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Evaluating the WATBAL Sediment Loading Model, Clearwater National Forest, Idaho

Abstract

Efforts to protect water quality while managing national forests for logging purposes are currently constrained by limited information on the application, interpretation, and validation of sediment loading models. For years, these models have been used to predict the impacts of logging, road-building, and fires on sediment loading to streams. However, in the Clearwater National Forest, where the WATBAL sediment loading model is used, model results have never been compared to actual field measurements. Without model validation, forest managers are working with unverified information regarding the impacts of logging activities on aquatic systems. To effectively manage our national forests and their aquatic ecosystems, we must provide accurate information to forest managers. This paper presents the results of comparing the WATBAL output to field measurements of sediment loading to streams in the Clearwater National Forest, ID.

Introduction

In the northern Rocky Mountains, national forests are managed for two primary purposes which are often at odds with each other: logging and recreation. Logging and associated roadbuilding activities negatively impact both water quality and aquatic ecosystems by increasing sediment loading in the streams (Megahan and Kidd, 1972; Megahan, 1975; Meehan, 1991; Ketcheson, 1986). Unfortunately, most quantitative methods for evaluating sedimentation are limited by a poor understanding of the processes involved (Klemes, 1986). Thus, attempts to predict sedimentation have focused upon land-use based models (Gloss, 1995).

Due to the complexity of sediment yield modeling, efforts within the United States Forest Service (USFS) have been "based primarily on professional judgment of field hydrologists with some extrapolation of published research" (Knighton and Solomon, 1989, p. 345). The "Guide for Predicting Sediment Yields from Forested Watersheds" (Cline, et. al, 1981) was developed by the Northern and Intermountain Regions of the USFS to provide a consistent framework under which the individual national forests would develop their own sediment yield models. In the Clearwater National Forest, the USFS uses the sediment loading model WATBAL (Patten, 1989) to predict the impacts of logging and logging-related road building. The output is given in two components: mass wasting and surface erosion.

The objective of this study is to evaluate the WATBAL model as a tool for predicting the cumulative effects of land management activities on sediment yield in the Clearwater National Forest, ID. The intent is to provide information necessary to more successfully apply and interpret the WATBAL model for management of non-point source sediment caused by logging and recreation. Specific objectives of the study are to:

1) Determine if average annual sediment yields predicted by WATBAL are comparable to average annual sediment yields computed from field data.

2) Test the relations between stream discharge, precipitation, and the accuracy of WATBAL predictions.

To accomplish these objectives, the measured and modeled sediment yield values were compared to field measurements of suspended and bedload sediments in two watersheds. In addition, the errors (model minus measured sediment loads) were compared to stream discharge and precipitation to determine whether or not the magnitudes of the errors are a function of discharge or precipitation. In addition, the WATBAL model was examined for other potential sources of error, particularly those associated with roads or the scale of analysis (minimum mapping unit).

Study Site and Watershed History

This study evaluates two watersheds in north-central Idaho; the upper Lolo Creek and Pete King

