Authors Note: The original symposium paper contained an error which has been corrected in this version.

ADAPTIVE MANAGEMENT OF WATER RESOURCES
AWRA SUMMER SPECIALTY CONFERENCE
Missoula, Montana
June 26-28, 2006

USE OF REGRESSION AND TIME-SERIES METHODS TO ESTIMATE A SEDIMENT BUDGET FOR NEVADA CREEK RESERVOIR, MONTANA, USA

Chuck Dalby[1]

ABSTRACT: The effect of Nevada Creek Reservoir on downstream fine-sediment concentration, loads and turbidity was evaluated through measurement and modeling of inflowing and outflowing fine-sediment loads and turbidity monitoring. Located in the upper Blackfoot drainage of western Montana, Nevada Creek Reservoir is a storage project developed and operated for irrigation-water supply by Montana Department of Natural Resources and Conservation (DNRC) and Nevada Creek Water Users Association (NCWUA). Total suspended-solids concentration (TSS) was measured daily to twice daily (April-October runoff of 1999 and 2000), above and below the reservoir, using automatic pumping samplers with depth-proportional intake booms designed to minimize bias of point intake samples. The TSS dataset and suspended-sediment concentration (SSC) data, collected by the U.S. Geological Survey at the same sites, were analyzed using time-harmonic regression methods to calibrate statistically significant models relating log-transformed mean daily TSS or SSC to mean daily stream discharge and decimal time of sample. Lag-1 serial correlation of daily values of discharge and TSS was large (ρ=0.7), but an attempt to fit time-series models (e.g. transfer-function models) to the daily TSS dataset was unsuccessful. Calibration sample size was reduced to minimize ρ, and best-fit regression models were developed and used to estimate daily TSS and SSC loads at the stations. Monthly, seasonal and annual reservoir sediment budgets, for the period 1995-2004, were calculated as the difference between loads above and below the reservoir. The pattern of monthly variation in mass balance was consistent from year-to-year; November through June the reservoir mass balance was positive, with inflowing sediment stored, while in July through October (during reservoir drawdown when inflowing sediment loads are small) the mass balance was negative, with more sediment transported from the reservoir than enters. Over the 10-year period, average annual mass balance was positive, with about 60% to 90% of the inflowing load stored in average and above average water years; in low water years (e.g. 2000) annual mass balance was negative, with more sediment lost from storage than gained from spring runoff. During 1999-2000 peak spring runoff, turbidity and TSS were greater above the reservoir than below; at low flow turbidity and TSS and were slightly larger below the reservoir. Variable trap efficiency of the reservoir increases its useful life, but creates potential for excessive sediment flushing at low flow and in low-water years. Recognizing this potential, DNRC and NCWUA have established minimum reservoir pool elevation and capacity guidelines to prevent excessive reservoir sediment entrainment and resulting downstream spikes in concentrations and loads during low flow.
KEY TERMS: Reservoir; sediment budget; turbidity; regression; serial correlation; time-series.

INTRODUCTION

Nevada Creek has been identified as a contributor of suspended-sediment, metals, and nutrients to the Blackfoot River in southwestern Montana; potential sources include natural erosion, historic mining activities, grazing practices/ bank erosion, and Nevada Creek Reservoir (DTM, 2004). Currently the TMDL planning process is developing water-quality restoration strategies for impaired segments. The Montana Department of Conservation and Natural Resources, Water Resources Division (DNRC), who owns Nevada Creek Reservoir (an on-stream, irrigation-water storage project operated in cooperation with the Nevada Creek Water Users Association--NCWUA), collected fine-sediment transport data in 1999 and 2000 to evaluate the effect of Nevada Creek Reservoir on downstream turbidity, fine-sediment concentrations (total-suspended solids-TSS) and loads. Information collected at stream gaging stations, located above and below the reservoir, was analyzed using regression and time-series methods, and results were used to develop monthly, seasonal, and annual mass balances (e.g. fine-sediment budget) for the reservoir. Near-monthly to quarterly, suspended-sediment concentration (SSC) data, collected by the U.S. Geological Survey at the same stations over the time period 1980-2000 (USGS, 2005), was also analyzed to

---

[1] Hydrologist, Water Management Bureau, Montana Department of Natural Resources and Conservation, 1424 9th Ave., P.O. Box 201601, Helena, MT 59620. (email cdalby@mt.gov).

provide an independent assessment of fine-sediment loading and reservoir mass balance. Results of the investigation are summarized here; see Dalby (2006) for additional details of the investigation.

Study Area

Nevada Creek drains a humid forested watershed in southwestern Montana and is a principal headwater tributary of the Blackfoot River. Elevation ranges from about 8,280 feet to 4,240 feet near its mouth, with a mean basin elevation of 5,490 feet. Precipitation occurs mainly as snowfall, and the hydrograph is dominated by March though June snowmelt, with an early low-elevation peak in March and a later peak in May-June. Bedrock geology consists of Cretaceous and Tertiary volcanic and sedimentary rocks (60% of the basin area), Pre-Cambrian metasediments (25%), and Paleozoic sediments (4%); Quaternary alluvium and glacial deposits cover about 10% of the basin area. Nevada Creek displays both single-thread (pool-riffle) and multi-thread (anabranching) channel types, and typically has a gravel-bed channel and silty, sandy, banks. Riparian grazing practices, channel-straightening and modification, coupled with erosive bank material, have resulted in accelerated lateral migration and elevated fine-sediment production in some channel reaches (DTM, 2004).

Nevada Creek Reservoir is impounded by a 105ft. earth-fill dam completed in 1938 with an original storage capacity of 12,723 acre-feet (12,640 acre-feet active). Drainage area above the reservoir is 143 mi^2. The project is operated primarily for irrigation water storage and supplies water via two canals to approximately 5,600 acres. Current (2000) capacity is about 11,152 acre-feet, indicating a capacity loss of about 1,571 acre-feet or 12% -- about 2%/year since construction. Assuming a specific weight of reservoir sediments of 90lb/ft^3, the 62-year average rate of accumulation amounts to about 50,000 tons/year (350 T/mi^2 /year).

