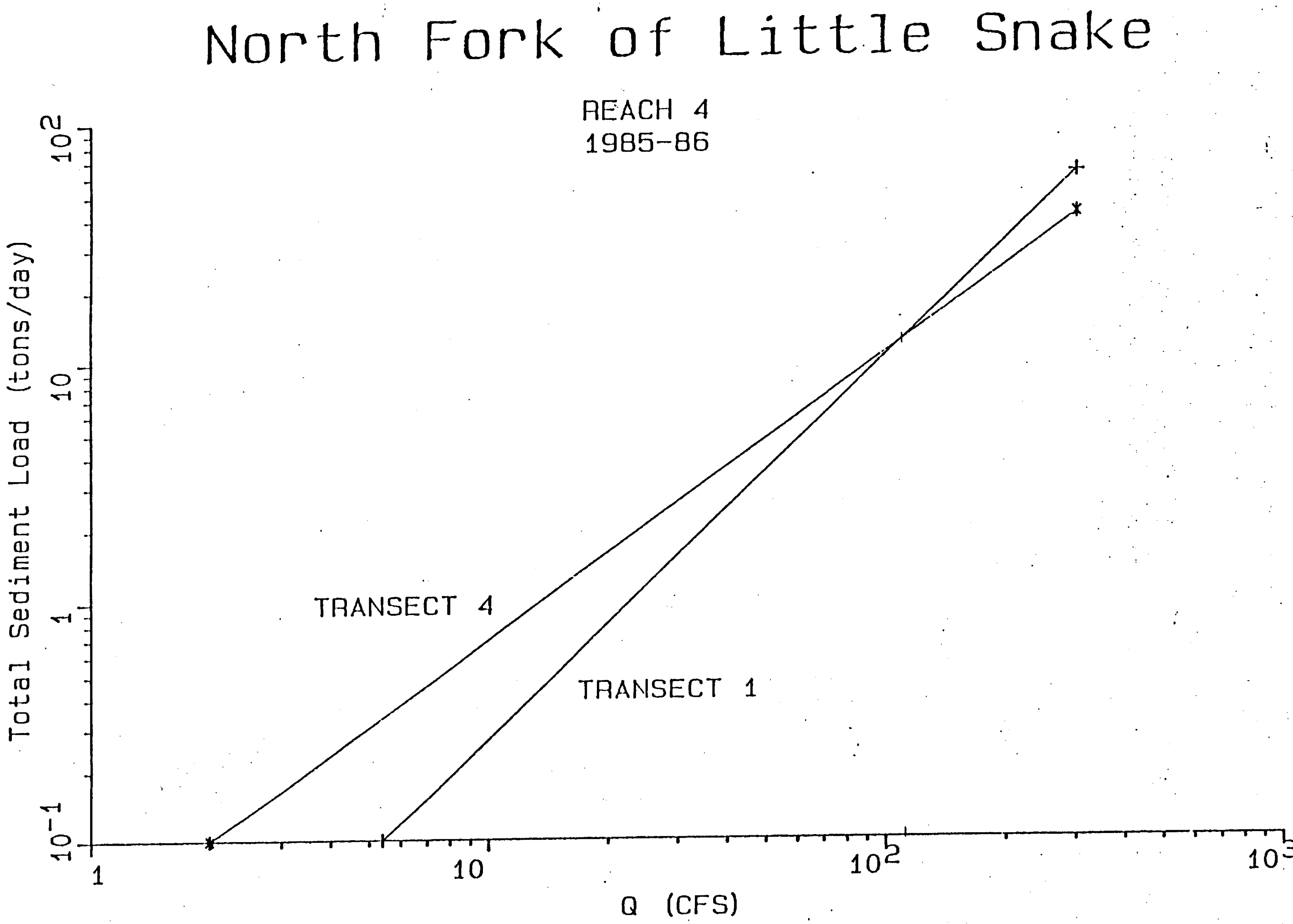


Figure 9. Total Sediment Load Transport at Transects 1 and 4, Reach 4, North Fork of Little Snake River.

the sediment load entering the pool exceeds sediment exiting and deposition occurs. Above 110 cfs, sediment transport exiting exceeds that entering and scour or flushing occurs. Knowing the "crossover" discharge defines the minimum boundary for the magnitude of the flushing flow. Combining this information with knowledge of the quantity of material to be flushed and water availability facilitates the hydrologist in the design of a flushing flow regime to achieve specific management goals.

Comparing the results of the "input-output" model to the 1986 flushing hydrograph and time-series deposition quantity plots for Reach 4 shows a remarkable degree of similarity. Between May 15 and June 22, 1986, the flushing regime removed 35,500 pounds of material from the pool, based upon deposition depth measurements. Applying the total sediment transport curves for Transects 1 and 4 to the mean daily discharges for that same period results in an estimate of approximately 34,500 pounds being transported out of the pool, a discrepancy of approximately three percent.

CONCLUSIONS

Based upon our analysis to date, the following conclusions can be drawn:

1. In the North Fork of the Little Snake River, a steep, rough, well armored tributary stream, the magnitude and variability of stored sediment is much greater in low gradient pool habitats than in high gradient riffle-cascades. This, coupled with the apparent value of such deep, slow habitats for Colorado River cutthroat trout, established such pools as critical areas for flushing flow analysis.

2. Flushing flow releases on the North Fork have been successful in reducing stored sediment in the stream reaches most directly influenced by the late 1984 sediment spill. Below this zone of greatest impact, deposition quantity decreases and quality increases in a downstream direction, indicating the effects of the spill are being moderated both temporally and spatially.

3. Given the above normal runoff of 1986 and the continued pool aggradation during the late fall, winter and early spring, a direct evaluation of the mitigative flushing flow regime recommended for the North Fork was not possible.

4. Preliminary evaluation of a sediment transport "input-output" model to determine the magnitude and duration of required flushing flow releases to meet specific management objectives was encouraging. This, as well as other flushing flow and sediment transport models, will be more thoroughly evaluated against the North Fork database in the next 12 to 24 months.

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