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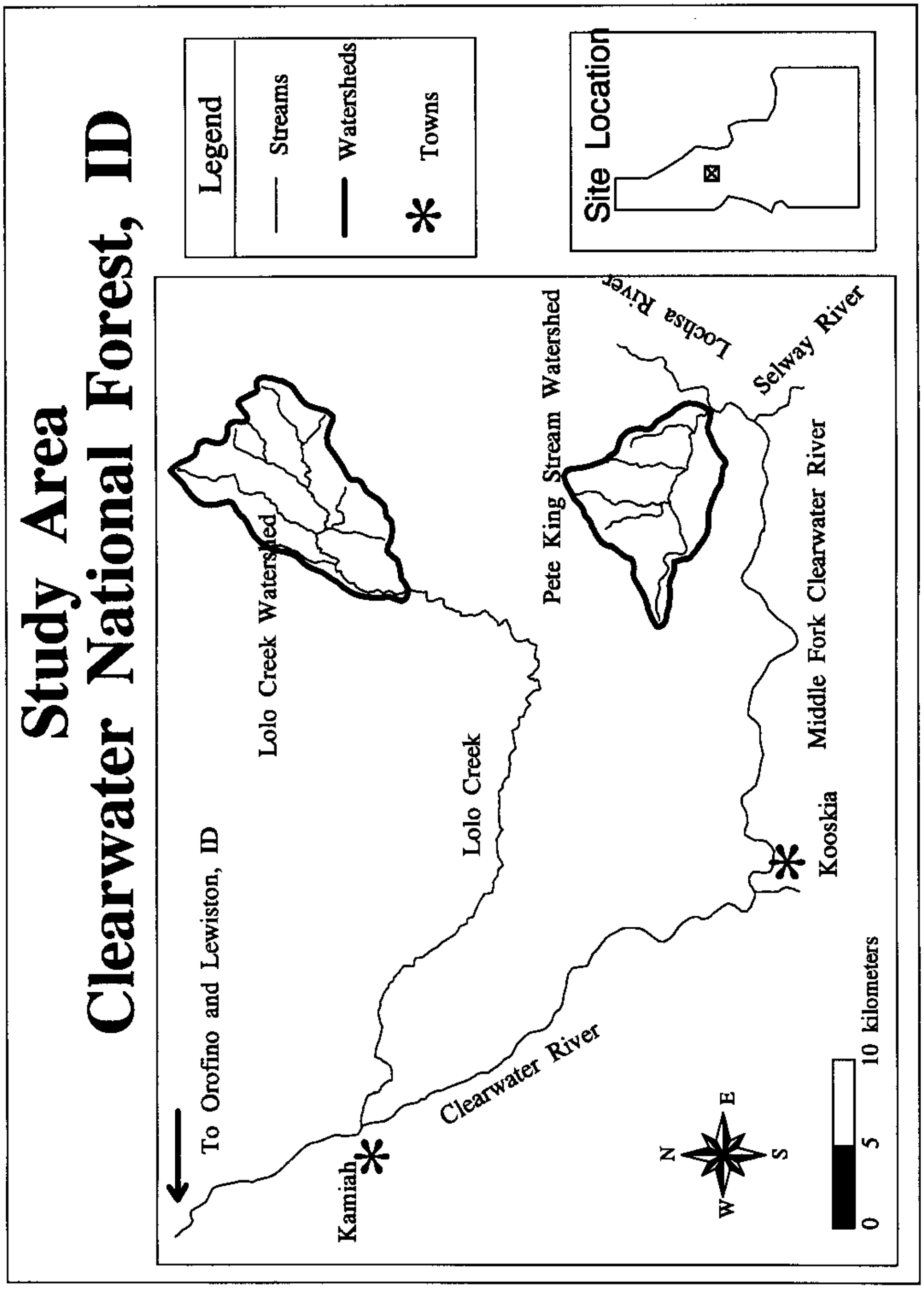

Figure 1. Study site location map.

TABLE 1. Basic watershed characteristics (from WATBAL output files).

	Lolo Creek	Pet King King Stream
Elevation (meters)	902-1845	450-1591
Total Area (sq. kilometers)	103	72
Av. Annual Precipitation (cm.)	122	97
Avg. Annual Runoff (cm.)	61	41

Stream watersheds (Figure 1, Table 1). These were selected because they are the two watersheds with the longest sampling histories (9 and 19 years, respectively) in the Clearwater National Forest. The hydrology is dominated by spring snowmelt, with approximately two-thirds of the annual precipitation occurring between November and April. The geology is predominantly Belt Supergroup (gneiss and schist) and Idaho Batholith granites. Landuses are primarily logging and recreation.

Information regarding the Lolo watershed indicates that logging and roadbuilding activities have occurred almost continuously during the years 1954 through 1991. By 1991, the last year that logging occurred in the Lolo Creek watershed, 4708 hectares (11,634 acres) (46.4% of the watershed) had been disturbed. Table 2 describes predicted and measured sediment loads and stream discharge for Lolo Creek. Field measurements of sediment yields have been collected only since 1984.