METHODS and DATA COLLECTION

A variety of methods are available for estimating the sediment discharge of streams (Porterfield, 1972; Cohn, 1995; Edwards and Glysson, 1999). The total sediment load of a stream consists of the sum of the suspended-sediment and bed-material discharges. Generally, fine sediment (e.g. sand, silt and clay) is transported suspended in the water column and comprises the majority of the sediment load; normally suspended load is at least 70 to 95% of the total load, even in gravel-bed channels (Leopold, 1992; Lisle, 1995; King and others, 2004). Since this investigation was concerned primarily with effects of fine sediment on physical water quality, fine-sediment concentration (and load) was measured, and bed material discharge was neither measured nor estimated.

DNRC Sediment Data

Sediment monitoring stations were established at the USGS stream gaging station above Nevada Creek Reservoir (12-335500) and the DNRC stream gaging station below the dam (76F-2000). Water samples were collected for analysis of TSS concentration and turbidity using ISCO 6700 pumping samplers installed at locations near (±50 feet) stream gages. Samples were collected with varying frequency, depending upon runoff conditions, from April (or May) through September of 1999 and 2000. Samples were collected with a twice daily frequency, during spring runoff, and once daily for the remainder of the monitoring period.

Under uniform flow conditions, and at constant sediment load, the concentration and particle-size distribution of suspended-sediment, at a given river cross-section, varies with lateral and vertical position. Laterally, sediment concentration increases toward the central core of high velocity flow in a trapezoidal channel; vertically, concentration increases with depth, and is greatest near to the bed of the channel (Vanoni, 1977). Pumping samplers collect a sample from a "fixed" intake point in the water column, and the resulting point samples are normally biased when compared with the mean concentration of sediment in the cross-section at the time of sampling. Pump sampler bias is due to several factors including, efficiency of sampler intake (especially with the sand fraction), non-isokinetic nature of intake region, and changing relative position of fixed-position intake with varying flow depth (Edwards and Glysson, 1999). To minimize these effects, each pump sampler intake was attached to a depth-proportional sampling boom, that was anchored to a fixed point near the center of the streambed, in a relatively uniform flow section (Eads and Thomas, 1983; Rand Eads, U.S. Forest Service, written communication, June 1998). Although the lateral position in the sampling cross-section was constant, use of the sample boom allowed the vertical position of the sampler orifice to maintain a relatively constant percentage of flow depth (0.60) as discharge varied. The resulting intake orifice orientation was directly downstream; downstream orientation of the intake orifice in pumping samplers provides the best efficiency for sampling fine sediments coarser than 0.062mm (Winterstein and Stefan, 1983; Edwards and Glysson, 1999). Moveable nature of the boom also discouraged collection of debris around the intake. A set of equal-width increment (EWI) calibration samples was collected to evaluate bias of sampling methodology and adjust pump samples to a mean cross-section value.

U.S. Geological Survey Sediment Data

The USGS (2005) has collected quarterly to near-monthly water-quality data, at stations above (1980-2004) and below the reservoir (1994-2000), as part of various investigations. Samples were collected using equal-width increment methods and analyzed for suspended-sediment and particle size (percent sample < 0.062mm—"sand-silt break") using standard USGS methods (Lambing and Dodge, 1993). Samples generally span the range of low and high flow conditions occurring at both sites.

Comparability of TSS and SSC Data

Due to differences in analytical methods, TSS concentrations may underestimate the true amount of suspended-sediment in a sample by as much as 25 to 34 % (Gray and others, 2000; Glysson and others, 2000). Since TSS is measured on an aliquot extracted from an agitated sample, sand-sized material may settle, and ultimately the reported concentration may be less than the actual suspended-sediment concentration. The USGS method for analyzing suspended-sediment concentration is performed on the whole sample and captures the entire suspended load (Lambing and Dodge, 1993). Concurrent samples of TSS and SS were not available for comparison. However, during the 1999-2000 sampling period, four observations of TSS and SSC were collected within a similar time interval and over a range of low to high flows; although these observations compared favorably (r^2=97%), sample size is too small to ensure comparability of TSS and SSC values. Measurements of particle size (% <0.62mm), reported for USGS suspended-sediment samples, indicate a flow-dependent trend. Samples collected at flows greater than 100cfs range from about 5 to 45% sand sized, at the station below the dam (n= 50), and 20 to 40% sand above the dam (n=60); at flows less than 100 cfs, about 20 % of the suspended-sediment load was sand-sized above the reservoir and 10% sand-sized below the reservoir. For much of the year, fine-sediments suspended in flow are largely comprised of silt and clay sized particles, however during spring runoff when most of the annual load is transported, a significant proportion may be sand sized. Therefore it is possible that TSS analytical methods may not represent true SSC for significant sediment transporting flows; it was decided to analyze the DNRC-TSS and USGS-SSC datasets separately and not to merge them into a single dataset for statistical analysis.

ESTIMATING SEDIMENT LOADS and RESERVOIR MASS BALANCE

Estimation of the amount of fine sediment (or any dissolved or suspended constituent) transported past a point in a river channel requires evaluating the load integral Eqs.(1) and (2):

$$(1)\ L \cong \int_{t_a}^{t_b} L(t)dt \quad = \quad (2)\ L \cong \int_{t_a}^{t_b} K \bullet Q(t) \bullet C(t)dt$$

where,

L = integrated load over the time interval $\{t_a, t_b\}$;

$L(t)$ = instantaneous load at time t or total load over interval represented by $\{t_a, t_b\}$;

K = unit conversion factor (0.0027 for daily values and English units Q in cfs, and C in mg/l -- or 0.00135 for twice daily values

$Q(t)$ = streamflow at time t (for instantaneous values), or mean streamflow for the period $\{t_a, t_b\}$ for twice daily values;

$C(t)$ = average cross-section concentration at time t, or for the period $\{t_a, t_b\}$ for twice daily values;

While the calculation of instantaneous load is relatively simple (e.g. load is the product of stream discharge, mean cross-section concentration, and a unit conversion factor), the estimation of an accurate integrated load over an extended time interval of varying streamflow and concentration is more complicated (Cohn, 1995).

Three methods are available for estimating L. The first relies on developing near continuous traces of concentration and discharge, or a "temporal concentration graph" (Porterfield, 1972), to account for the variability inherent in runoff-driven fine sediment transport, and graphical (numerical) integration of Eq.(1). Although near continuous (e.g. 15min) observations of Q are frequently available at U.S. Geological Survey gaging stations, similar observations of C are not, and in most situations it is not possible to reliably estimate a continuous graph trace of C, and that method was not used.

