

PROCEEDINGS
OF THE
THIRD FEDERAL INTER-AGENCY
SEDIMENTATION CONFERENCE
1976

PARTICIPATING AGENCIES

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Water Resources Council

March 22-25, 1976

Denver, Colorado

Prepared by
Sedimentation Committee
Water Resources Council

The Use of Color Infrared Photography
For the Determination of
Suspended Sediment Concentrations and Source Areas

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ABSTRACT

The concepts and special techniques for applying color infrared photography in sediment studies are presented. These techniques were developed and evaluated through a low elevation color infrared photography flight and concurrent water quality sampling conducted on 164 km (100 miles) of stream over the West Fork of the Madison River in southwestern Montana. The concentrations and sources of sediment produced during peak snowmelt runoff were determined by photo densitometric analysis coupled with specifically located ground control stations.

Excellent correlations were established by regression analysis of the ground truth variables including stream width to discharge and suspended sediment to turbidity. Photo density was correlated with suspended sediment and turbidity, both produced strong correlations which were significant at the 99% confidence level. These correlations made it possible to determine reliable estimates of sediment concentrations from the aerial photography where stream measurements were not obtained.

Sediment production estimates were made by using the concentration data linked with stream discharge as a function of stream width. The photo-scale control markers were used to obtain stream widths from the aerial photography.

The photographic analysis indicated that the majority of the suspended sediment sources during the snowmelt runoff event were derived primarily from channel erosion. Additional interpretations which can be derived from photo analysis are also presented and discussed.

INTRODUCTION

Sediment production is one of the most serious water pollution problems of mountainous watersheds. Information is vitally needed about the source, magnitude, and consequence of accelerated sediment production, especially in relation to resource management activities. Watershed specialists have attempted to locate and quantify sediment production in many drainages; however, the problem of obtaining water resource data over large, inaccessible areas during short-term climatological events has been insurmountable by traditional methods. As a result, most of the sediment studies have been located at the confluences of relatively large watersheds.

Since 1966 accessibility and financial limitations have hampered efforts by watershed specialists to determine the amounts, sources, and distribution of suspended sediment in the West Fork of the Madison River in southwestern Montana. Public concern over the disproportionately high sediment contributions from the West Fork to the Madison River (a nationally famous trout stream), provided the impetus for additional studies. The objectives of these studies were to determine the sources of the high sediment concentrations and what effect the large array of land use activities have on sediment production.

Not only was accessibility a serious problem in the large watershed of 51,800 hectares (200 mi²), but the extremely complex array of vegetation types, geologic formations and soils produced varying levels of natural erosion, stream channel types, and resultant sediment concentrations within the subdrainages involved. In conjunction with this variability was a variety of land use activities including grazing, timber harvest, road construction, wildlife and recreation. Under "traditional" water collection and analysis procedures, there were not enough people, funds, time or water bottles to meet the objectives of the water quality study.

It was evident that some type of remote sensing technique was needed to overcome these inventory and analysis difficulties, thus a color infrared photographic (CIR) flight was conducted concurrent with selected ground truth sampling. This flight was to provide a quantitative evaluation of the sources, concentrations and distribution of suspended sediment during the high elevation snowmelt runoff period, when sediment production was at its highest.

REMOTE SENSING CONCEPTS AND APPLICATION

There are many sensing devices which can be used to obtain images from the earth's surface. Sensors which can be used by aircraft include the human eye (visual reconnaissance), cameras, thermal and multispectral scanners in addition to radar and passive microwave sensing instruments (Keifer and Scherz, 1971). Airborne radiometers can be quite useful in determining surface temperatures of water, but it is the image-producing systems which appear to be the most useful for water quality studies (Scherz, 1971).