Landforms within the Pete King Watershed consist of approximately 50% breaklands and 50% rolling uplands and mountains. The breaklands typically have very high mass wasting and sediment delivery potential (Jones, 1992). Human activities in the watershed began in 1953 with the introduction of the first logging road. Logging, fire, and roadbuilding activities have continued through 1991. A complete history of mass wasting events has not been developed. However, a number of landslides occurred in the 1970's, dumping excessive amounts of sediment into Pete King Stream (Jones, 1992). A 1978 event, and another in 1987, are obvious when viewing sediment loading data (Table 3). Both events were caused by road failures (D. Jones, pers. comm, 1995). To date, 2582 hectares (6,381 acres) of forest have been harvested and 256 kilometers (153.6 miles) of roads have been constructed, covering 36.3% of the watershed. In 1934, a large fire burned 34% of the watershed—thus, in the last 60 years, approximately 70% of the watershed has been disturbed (Jones, 1992). Table 3 describes predicted and measured sediment loads and stream discharge for Pete King Stream. Field measurements of sediment yields have been collected only since 1976.

Model Description

The WATBAL sediment loading model is derived from the "Guide for Predicting Sediment Yields from Forested Watersheds" (Cline et al., 1981). This manual sets the objectives, standards, limitations, assumptions, and conceptual background for all sediment yield models in the Northern and Intermountain Regions of the USFS. The two

TABLE 2. Original data, Lolo Stream.

Dates	Mean Discharge	Maximum Discharge	Field Meas. tons/sq. mi./yr.	WATBAL tons/sq. mi./yr.	WATBAL.-Field meas.
10/1/84—9/30/85	89.5	312.1	20.7	9	-11.7
10/1/85—9/30/86	97.9	298.6	17.1	9	-8.1
10/1/86—9/30/87	132.2	575.9	75.6	10	-65.6
10/1/87—9/30/88	57.7	177.9	9.8	9	-0.8
10/1/88—9/30/89	81.9	326.5	28.9	8	-20.9
10/1/89—9/30/90	75.8	278	36.9	8	-28.9
10/1/90—9/30/91	90.4	231.3	39	8	-31
10/1/91—9/30/92	69.1	168.7	20.5	8	-12.5
10/1/92—9/30/93	88.4	311.2	no data	7	
10/1/93—9/30/94	52.3	187.4	26.6	7	-19.6

TABLE 3. Original data, Pete King Stream.

Dates	Mean Discharge	Maximum Discharge	Field Meas. tons/sq. mi/yr.	WATBAL tons/sq. mi./yr.	WATBAL. - Field meas.
10/1/75—9/29/76	96.6	202.6	59	56	-3
10/1/76—9/30/77	24.1	46.9	8.4	50	41.6
10/1/77—9/30/78	40	131.2	17.4	42	24.6
10/1/78—9/29/79	51.2	212.1	173.9	40	-133.9
10/1/79—9/30/80	37.7	92.7	20.3	39	18.7
10/1/80—9/30/81	45	83.5	33.1	38	4.9
10/1/81—9/30/82	72.5	163.9	70.2	36	-34.2
10/1/82—9/30/83	50	121.2	19.4	33	13.6
10/1/83—9/30/84	57.7	153.7	69.6	33	-36.6
10/1/84—9/30/85	46.6	131.7	44.6	32	-12.6
10/1/85—9/30/86	59.5	179.1	26.1	31	4.9
10/1/86—9/30/87	28.9	67.4	401.3	34	-367.3
10/1/87—9/30/88	29.1	80.9	58.7	33	-25.7
10/1/88—9/30/89	68.8	205.6	71	29	-42
10/1/89—9/30/90	29.9	59.8	54.8	29	-25.8
10/1/90—9/30/91	35.4	76.2	16.6	29	12.4
10/1/91—9/30/92	24.7	48.2	16.9	28	11.1
10/1/92—9/30/93	32	78.6	18.1	28	9.9
10/1/93—9/30/94	27.5	65.5	20.4	28	7.6

limitations/assumptions that are of particular interest to this analysis are (pgs. 3-4):

> "1. Sediment yield can be usefully displayed as an expected average annual event although it is subject to considerable variability from year to year and within any single year.
>
> 2. Model outputs are primarily intended to indicate trends and to compare management alternatives and secondarily to provide quantified estimates of sediment yield."