The second method uses observations of instantaneous concentration and mean daily Q to estimate mean daily load (Eq3):

$$(3)\ \ \hat{L}_T = \Delta t \sum_{i=1}^{NP} \left(Q\hat{C}\right)_i = \Delta t \sum_{i=1}^{NP} \hat{L}_i \ \ ; \ \ (4)\ \ \bar{L} = \frac{\hat{L}_T}{\Delta t + NP}$$

where $\hat{L}_i = \left(Q\hat{C}\right)_i$ is an estimate of instantaneous load, $\hat{L}_T$ is an estimate of total load, NP is the number of discrete points in time, and Δt is the time interval represented by the instantaneous load (NP=365 and Δt =1 day for daily values). The mean load for the time period of interest is defined by Eq.(4), where $\bar{L}$ is the mean load. Approximation of Eq.(1), and calculation of loads using Eqs. (2),(3), and (4), assumes that each interval is constant, and each estimate of instantaneous load is representative of the average conditions during the sampling interval. This method was used to calculate mean daily, monthly, and annual (1999-2000) TSS loads for the DNRC datasets. For periods with twice daily samples, mean daily concentrations were computed as the product of C and mean discharge for the 12-hour segment of the daily hydrograph with the sample time at its center (e.g. 6am ±6 hours and 6pm±6 hours); this method accounts for diurnal variation, in stage and concentration, which was significant during snowmelt runoff.

The third method used statistical analysis of the relationship between C (mean daily TSS or SSC) and explanatory variables, Q (mean daily discharge) and T (decimal time of sample), to extend the density of concentration values for load calculation; Q accounts for variation in C associated with stage changes, and T accounts for lag effects and seasonality in complex concentration-discharge relationships. Statistical relationships were developed using regression and time-series methods. The regression method used a three-step approach: 1) a conceptual model was formulated based on knowledge of the watersheds hydrology and channels sediment regime, 2) the model was calibrated with observed datasets of Q and C, and 3) the daily load was estimated for 1995-2004 using the calibrated regression models.

Linear regression models were fit to log-transformed values of $\hat{L}_T$ (or C), Q and T; "rating curves" (similar to a stage-discharge relationship) were developed and used in Eqs. (3) and (4) to provide estimates of $\hat{L}_T$ and $\bar{L}$. A simple Ordinary Least Squares (OLS) fit of Eq.(5) to log-transformed values of Q and C is frequently used as the statistical basis for estimating L_i:

$$(5)\ \ln(\hat{L}_i) = a_0 + \sum_{j=1}^{NV} a_j X_j$$

where, a_0 and a_j are model coefficients, NV is the number of explanatory variables, and X_j are explanatory variables (Q and T). ;

However, maximum likelihood estimation (MLE), or adjusted maximum likelihood estimation (AMLE), has been recommended as a better method for estimation of regression model coefficients (Runkel and others, 2004; Cohn, 2005):

$$(6)\ \ \hat{L}_{MVUE} = \exp\left(a_o + \sum_{j=1}^{NV} a_j\ X_j\right) g_m(m, s^2, \mathrm{V})$$

where, $\hat{L}_{MVUE}$ is the MLE estimate of instantaneous load, m is number of degrees freedom, s^2 is residual variance, V is a function of explanatory variables, and $g_m(m, s^2, V)$ is the bias correction factor of Bradu and Mundlak (1970).

Model coefficients were estimated using MLE, and the equations were used to calculate values of [$\ln(\hat{L}_i)$] for the calibration dataset. Residuals of the fit [$\ln(L)$ - $\ln(\hat{L}_i)$] were examined to asses validity of the regression models. Eq.(5) was then applied to the larger estimation dataset (e.g. daily values of explanatory variables for 1995-2004), and results in log values were exponentiated to provide an estimate of the instantaneous load, Eq. (6).

Re-transformation from logs to real numbers, accomplished by exponentiation, can result in "rating curve" estimates of instantaneous load ($\hat{L}_{RC}$) that are significantly biased with the true load underestimated by as much as 50% (Ferguson, 1986; Cohn and others, 1989; Cohn, 1995). Several alternative methods have been developed to correct for transformation bias and provide minimum variance unbiased estimates of instantaneous loads (Cohn and others, 1989; Cohn, 2005). However if the regression model does not meet criteria for valid regression models (e.g. residuals are independent and randomly distributed with equal variance-- conditions frequently not met when analyzing discharge and water-quality data), additional adjustments must be made to the calibration dataset or other statistical estimation methods must be used. Two frequent problems are correlation between explanatory variables (mullticollinearity), and serial dependence and/or seasonality of residuals (Helsel and Hirsch, 2002). Serial correlation, caused by similarity of observations closely spaced in time, was significant in the daily DNRC-TSS dataset; accordingly, a combination of regression and time-series methods were used to develop daily sediment concentration models, and estimate sediment loads, at stations above and below the reservoir.

STATISTICAL ANALYSIS AND RESULTS

LOADEST Regression Models

The U.S. Geological Survey developed LOADEST, a FORTRAN program for estimating constituent loads in streams and rivers, that accounts for many of the statistical challenges encountered when formulating, calibrating, and applying regression models to load estimation (Runkel and others, 2004). LOADEST uses AMLE to fit regression parameters when calibration model errors are normally distributed (equivalent to MLE for uncensored values such as TSS and SSC). Re-transformation bias that typically accompanies model parameters fit to log-transformed data is adjusted for using the Bradu-Mundlak bias correction factor. LOADEST does not account for serial (or autocorrelation) between residuals of closely spaced observations of streamflow and concentration. Serial correlation between residuals of regression models violates the assumption of independence and must be accounted for by reducing it to an acceptable level (e.g. editing the dataset by removing observations until the serial correlation coefficient is sufficiently reduced) before applying regression models, or by using time-series methods to develop the statistical relationship between discharge and load (or concentration).