A type of image-producing system which appears to be the most suited for physical water quality studies is color infrared photography (CIR) or false-color film. This film is named because objects do not appear on transparencies of prints in the same color as they do to the human eye. The film is used with a "minus blue" (Wratten No. 12) filter which prevents blue light from exposing the film (Heller, 1970). Thus, only reflected green, red and infrared wave lengths (.6 to .9 μ m) reach the emulsion. The CIR film has a great ability to cut haze, which provides good resolution. One major disadvantage is that it has poor shadow penetration and needs uniform sky light conditions for consistent photo images. Thus, on heavy overcast days with variable sunlight reflection its use is limited for this purpose. Until recently there has been a

lack of documented research for the specific application of CIR photography for the quantitative analysis of suspended sediment concentrations. Some investigators, however, have obtained preliminary results on some practical applications. Logan (1967) had been using CIR film for sediment detection purposes on National Forest land in southwestern Montana. By adapting a handmade microdensitometer, he found an apparent relationship between the photo density and the concentrations of sediment in the water. Clear water appeared dark blue as most of the energy was absorbed by the water. As the concentration of suspended sediment increased, there was more energy reflected, thus the image recorded on the film appeared in lighter tones of blue. Scherz (1971) reported that the energy from water targets which arrives at the camera using CIR film is a function of the suspended and dissolved material in the water, the material floating on the water, and the sum of energy that penetrates to the bottom and reflects back the images of the bottom. From the interpretation of reflectance curves he reported that the concentration of suspended solids appears to be correlated with the amount of light reflectance (Figure 1).

A suspended solids/density model was developed by Lillesand (1973), utilizing CIR photography, where a prediction of suspended solids concentration was determined from photodensitometric measurements. The model was developed from a relationship between image density, film exposure and scene reflectance. Their prediction equation as compared to observed suspended solids versus image density is shown in Figure 2.

Additional work by Lillesand, Scarpace and Clapp (1975) indicated that photodensitometric measurements, coupled with ground truth and analyzed with due regard for peripheral effects, can be used reliably to predict suspended solids in the mixing zone. Their research obtained more reliable and detailed information from densitometric analysis than by traditional surface measuring techniques.

Klooster and Scherz (1973) showed sample reflectance as a function of turbidity and related suspended solids (Figure 3). They concluded that using CIR photography in conjunction with densitometric analysis and ground truth provides a more complete and extensive quantitative evaluation of turbidity or suspended solids than conventional techniques. Turbidity, as an optical property, is related to light scattered from suspended material in the water (Klooster and Scherz, 1973). Since turbidity is what the aerial camera actually detects, it is important to establish a correlation of suspended sediment to turbidity and be aware of the relationship of the two for a particular stream.

Heller (1970) describes several quality control factors for applying densitometric analysis including: (1) physical factors such as ground luminance and reflectance, atmospheric scattering of light, angle of sun, and spectral quality of sunlight; (2) film, emulsion and filter properties; (3) camera and equipment factors such as image motion, etc. Heller also reported that, under clear weather, illumination drops off as latitude increases north or south from the equator by season of the year or by hours before and after local apparent noon. Thus, photographic flights for detailed quantitative analysis should be made within

two hours of local apparent noon. If the investigator is to quantitatively analyze the film, variations in the optical density of the film against effective exposure should be determined through sensitometry techniques as explained by Dana (1971).

Another factor involving a very important peripheral effect is the surface reflection of energy due to the discontinuity in refractive index at the air-water interface. The percentage of the energy reflected at the interface is a strong function of angle (Pietch and Walker, 1971). Below 49° the percentage of energy reflected is small and constant (Figure 4). This can be adjusted in the photo analysis procedure. If sky light intensity is influenced by an overcast condition, this factor is not as significant in the photo analysis due to the uniformity of the light conditions. These and other spectral variability factors must be considered in planning aerial water quality surveys.