The WATBAL model has been under constant development since 1973, with a stated objective of "estimating water yields in response to cumulative watershed development and vegetative manipulation and recovery over time" (Patten, 1989, pg. 1). At present, WATBAL "is designed to simulate the potential and most likely effects of primary forest management practices (timber harvest, road development, and fire) on the responses of watershed and water resource systems with regard to stream flow and sediment regimes." (Patten, 1989, pg. 1) In the Clearwater National Forest, the WATBAL program and associated data files serve as the primary watershed inventory (Patten, 1989).

Watersheds are divided into areas that are relatively homogeneous (landtypes), for which a number of response characteristics are determined. The physical characteristics measured include: slope angle, slope shape, slope length, surface drainage, soil depth, soil texture, soil structure, soil consistency, bedrock type, bedrock weathering, bedrock structure, and vegetative habitat. From these characteristics, each landtype is assigned a series of hazard ratings which describe potential a) rotational mass erosion, b) debris avalanche, c) surface erosion from undisturbed soil surfaces, d) surface erosion from subsurface horizons, and e) surface erosion from the substrata (Patten, 1989). The model output from these original hazard ratings serves as the estimate of natural sediment yield in tons per square mile per year. The natural sediment yield values are based upon sediment measurements from several representative landtypes. These measurements were then extrapolated to other landtypes using an algorithm which assumed that approximately 80% of the natural sediment is derived from long-term mass erosion processes—the remainder is from surface erosion processes related to the fire history of the landtype (Patten, 1989). Each individual landtype file also includes the stream density within that particular landtype.

Additional surface erosion is assumed to be induced, and mass erosion accelerated, by different logging, fire, and roadbuilding activities. Thus, excess (above natural amounts) erosion is a function of the type and location of different management activities. The acceleration factors for mass erosion were derived from a landslide study by Megehan, et. al (1978). Acceleration factors for roads and burned areas are also included. Surface erosion, which is assumed to be insignificant in undisturbed forests (Cline, et al., 1981), is estimated for roads, burned regions, and logged areas. Each is modified by the physical characteristics of the land and the age, size, and intensity of the disturbance.

To estimate water yields to streams, WATBAL uses a hydrograph generated from a combination of average annual discharge (a function of the average annual precipitation within the watershed) and the hydrograph of a stream deemed similar to the stream in question (Patten, 1989) (Figure 2). The average annual discharge contributes the annual volume of water and the representative hydrograph defines the shape of the hydrograph. The annual precipitation data were derived for each watershed from 1960's precipitation isohyets developed from a network of long-term storage gauges around the forest, a few recording sites west of the forest, the Natural Resources Conservation Service snow courses and climatic telemetry sites (SNOWTEL), and several stream gauges (Patten, 1989; Gayle Howard, Hydrologic Technician USFS, personal comm., 1997). Average annual precipitation and discharge are stored as constants within the watershed files, not as variables associated with landtype files.

Combining a sediment routing equation with the landtype, management, and precipitation data then allows the calculation of predicted sediment yields within a watershed (Figure 2). The WATBAL equation which calculates the total sediment yield only considers the area of the watershed. Details of stream routing, hydrology, and dynamics are not included; however, they are recognized as a weakness in the WATBAL model (Patten, 1989).

Research Methodology

Data collected by the USFS includes physical descriptions of the two watersheds, WATBAL output (sediment and mass loading), and field measurements of suspended sediment, bedload, and stream discharge. As WATBAL output is given as a yearly value, the field measurements had to be aggregated from monthly to yearly data. In addition, the suspended sediment and bedload components of sediment loading were combined to provide a single yearly estimate of total sediment loading. Stream discharge was aggregated to average and maximum monthly discharge.

There were no field components to this research, so accuracy estimates of sampling methods are not included in this analysis. Therefore, model validation focuses on a statistical comparison between measured and modeled values (Mayer and Butler, 1993; Donigian, 1981). In this analysis, subjective assessment, deviance measures (mean absolute error and the mean absolute percent error), and statistical tests (descriptive statistics, regression, and modeling efficiency) were used to evaluate the WATBAL output.

The interpretation of the Lolo Creek data was relatively straightforward; however, at Pete King Stream, there are two outliers in the dataset caused by road failures (1978 and 1987) which dumped excessive amounts of sediment into the stream. Thus, two different analyses were run for the Pete King watershed: one which included all the data, the other which represents years in which there were no catastrophic road failures.