Using the automatic selection option, AMLE was used to determine model coefficients and estimates of log(load) for each of the nine predefined models in LOADEST. However, a custom model including terms for rising and falling stage effects on concentration, provided the best-fit for DNRC and USGS datasets above the reservoir, and met conditions of normal residuals and significant regression parameters. (Table 1). The general form of the LOADEST model with the best fit for the DNRC and USGS datasets above the reservoir was a 6-parameter regression model of the form:

$$\ln[C] = a_0 + a_1 \ln Q + \ln a_2 Q^2 + a_3 R_\mathrm{i} + a_4 \mathrm{F}_\mathrm{i} + a_5 \sin[2\pi dtime] + a_6 \cos[2\pi dtime] + \varepsilon \qquad (7)$$

where,
C = adjusted TSS concentration (mg/l)
$a_{0\ldots5}$ = regression model parameters
$\ln Q$ = ln(*streamflow*) – center of ln(*streamflow*), and *streamflow* is mean daily discharge in cfs
R_i = rising stage indicator variable
F_i = falling stage indicaror variable
dtime = (decimal time – center of decimal time)
ε = model error

$$\tilde{T} = \overline{T} + \frac{\sum_{k=1}^{N} (T - \overline{T})^3}{2\sum_{k=1}^{N} (T - \overline{T})^2} \qquad (8)$$

where,
N = number of observations in calibration dataset,
$\overline{T}$ = mean of the data, and
T = quantity centered (log streamflow or decimal time)

Within Eq. (7) terms 1 and 2, account for TSS or SSC concentrations dependence on discharge, terms 3 and 4 are binary variables (0=base flow, R_i =1 for rising stage, F_i =1 for falling stage) that account for hysteresis in the discharge concentration relationship, and terms 5 and 6 (a first-order Fourier series) account for seasonal variation. When using multiple explanatory variables in a regression equation, multicollinearity arises if the explanatory variables are related, or if one explanatory variable is a function of another explanatory variable, as with the quadratic term for log Q in Eq. (7). To eliminate the collinearity, the variable $\ln Q$ was centered using Eq. (8); centering the linear and quadratic terms for $\ln Q$ ensures that the two explanatory discharge variables are orthogonal and not collinear (Runkel and others, 2004). Models for below reservoir datasets included a reduced number of parameters (Table 1).

Serial correlation coefficients for the DNRC-TSS regression models (A and D) were high indicating significant lag-1 autocorrelation. The effect of this is that errors are not independent, and although regression coefficients may still be unbiased, uncertainty may be significantly underestimated (Helsel and Hirsch, 2002). Calibration datasets were reduced in size and models were progressively re-fit using successively smaller sample sizes (Table 1.) Reducing calibration sample size by about 70%, reduced serial correlation to acceptable levels for the above reservoir model (B: ρ= 0.20), but not for the below reservoir model (E: ρ=0.49). Reducing calibration sample size did not appreciably affect the model parameters, normality of residuals or correlation coefficients, but did generally increase the uncertainty ($\mathrm{MSE_P}$). The USGS data models (C and F) displayed minimal serial correlation, due largely to the monthly to quarterly frequency of data collection.

Modeled and measured monthly TSS load mass balances, for the calibration period,1999-2000 (Figure 1.), are generally in good agreement, with the exception of June 1999 where the model overestimates the load gain by about 33%. Modeled and measured results indicate that the reservoir stores (traps) sediment during spring runoff and loses sediment during the late summer-fall irrigation season. In an average year, the amount of sediment stored is significantly (>60% of annual flux) larger than the amount lost, and mass balance is positive (1999 mean annual reservoir inflow was 35 cfs compared with the 63-year mean of 36 cfs); conversely, in a low-water year (e.g. 2000 mean annual reservoir inflow was 20.2 cfs), sediment mass balance may be neutral or slightly negative. Paired calibrated models (Table 1, DNRC: B and E, and USGS: C and F) were used to calculate mean daily *C* and *L* for the period 1995 to 2004; *L* was summed into monthly total loads to express the monthly sediment flux, and the difference was calculated to estimate monthly reservoir mass balance of TSS or SSC load.

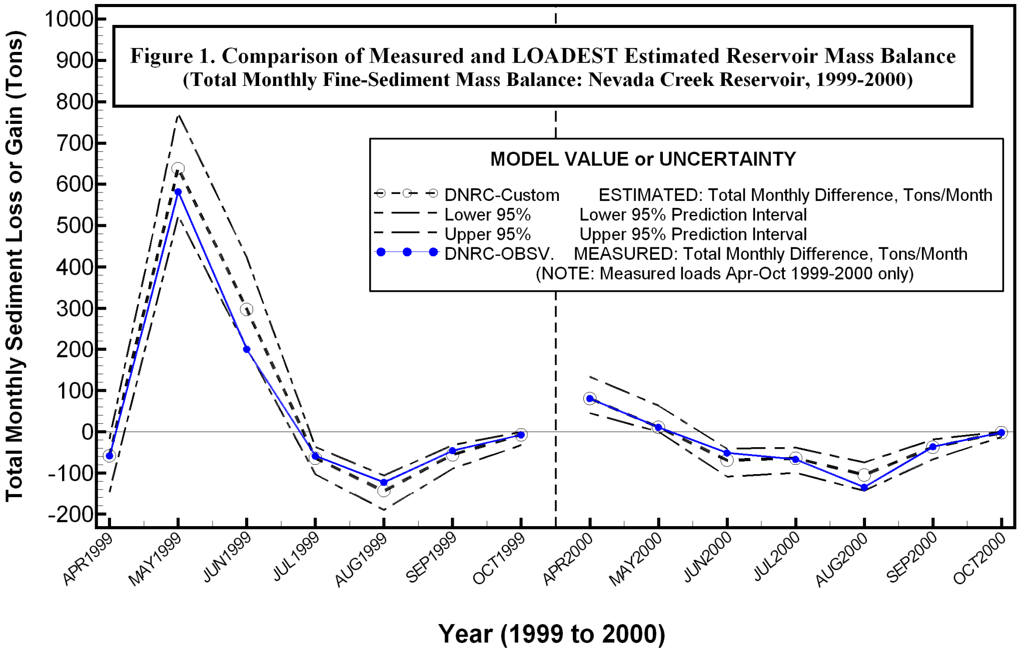
Figure 1. Comparison of Measured and LOADEST Estimated Reservoir Mass Balance (Total Monthly Fine-Sediment Mass Balance: Nevada Creek Reservoir, 1999-2000)