AERIAL PHOTOGRAPHY AND FIELD SAMPLING PROCEDURE

Photography

The author conducted the flight in June, 1971 on the Beaverhead National Forest, Northern Region of the U.S. Forest Service. A hand-held 70 mm Maurer P-2 camera fitted with a 6.8 cm (3-inch) lens and a Wratten 12, "minus blue" filter, was used with Kodak Aerochrome color infrared (type 2443) film. This camera system is described by Heller, et al., (1959). The film was loaded in three separate 15.5 m (50 feet) rolls. The photographs were taken vertically from the door of a helicopter, with a flying height of 91 meters (300 feet), which provided a 1:500 photo scale. Photo scale control was obtained by placing white 1.2 x 1.8 meter (4' x 6') markers at specified stream junctions prior to the flight. The photography was taken within 10 minutes of the actual field sampling.

The aerial flight was timed to coincide with the high elevation, snow-melt-generated peak runoff of the West Fork. Selection of the flight day also was closely coordinated with sky conditions. The flight was conducted two hours before and after local apparent noon. If sky conditions such as cloud shadows changed significantly, the helicopter would land and wait for favorable conditions. Figure 5 shows the hydrograph of the West Fork in relation to the flight. Over 161 kilometers (100 miles) of stream were flown with 46 meters (150 feet) of film taking intermittent photographs.

Field Sampling

In order to correlate the photo density with various water quality characteristics, 20 water sampling stations were established. These stations were stratified by hydrophysiographic units where sediment rating curves were expected to be different. These stations were also selected to provide the greatest variation in concentrations, differences in stream channels (materials and patterns), upstream management and elevation. All sampling was done concurrent with the flight.

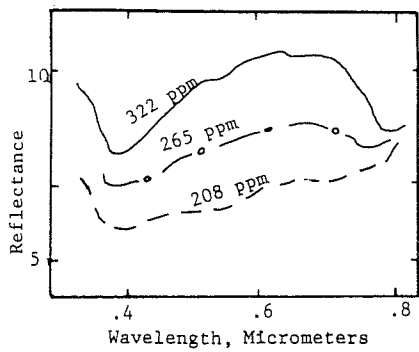


Figure 1. Change in reflection of steel mill discharge from Chicago area as a function of concentration of solids (Scherz, 1971).

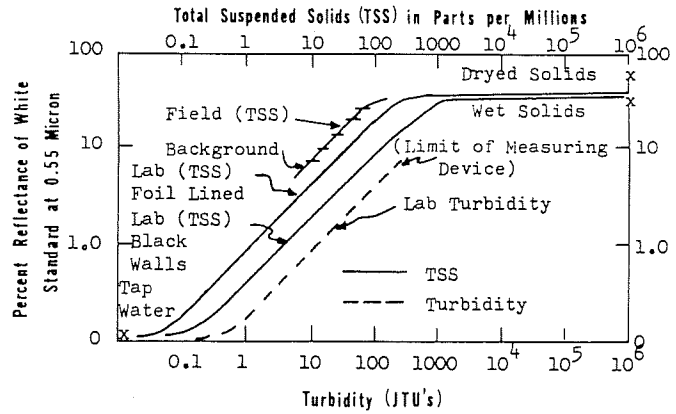


Figure 3. Reflectance vs. turbidity and suspended solids. Field reflectance was obtained from film. (Klooster and Scherz, 1973).