Results

Tables 4 through 6 contain the measured and calculated sediment yields and the differences between the two. The output from the statistical comparisons of the measured and calculated sediment yields are shown in Table 7. The deviance measures are based upon the differences between the measured and calculated data and show the average absolute difference between model and measured data (MAE) and the average absolute percent error (MA%E). In the case of the MA%E,

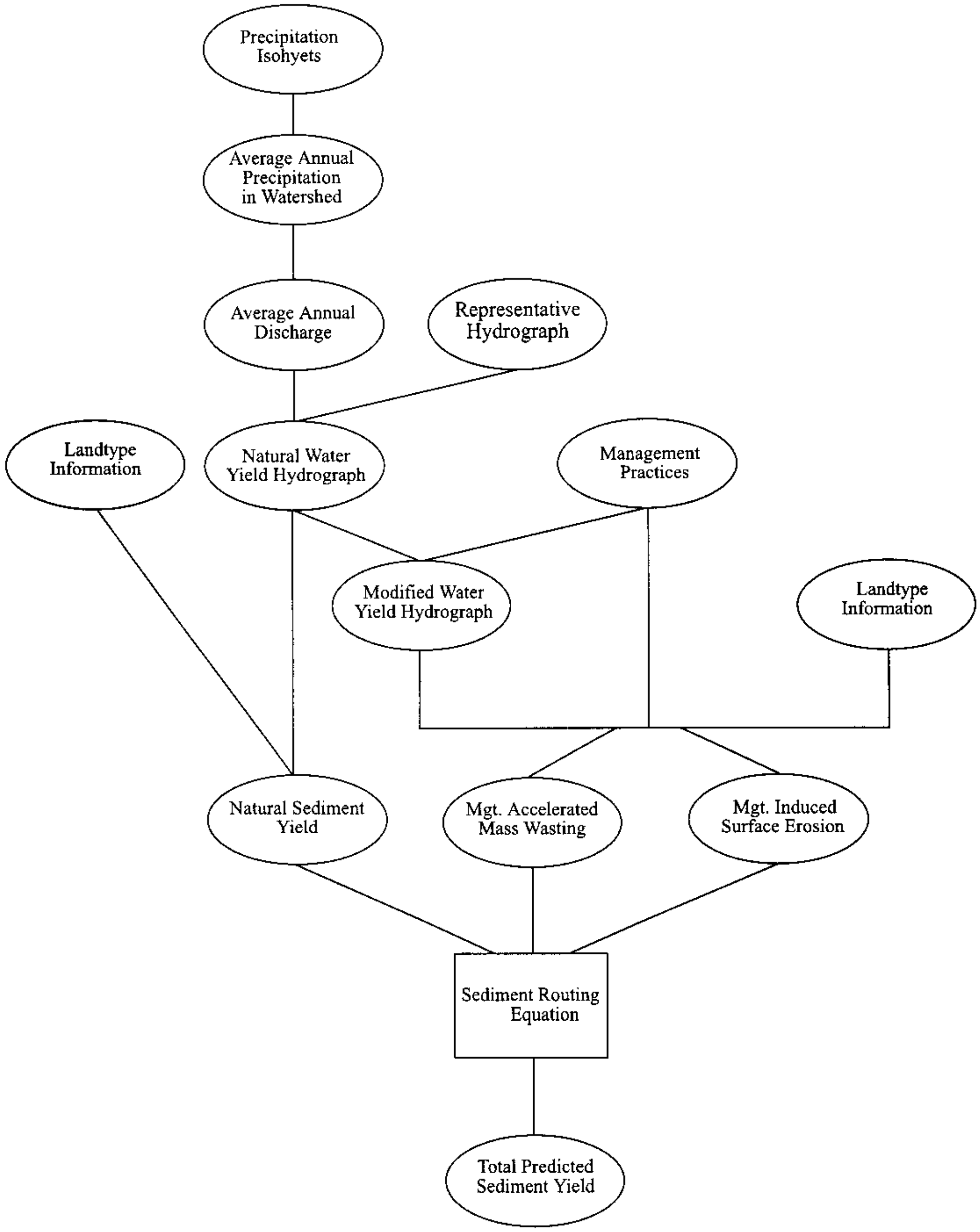

Figure 2. Generalized diagram of WATBAL model components with emphasis on precipitation data.