Time-Series Analysis

Due to the high autocorrelation between daily values of streamflow (*Q*) and sediment concentration (*C*) in the DNRC-TSS dataset, time-series methods were used to examine the error structure of residuals, and an attempt was made to develop Box-Jenkins transfer-function models that use *Q* as an input and yield *C* as output (Box and Jenkins, 1994; Singer and Dunne, 2001). The relationship between *Q* and *C* was modeled as a combination of moving average and autoregressive processes to give model formulations where *C*, at time t (days), is a function of *Q* on a given day and previous days (a moving-average or MA parameter), and *C* on previous days (an autoregressive or AR parameter):

$$(1-\delta_1 B-\delta_2 B^2)C_s=(\omega_0-\omega_1 B-\omega_2 B^2)Q_t$$

(9) where,
B is the backshift operator so that $B_z Q_t = Q_{t-z}$,
and the general Box-Jenkins transfer-fucntion model is:

$$\mathrm{C}_{\mathrm{s}_t}=\frac{\omega(B)}{\delta(B)}Q_{t-d}+e_t$$

where $\omega(B)=(\omega_0-\omega_1 B-\omega_1 B^2\cdots-\omega_s B^2)$ and,
$\delta(B)$=$(1-\delta B-\delta_2 B^2)-\cdots-\delta_r B^r)$; s and r are orders of the MA and AR processes,
ω_s and δ_r are estimated model parameters, and e_t is a noise process at time t
that is independent of the input series and is represented as an ARIMA process.

Transfer-function models were fit to log-transformed, first differenced values of daily *Q* and *C* (using SAS Institute software, rel. 9.1.3--ARIMA procedure and ETS). Models with numerator (MA) and denominator (AR) terms were identified and estimated, but failed to provide reliable forecasts and backcasts of time series of *C*. Models of *Q* met criteria, but combined models of *Q* and *C* were inadequate -- likely due to the relatively short calibration period of observations, and the inability to reliably model the strong seasonality of the daily time series.

Reservoir Sediment Budget and Trap Efficiency

Reservoir mass balances were calculated as the difference (ΔL_{daily}) between daily fine-sediment loads, at the stations above (L_{Abv}) and below (L_{Blw}) the reservoir, for each pair of *TSS* (DNRC) or *SSC* (USGS) regression equation load estimates-- Eq. (10). Each ΔL_{daily} is accompanied by an uncertainty associated with the mean square error of prediction (MSE_P) and these errors propagate in quadrature (Taylor, 1997). Approximate 95% prediction intervals for (ΔL_{daily}) were estimated using a method (Eq.10), suggested by Cohn (T.A. Cohn, U.S. Geological Survey, written communication, 2006), that assumes independent errors between upstream and downstream load estimates and a lognormal error distribution (Cohn, 2005):

(10) $\Delta L_{daily} = L_{Abv} - L_{Blw}$, where ΔL_{daily} = difference in daily load, L_{Abv} = daily load above reservoir, L_{Blw} = daily load below reservoir, and

$$PI_{95} = \left\{ \exp\left(\mu_{LN} \pm 1.96 \bullet \sigma_{LN}\right) \right\}; \quad \mu_{LN} = \ln \hat{L}_{Daily} - \sigma_{LN}^2 / 2\,; \quad \sigma_{LN} = \sqrt{\ln\left(1 + MSE_P / \ln \hat{L}_{Daily}^2\right)}; \quad MSE_P = \sqrt{\left(MSE_{Pabv}\right)^2 + \left(MSE_{Pblw}\right)^2}$$

where, PI_{95} = 95% prediction interval, μ_{LN} = expected value of true load, σ_{LN} = standard deviation, $\ln \hat{L}_{Daily}$ = AMLE load estimate, σ_{LN}^2 = residual variance, MSE_P = mean square error of prediction of difference between loads, MSE_{Pabv} = mean square error of prediction of load above resv., MSE_{Pblw} = mean square error of prediction of load below reservoir.

Table 1. Summary of LOADEST Regression Models for Nevada Creek Stations Above and Below Reservoir

LOADEST MODEL RUN	Regresssion Equation	Estimation Period	Calibration Sample Size (n and period)	Conc. R^2	Serial Corr. Coeff.	Prob. Plot Corr. Coeff.	AMLE Mean Load (Tons/Day)	95 % Prediction Intervals		Standard Error Pred.
Above Reservoir								Lower	Upper	
Model A: DNRC TSS data	Model 8: Ln, Quadratic, Time Harmonic	1995-2004	n=222 period=1999-2000	0.80	0.64	0.99	Mean: 4.14	2.99	5.58	0.67
							Apr-Jun: 10.91	8.32	14.07	1.47
							Jul-Oct: 0.53	0.40	0.68	0.07
							Nov-Mar: 2.88	1.63	4.72	0.79
Model B: DNRC TSS data (Reduced n)	Custom Model: Ln Quad., Time Harmonic, Stage Ind. Variables	1995-2004	n=57 period=1999-2000	0.91	0.21	0.99	Mean: 4.62	3.56	5.89	0.60
							Apr-Jun: 14.09	10.61	18.35	1.98
							Jul-Oct: 0.59	0.40	0.82	0.11
							Nov-Mar: 2.01	1.26	3.04	0.46
Model C: USGS SSC data	Custom Model: Ln Quad., Time Harmonic, Stage Ind. Variables	1995-2004	n=65 period=1980-2004	0.75	0.01	0.98	Mean: 3.22	2.29	4.39	0.54
							Apr-Jun: 8.86	6.22	12.25	1.55
							Jul-Oct: 0.47	0.32	0.65	0.08
							Nov-Mar: 1.96	1.25	2.91	0.43
Below Reservoir										
Model D: DNRC TSS data	Model 8: Ln, Quadratic, Time Harmonic	1995-2004	n=246 period=1999-2000	0.17	0.73	0.99	Mean: 1.78	1.53	2.05	0.13
							Apr-Jun: 3.71	3.18	4.30	0.29
							Jul-Oct: 2.38	2.04	2.77	0.19
							Nov-Mar: 0.12	0.07	0.21	0.04
Model E: DNRC TSS data (Reduced n)	Model 6: Ln, Quadratic, Time Harmonic	1995-2004	n=77 period=1999-2000	0.17	0.49	0.99	Mean: 1.71	1.49	1.94	0.11
							Apr-Jun: 3.54	2.93	4.23	0.33
							Jul-Oct: 2.30	2.05	2.59	0.14
							Nov-Mar: 0.12	0.05	0.24	0.05
Model F: USGS SSC data	Model 2: Ln, Quadratic	1995-2004	n=53 period=1994-2000	0.16	0.03	0.99	Mean: 1.91	1.46	2.45	0.25
							Apr-Jun: 4.63	3.22	6.46	0.83
							Jul-Oct: 1.94	1.62	2.30	0.17
							Nov-Mar: 0.24	0.16	0.36	0.05