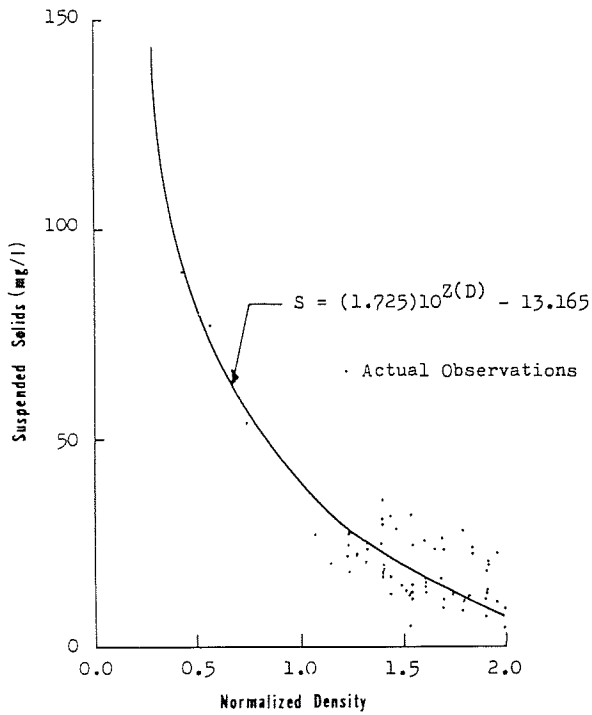


Figure 2. Suspended-solids/density model of red film layer (From Lillesand, Scarpace and Clapp, 1975).

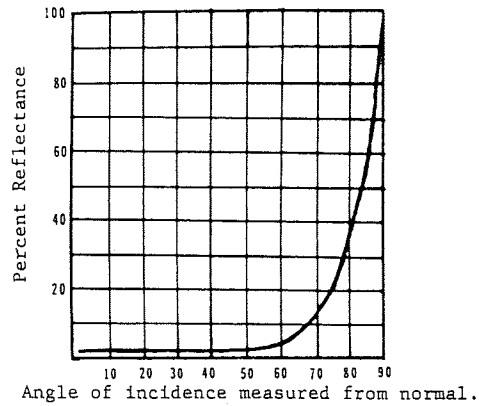


Figure 4. Percentage reflectance of air-water interface as function of angle of incidence, measured from normal direction (Pietch and Walker, 1971).

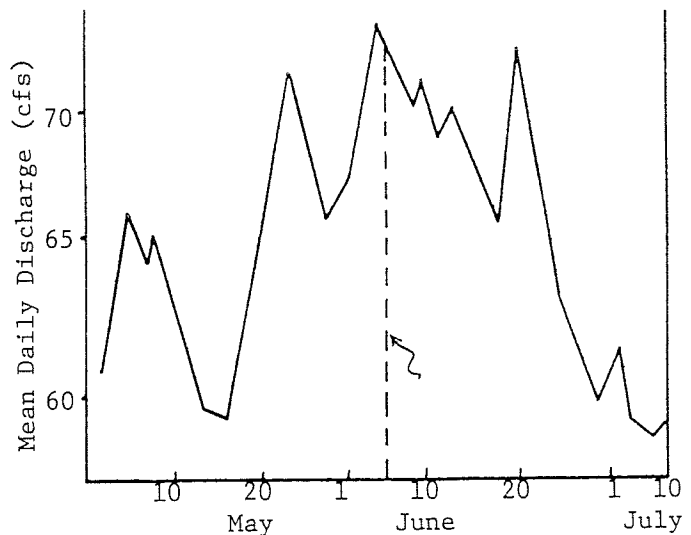


Figure 5. Hydrograph of the West Fork of the Madison River, Montana, 1971.

Suspended sediment samples were obtained using D. H. 48 and 59 depth-integrating hand samplers (Guy and Norman, 1970). The depth-integrating suspended sediment samples were averaged across the stream. Additional samples were obtained for turbidity, temperature, pH, and specific conductance. Stream discharge was measured at each site. These measurements were made to determine sediment production and to provide additional interpretation from stream velocity, depth, and width measurements.

The helicopter enabled ground truth data to be collected at inaccessible sites concurrent with the photographic flight. To speed up the photographic coverage of the watershed, field assistants provided ground truth data at a few accessible station locations as the helicopter approached.

DATA ANALYSIS AND RESULTS

Analysis

The water samples were analyzed for suspended sediment concentrations (mg/l) by the filtration procedure as described by Guy (1969). Turbidity (JTU) was determined with a Hach Model 2100 turbidimeter. Additional water analysis and stream measurements were obtained at the site during the flight.