TABLE 4. Descriptive statistics for Lolo Stream.

	Field Meas. tons/sq. mi./yr.	WATBAL tons/sq. mi./yr.	(WATBAL)-(field meas.)
Sample Size	9	9	9
Minimum	9.8	7	-65.6
Maximum	75.6	10	-0.8
Mean	30.6	8.4	-22.1
Median	8.0	8.0	-19.6
Standard Deviance	19.26	0.9	19.0
Variance	371.1	0.8	359.4
Std. Error	6.4	0.3	6.3

TABLE 5. Descriptive statistics for Pete King Stream; data for two years with exceptionally high sediment loading excluded.

	Field Meas. tons/sq. mi/yr.	WATBAL tons/sq. mi/yr.	(WATBAL)-(field meas.)
Sample Size	17	17	17
Minimum	8.4	28	-42.0
Maximum	74.0	56	41.6
Mean	36.7	34.9	-1.8
Median	26.1	33.0	4.9
Standard Deviance	22.4	8.0	23.8
Variance	501.7	64.6	566.4
Std. Error	5.4	1.9	5.77

TABLE 6. Descriptive statistics for Pete King Stream. All data are included.

	Field Meas. tons/sq. mi./yr.	WATBAL tons/sq. mi./yr.	(WATBAL)-(field meas.)
Sample Size	19	19	19
Minimum	8.4	28	-367.3
Maximum	401.3	56	41.6
Mean	63.1	35.2	-28.0
Median	33.1	33.0	4.9
Standard Deviance	90.2	7.7	90.4
Variance	8138.6	58.8	8170.7
Std. Error	20.7	1.8	20.7

10% has been suggested as an upper limit of acceptability (Kleijnen, 1987); however, this value will vary depending upon the model and its uses (Bratley, et al., 1987). In this case, values ranging from 62 to 80 percent are clearly unacceptable. The correlation results also support this evaluation—the correlation (R^2) between the measured and calculated values is less than 0.02 in all cases.

Modeling efficiency (EF) is a dimensionless statistic which directly relates model predictions to measured data (Loague and Green, 1991). EF has a lower bound of negative infinity, while a value of one indicates that the model perfectly predicts the measured values. Models which produce values less than 0 cannot be recommended (Mayer and Butler, 1993). As the EF values in this analysis are all negative, the EF interpretation supports the output from both the deviance and regression analyses.

Figure 3 illustrates the distribution of errors at Lolo Creek. In all cases, WATBAL underestimated sediment yields. The largest underestimation occurred in 1986/87—the same year in which there were catastrophic road failures in the Pete King watershed. These are probably due to an exceptionally heavy rainfall event.

The distribution of errors at Pete King Stream are shown in Figure 4. Of the nineteen years in which data were collected, WATBAL underestimated sediment loading nine times. On average, WATBAL underestimated sediment loading by 28 tons/sq. mile/year. However, if the two catastrophic years are dropped, the mean of the distribution falls to -1.8 tons/sq. mile/year.

As all of the above comparisons show little connection between the measured and predicted sediment yield values, the question becomes explaining the reasons for this. The possibilities are numerous, and include sampling errors, annual variations in precipitation (timing, intensity, amount), and model errors. However, the only data currently available are average and maximum monthly stream discharge and monthly/annual precipitation which were then compared to the errors. The errors are defined as the difference between the WATBAL output and the measured values. At Lolo Creek, there was a significant correlation between both mean and maximum stream discharge and the errors ($R^2 = 0.46$ and 0.60, respectively). This is not surprising, given

TABLE 7. A statistical comparison of measured and calculated sediment yields: deviance measures (Mean Absolute Error, Mean Absolute Percent Error), linear regression (R^2, slope, intercept, standard error), and modeling efficiency (EF).