Differences in mass balance of the reservoir vary within the year, and between years (Figure 2.), and are best described using the concept of reservoir trap efficiency (TE). TE is defined as the ratio of sediment mass trapped by an impoundment to the total sediment mass inflow. TE depends on particle size of inflowing sediment, retention time, reservoir geometry, type of outlets, and reservoir operation; it is not a static property but varies with time, as storage capacity is reduced over the projects lifetime, and also with annual runoff and reservoir operations. Reservoir operation that minimizes annual carryover storage (e.g. routine annual drawdown) tends to maximize throughput of sediment, as deposited material is available for re-suspension and transport during drawdown. Rough estimates of "average" TE were made using design-level engineering methods, and are as follows: Churchill Method: 80%; Brune 60% (U.S. Bureau of Reclamation, 1987).

LOADEST model estimates (Table 1.) were used to estimate the average annual, and seasonal TE (1995-2004), using the following relationship: $TE = In_{Seas} - Out_{Seas} / In_{Seas}$, where inflowing and outflowing quantities correspond to the mean annual and seasonal (April-June, July-October, and November-March) fine sediment fluxes for the 1995 to 2004 period. Average annual TE estimates range from 41% to 63 %; seasonal TE estimates range from: April-June (48% to 75%), July-Oct (-313% to -290%), and November-March (88% to 94%) -- where estimates of TE in parenthesis represent values calculated using LOADEST model results for the USGS dataset and DNRC datasets, respectively. The pattern of monthly variation in mass balance is consistent from year-to-year (Figure 2); from November through June the reservoir mass balance is positive with inflowing sediment stored, while in July through October (during reservoir drawdown when inflowing sediment loads are small) the mass balance is negative, with more sediment transported from the reservoir than enters. In general, the annual mass balance is positive, with about 60% to 90% of the inflowing load stored in average and above average water years; in low water years (e.g. 2000) the annual mass balance may be negative, with more sediment lost from storage than gained from spring runoff. Nevada Creek Reservoir is narrow and linear, and much of the accumulated sediment stored in the delta;

mechanisms of sediment re-entrainment, and transport from the reservoir, appear to include wave action in shallow water depths over the delta, and "short circuiting" of the reservoir that can occur when inflow occupies Nevada Creek's original channel--now incised into the delta (Mike McLane, DNRC, personal communication, 2006).

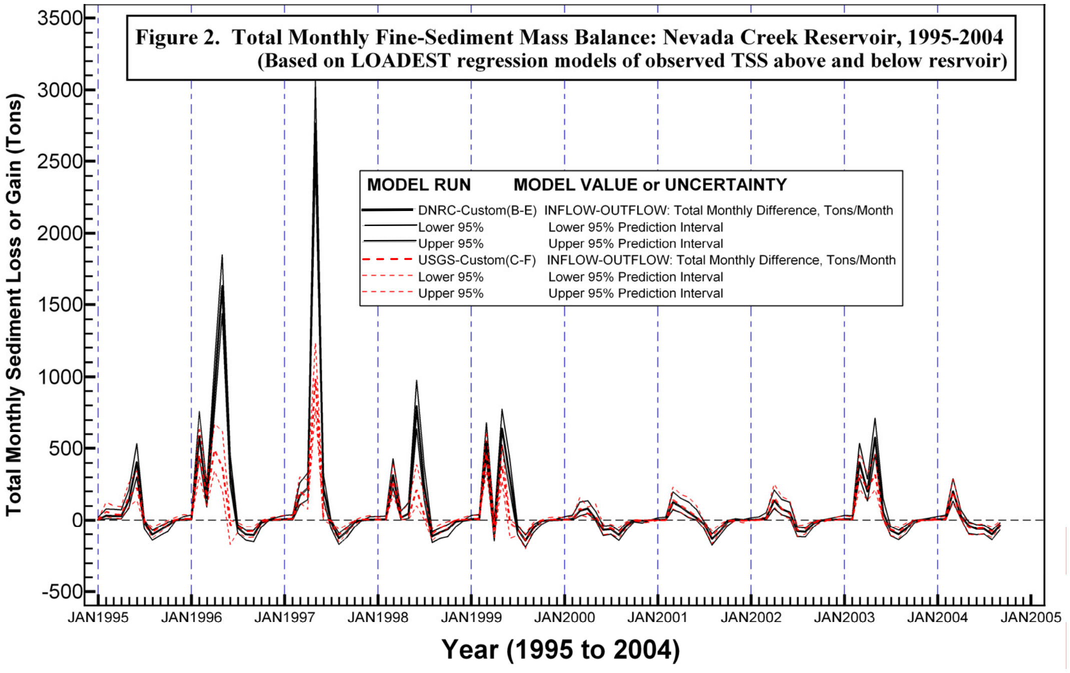
Figure 2. Total Monthly Fine-Sediment Mass Balance: Nevada Creek Reservoir, 1995-2004
(Based on LOADEST regression models of observed TSS above and below resrvoir)

Effect of Reservoir on Turbidity

Turbidity (measured with a Hach 2100-P, in nephelometric turbidity units, NTU) of samples collected above and below the reservoir was significantly correlated with observed TSS (OLS regression, Above: *ln*[Turbidity]=0.011+0.66 *ln* [TSS], n=177, r^2=0.57, p=0.0001; Below: *ln*[Turbidity]=0.744+0.59 *ln*[TSS], n=205, r^2=0.37, p=0.0001). Turbidity variation in reservoir inflows (range=2 to 62 NTU) was larger than in outflows (range=2 to 24 NTU). During spring runoff (April-June) turbidity measured above the reservoir was typically two to three times larger than that measured below the reservoir (Figure 3.). In summer and fall runoff (July-September), turbidity at both sites was similarly low (2 to 15 NTU). Turbidity measured below the reservoir, for discharges exceeding 150 cfs, is representative of reservoir drawdown for irrigation water supply and was typically in the range of 5 to 10 NTU -- similar to that above the reservoir.