The ground truth variables were analyzed by regression analysis. This analysis included the relationship of turbidity to suspended sediment and stream width to stream discharge.

After the CIR film was processed, the Pacific Southwest Forest and Range Experiment Station at Berkeley, California generously offered the use of their photometric data system's digital comparator microdensitometer and computer facility. This microdensitometer is described by Doverspike et al, (1965).

Optical densities were obtained by the microdensitometer on the 70 mm CIR film transparencies at the exact location where the water samples were obtained.

Density readings were obtained from the transparencies with clear, red, green and blue filters. Multiple regression analysis was used to determine which filter or filter combinations provided the best correlations with suspended sediment and turbidity variables with photo density.

The correlation coefficient, F-test, and standard of error estimates were obtained. Once the regression equations were developed for photo density to turbidity/suspended sediment, additional density readings were obtained where field data were not available. This was done to determine:

- Sources of sediment during the runoff event.
- Spatial distribution of sediment within the watershed.
- Concentrations of sediment by subdrainages as a function of stream discharge and channel type.

Results

The measured suspended sediment concentrations from the sampling stations varied from 22 mg/l to 660 mg/l. Turbidity levels varied from 15 JTU's to 202 JTU's.

Regression analysis of the ground truth variables produced the following correlations (Figures 6 and 7).

<u>Variables</u>	<u>Correlation Coefficient (r)²</u>	<u>Level of Significance</u>
Suspended sediment/turbidity (JTU) (mg/l)	.92	99%
Stream width/stream discharge	.90	99%

A multiple regression analysis involving a linear relationship of photo density to suspended sediment and turbidity for clear (none), red, blue, and green filters indicated that the best correlation was obtained with the clear (no filter) density (Norick, 1973, personal communication).

Based on a plot of the X, Y variables for both sediment-density and turbidity-density, a curvilinear relationship appeared to be the most representative. A multiple regression analysis indicated a strong correlation of both turbidity and suspended sediment to photo density with the clear filter. The statistics summary is shown in Table 1. The regression equation for both turbidity and suspended sediment is shown in relation to the observed values (ground truth) (Figures 8 and 9).

Table 1. Statistics Summary of Regression Analysis of Photo Density to Turbidity and Suspended Sediment

	<u>Turbidity (JTU)</u>	<u>Suspended Sediment (mg/l)</u>
Correlation coefficient (r ²)	0.84	0.81
Standard error of estimate	18.6	71.5
F Value at the .01 level	36.2	28.9
F .010 Test Significance	Highly Significant (99% level)	Highly Significant (99% level)

DISCUSSION

Variables in Photo Analysis

There are many spectral variables involved when taking direct photo density readings for quantitative analysis. The effects of many of the variables could not be evaluated in this study. They were, however, anticipated and isolated for later identity in the photography and ground control procedures. As discussed earlier high surface reflection occurred on many transparencies due to sun angle changes. However, this reflection

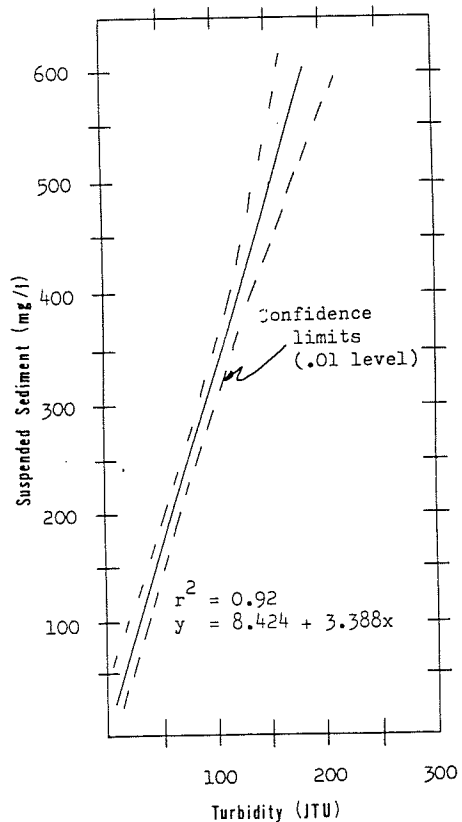


Figure 6. Linear regression of suspended sediment to turbidity.