Stream	n	MAE	MA%E	R^2	Slope	Intercept	Std. error	EF
Lolo	9	21.12	62.6	0.011	.0168	7.93	0.9	-1.45
Pete King	19	43.7	79.9	-0.06	.0016	35.05	7.9	-0.11
Pete King	17	19.4	79.4	-.07	-.0002	34.95	8.3	-0.14

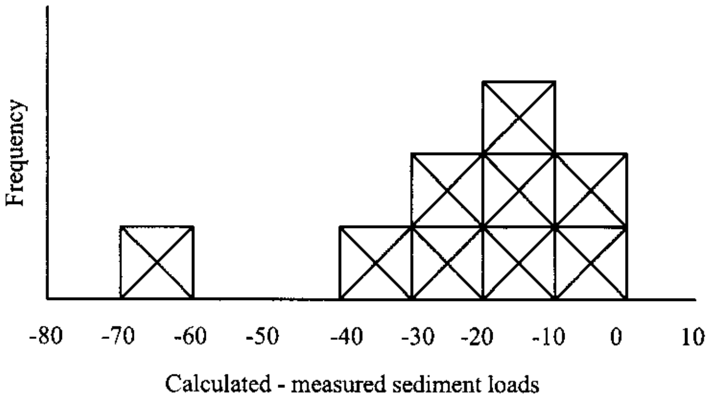

Figure 3. Distribution of errors at Lolo Creek.

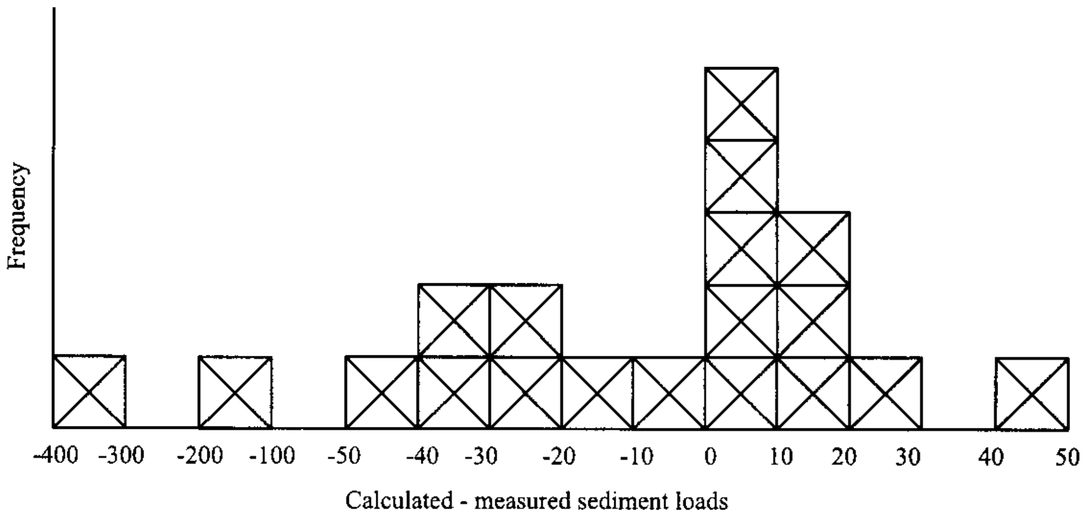

Figure 4. Distribution of errors at Pete King Stream.

that one of the model assumptions (Cline, et al., 1981) states that sediment yield can be effectively modeled using average precipitation values. However, at Pete King Stream, the correlations between mean and maximum stream discharge and the errors for the full dataset were extremely low (R^2 = -0.06). When the two outliers were eliminated, a slight correlation was shown: R^2 = 0.14 and 0.18 for mean and maximum discharge, respectively.

To test the relationship between precipitation and the errors, data (annual and maximum monthly precipitation) from monitoring stations closest to the two watersheds was obtained. For reference, the Fenn and Pierce station data were compared to the Pete King and Lolo watersheds, respectively.

The relationship between maximum monthly precipitation and the model errors was nonexistent ($R^2 = 0.007$ and 0.01); correlations between annual precipitation and errors were slightly higher ($R^2 = 0.13$ and 0.07 at Pete King and Lolo), but still remained unimportant.

Summary

Comparisons between measured and model sediment yields at Lolo Creek show that the WATBAL model consistently underestimates the amount of sediment reaching the stream. In fact, not once did WATBAL overestimate sediment loading. Analyses comparing the differences between model and measured sediment yield indicate that stream discharge, particularly maximum stream discharge, is a primary factor in explaining the magnitude of the errors.