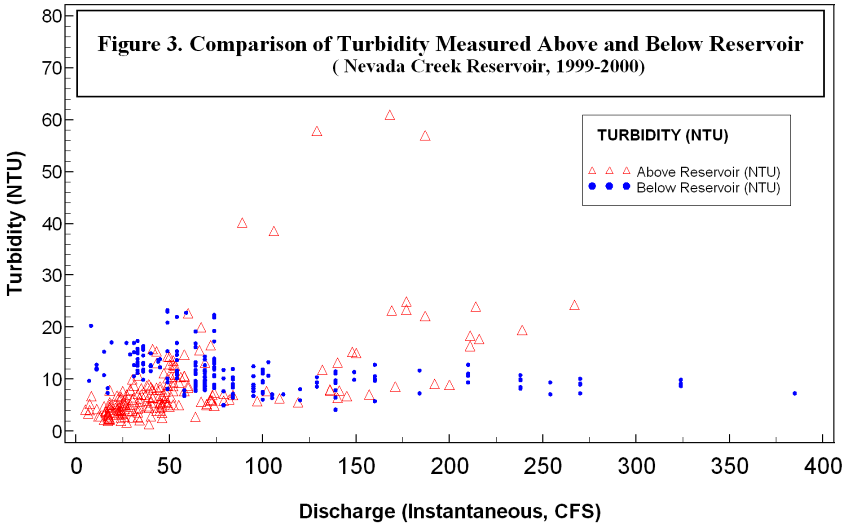
Figure 3. Comparison of Turbidity Measured Above and Below Reservoir
(Nevada Creek Reservoir, 1999-2000)

Differences between paired observations of turbidity and TSS (*Difference= Above -Below*) were tested to determine if values were significantly different. None of the differences were normally distributed so the nonparametric Wilcoxon signed-rank test, for symmetric differences, and sign test, for asymmetric differences, (Helsel and Hirsch, 2002), were performed (Table 2); both test if the median difference between paired observations is significantly different from zero. The null hypothesis tested was that median differences in paired values of turbidity or TSS, measured above and below reservoir, were not significantly larger or smaller than zero (two-sided test); reference probability for the test was selected as α=0.05. The test was performed on three stratifications of data: all observed values of turbidity and TSS, a high flow dataset (values occurring at below dam discharges > 90cfs), and a low-flow dataset (values occurring at discharges $\leq$90cfs). Median differences in turbidity above and below the dam were slightly larger at low flows (-5.0 NTU) than for all flows (-3.6NTU), and were not significant for high flows. Median differences in TSS were small for all data (range -4.7 mg/L to -6 mg/L). Note that negative values indicate values are larger in outflow than in inflow.

Table 2. Hypothesis Tests of Differences in Turbidity and Total Suspended Solids Concentration Above and Below Nevada Creek Reservoir

Difference Tested (Above - Below)	Sample Size	Wilcoxon Signed-Rank Test Statistic	Signed-Rank Probability (Two-sided)	Median Difference (Hodges-Lehman Est.-- Helsel and Hirsch 2002)	Sign Test Statistic	Sign Probability (Two-sided)	Median Difference	Differences Symmetric ?
Turbidity (All)	167	-3550.5	<0.0001	-3.6 NTU	-45	<0.0001	-3.7	Yes
Turbidity (High Flow)	52	211.5	0.0463	0.00	0.5	1.0 (N.S)	0.00	No
Turbidity (Low Flow)	115	-2857	<0.0001	-5.0 NTU	-45.5	<0.0001	-5.3	Yes
TSS (All)	205	-3245.5	0.0001	-4.7 mg/L TSS	-42.5	<0.0001	-4.8	Yes
TSS (High Flow)	54	356	<0.0015	5.1 mg/l TSS	5.0	0.2203 (N.S.)	4.0	No
TSS (Low Flow)	151	-3375.5	<0.0001	-6.0 mg/L TSS	-47.5	<0.0001	-6.8	Yes

ADAPTIVE RESERVOIR SEDIMENT MANAGEMENT

Nevada Creek Reservoir has affected the sediment budget of the stream by interrupting the normal flux of coarse and fine sediments supplied to the channel network by the upstream watershed. The principal effect on downstream fine-sediment flux is seasonal and annual redistribution of the fine-sediment load. Sediments are stored during spring runoff, when inflowing loads are relatively large, and then gradually released in the summer and fall, when the reservoir is drawn down for irrigation water supply. In addition to reservoir geometry, reservoir operation creates conditions that reduce overall trap efficiency and minimize sediment storage over the long term. From the standpoint of long-term use of the reservoir for water supply, reduced and variable trap efficiency is beneficial because it increases reservoir longevity and helps to ensure a dependable future supply of water. Within the limits of any storage projects typical effects on downstream water quality, it also has benefits for maintenance of downstream water quality; variable trap efficiency helps to avoid spikes in downstream sediment concentrations and turbidity that can occur when sediment is stored continuously for long periods and then abruptly released (Dalby and others, 1999). Recognizing potential for the latter, DNRC and the NCWUA have established minimum reservoir pool elevation and capacity guidelines to prevent excessive reservoir sediment entrainment, and resulting downstream spikes in concentrations and loads during low flows .

ACKNOWLEDGMENTS

Numerous folks assisted with this effort. Paul Azevedo, Mike McLane, Jim Domino, and Kurt Hafferman (DNRC) helped with various aspects of sediment sampling and data collection. Randy Hawkins (reservoir dam-tender, NCWUA) also assisted with data collection, and provided information on reservoir operations. Robert Runkel (U.S. Geological Survey) provided useful insights into the application of LOADEST. Bill Stroud (Manager, PNW Regional Water-Quality Lab, U.S. Bureau of Reclamation) and his lab analyzed TSS samples, provided ISCO samplers, and other technical and financial support.

REFERENCES

Box, G. and G. Jenkins, 1994. Times series analysis, forecasting, and control. Holden Day, SanFrancisco, CA.