The differences between model and measured sediment yields at Pete King Stream cannot simply be explained by stream discharge, even though there are slight correlations. However, with the exception of those years which contributed extremely high amounts of sediment due to catastrophic road failures, the errors are distributed (approximately) normally about zero.

One model weakness is the manner in which WATBAL treats precipitation—particularly storm intensity. Correlations between model error and precipitation are extremely low ($R^2 = 0.007$—0.13); however, correlations between error and stream discharge are much higher ($R^2 = 0.14$—0.60). The reason for this difference may be that the effects of intense storms are often lost within monthly/annual precipitation volumes, whereas discharge is more directly related to storm intensity. The catastrophic failures of roads during 1979 and 1987 illustrate this relationship clearly—high discharge and sediment yield, but average to below average precipitation volumes for the months in question.

A closer examination of the WATBAL Technical User Guide (Patten, 1989) and the Guide for Predicting Sediment Yields from Forested Watersheds (Cline, et al., 1981) revealed four other potential sources of error. 1) Both publications make the assumption that surface erosion is insignificant on undisturbed forests—even during intense rains. 2) The WATBAL model reduces erosion rates for roads based upon the road's age. While this assumption may be valid during normal hydrologic conditions, the occurrence of road-related mass movement events increased with increasing road age during the exceptionally wet winter/spring of 1995/96 (Jones, 1996). 3) The calculation of road-related erosion mitigation (in percent reduction of erosion) is directly, rather than proportionally, cumulative. For example, if a rep-rap fill will reduce erosion by 50% and a seed and fertilizer application 25%, WATBAL calculates a 75% erosion reduction rather than 50% plus 25% of the remainder (12.5%) for a total reduction of 62.5%. 4) Finally, the size of an individual landtype unit, 8.1—81 hectares (20—200 acres), requires averaging which can potentially contribute to significant error. If nothing else, slope length is not constant from one side of a landtype unit to the other. Slope angle probably is not a constant either, and both exert considerable influence upon surface erosion calculations.

Conclusions

The implications of this study are 1) the limitations built into WATBAL by the "Guide for Predicting Sediment Yields from Forested Watersheds" (Cline, et al., 1981) are a primary reason for differences between measured and predicted sediment yields, 2) model validation should be an integral part of sediment yield modeling, and 3) if used as a planning tool, WATBAL output must be carefully evaluated. At Lolo Creek, sediment yields have been invariably underestimated, potentially setting the stage for long-term damage to the stream. At Pete King Stream, WATBAL is effectively predicting an average sediment yield (if catastrophic road failures are ignored). This statement must be further qualified, however, because the differences between predicted and measured sediment yields may be as high as an order of magnitude. Thus, a single road failure can deliver 10 years of average annual sediment supply into a stream at once. Such an event can severely impact fisheries for a number of years (Megahan, et al., 1992).

A possible solution to a number of the limitations of WATBAL would be to re-build the model within a geographic information system (GIS). Some of the advantages include:

a) The scale of the minimum mapping unit could be increased to, for example, a 30x30 meter cell.

b) Much of the important physical data is already available, for example, digital elevation models (DEM), soils maps, and Landsat imagery.

It is important to note that cell-by-cell calculations of slope angle and slope length are possible—rather than using averages for large areas (Hickey, et al., 1994).

c) The database could be easily updated using Landsat imagery.

d) Drainage paths and directions can be calculated and included in the model.

e) The relatively generic database structure allows the use of both average annual and discrete event modeling. As new techniques and improved software are developed, the models used in the Forest can be modified without having to alter the original data—only how it is used.

In summary, regardless of the type of model used, the limitations inherent in all models should be taken into consideration. In the case of the WATBAL model, average sediment yields are calculated—therefore, the inherent limitation is that 50% of the time, sediment yields are underestimated. Thus, forest management plans should be based upon higher than average sediment yields. To draw an engineering analogy, bridges are not built to withstand average (yearly) stream discharges, but to tolerate 50 or 100 year flood levels. Forest planning need not be based around such catastrophic events; however, tolerances for some above normal rainfall events (or years) should be included in planning considerations—i.e. using sediment yield values one standard deviation above normal.

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