Bradu, D., and Mundlak, Y., 1970. Estimation in lognormal linear models. J.Am. Stat.Assoc., v. 65, no. 329, p. 198–211.

Cohn, T.A., 1988. Adjusted maximum likelihood estimation of the moments of lognormal populations from type I censored samples: U.S. Geological Survey Open-File Report 88-350, 34 p.

Cohn, T.A., Delong, L.L., Gilroy, E.J., Hirsch, R.M., and Wells, D.K., 1989. Estimating constituent loads: Water Resources Research, v. 25, no. 5, p. 937-942.

Cohn, T.A., Caulder, D.L., Gilroy, E.J., Zynjuk, L.D. and Summers, R.M., 1992. The validity of a simple statistical model for estimating fluvial constituent loads—an empirical study involving nutrient loads entering Chesapeake Bay: Water Resources Research, v. 28, no. 9, p. 2353–2363.

Cohn, T.A., 1995. Recent advances in statistical methods for the estimation of sediment and nutrient transport in rivers: Reviews in Geophysics, v. 33 (Supplement), p. 1117–1124.

…………., 2005. Estimating contaminant loads in rivers: an application of adjusted maximum likelihood to type 1 censored data. Water Resources Research, V. 41 W07003 13p.

Crawford, C.G., 1991. Estimation of suspended-sediment rating curves and mean suspended-sediment loads. Journal of Hydrology, v. 129, p. 331–348.

Crawford, C.G., 1996. Estimating mean constituent loads in rivers by the rating-curve and flow-duration, rating-curve methods: Bloomington, Ind., Indiana University, Ph.D. dissertation, 245 p.

Dalby, C.E. , L.Dolan and M. Downey, 1999. Implementation of flushing flows to remove fine-grained sediments released from Ruby Dam, Southwestern Montana. Proceedings of the Specialty Conference on Wildland Hydrology, June 30-July2, 1999 Bozeman, MT. American Water Resources Association. eds., D.S. Olsen and J.P. Potyond y, p125-132.

Dalby, C.E. 2006. Sediment monitoring and development of a sediment budget for Nevada Creek Reservoir. Project Completion Report. Water Management Bureau, Montana Department of Natural Resources and Conservation. Helena, MT.

Draper, N.R., and Smith, H., 1998. Applied regression analysis (3d ed.): New York, John Wiley and Sons, 709 p.

DTM Consulting, 2004. Nevada Creek TMDL planning area watershed characterization report, March 31, 2004. Consultant report to Montana Dept. of Env. Quality. 32.p.

Duan, N., 1983. Smearing estimate—a nonparametric retransformation method: Journal of the American Statistical Association, v. 78, p. 605–610.

Eads, R.E. and R.B. Thomas, 1983. Evaluation of a depth proportional intake device for automatic pumping samplers. Water Resource Bulletin, American Water Resources Association, V19, No. 2, p289-292.

Edwards, T.K. and G.D. Glysson, 1999. Field methods for measurement of fluvial sediment USGS—TWRI Book 3, Chapter C2.

Ferguson, R.I., 1986. River loads underestimated by rating curves: Water Resources Research, v. 22, no. 1, p. 74–76.

Gilroy, E.J., Hirsch, R.M., and Cohn, T.A., 1990. Mean square error of regression-based constituent transport estimates: Water Resources Research, v. 26, no. 9, p. 2069–2077.

Glysson, G.D., J.R. Gray, and L.M. Conge , 2000. Adjustment of total suspended solids data for use in sediment studies. In Proceedings of the ASCE 2000 Joint Conference on Water Resources Engineering and Water Resources Planning and Management, July 30-August 2, 2000. Minneapolis, Minn. 10p.

Gray, J.R., G.D. Glysson, L.M. Turcois, and G.E. Schwarz, 2000. Comparability of suspended-sediment concentration and total suspended solids data. U.S. Geological Survey Water-Resources Investigations Report 00-4191, 14.p

Helsel, D.R., and Hirsch R.M., 2002. Statistical methods in water resources: U.S. Geological Survey Techniques of Water-Resources Investigations, book 4, chapt. A3, 510 p. (http://water.usgs.gov/pubs/twri/twri4a3)

King, J.G., W.W. Emmett, P.J. Whiting; R.P Kenworthy, and J. Barry, 2004. Sediment transport data and related information for selected coarse-bed streams and rivers in Idaho. U.S. Dept. of Ag. Rocly Mtn. Res. Sta. .RMS-GTR 131. 26p.

Lambing, J.H. and K.A. Dodge, 1993. Quality assurance for laboratory analysis of suspended-sediment samples by the U.S. Geological Survey in Montana. U.S. Geological Survey Open-File Report 93-131, Helena, MT 34p.

Leopold, L.B., 1992. The sediment size that determines channel morphology. in Dynamics of Gravel-Bed Rivers, ed.s p. Billi, R.D. Hey, C.R. Thorne and P.Tacconi p. 297-312.

Lisle, T.E., 1995. Particle size variations between bed load and bed material in natural gravel bed channels. Water Resources Research, v. 31, no.4. p 1107-1118.

Porterfield, G., 1972. Computation of fluvial-sediment discharge. U.S. Geological Survey Techniques of Water-Resources Investigations. Book 3, Chapter A3. 66p.

Runkel, R.L., C.G. Crawford, and T.A. Cohn, 2004. Load Estimator (LOADEST): A FORTRAN program for estimating constituent loads in streams and rivers. Techniques and Methods Book 4, Chapter A5. U.S. Department of Interior, U.S. Geological Survey, Reston, Virginia. 69p.

Singer, M.B. and T. Dunne,2001. Identifying eroding and depositional reaches of valley by analysis of suspended sediment transport in the Sacramento River, California. Water Resources Research, V.37, No.2, p3371-3381.

Taylor, J.R., 1997. An introduction to error analysis. 2nd edition. University Science Books. Sausalito, CA. 323p.

U.S. Bureau of Reclamation, 1987. Design of Small Dams. U.S. Department of Interior, Appendix A, p 529-564

U.S. Geological Survey, 2005. National Water Information System, NWISWeb: Water-quality data for Montana.

Vanoni, V.A., 1977. Sedimentation Engineering. ASCE. Manuals and reports on engineering practice. No. 54. New York, N.Y. 745p.