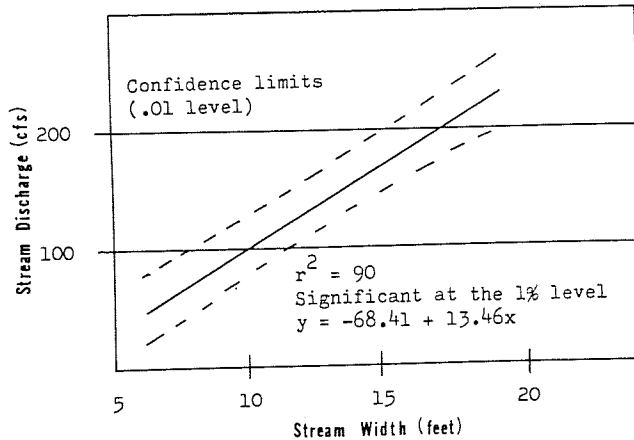


Figure 7. Regression of discharge as a function of width.

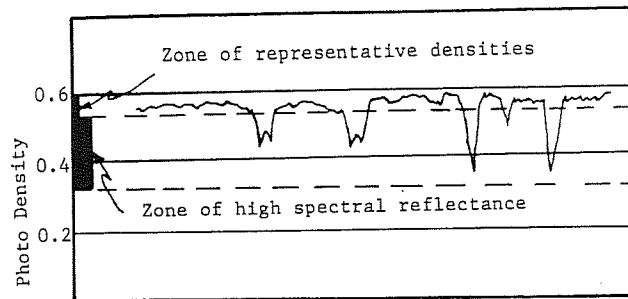


Figure 10. Chart trace of printout of micro-densitometer readings indicating zone of representative densities and a zone of high spectral reflectance as a result of super-critical flow, sun angle, etc.

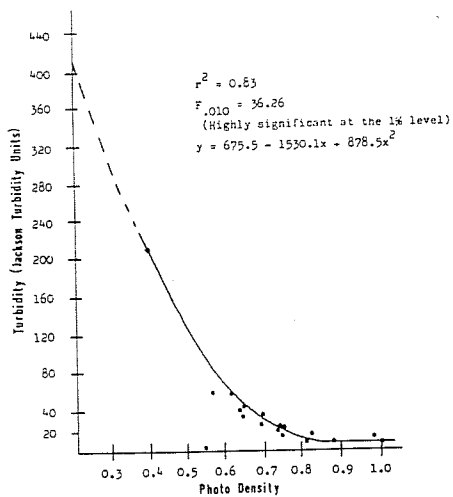


Figure 8. Curvilinear regression of turbidity to photo density.

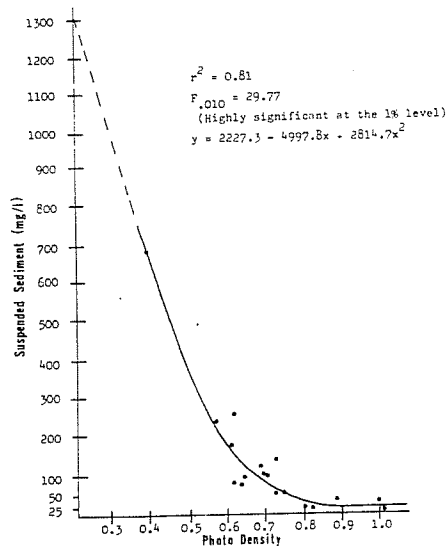


Figure 9. Curvilinear regression of suspended sediment to photo density.

only occurred on portions of the transparency, allowing the remaining areas to be analyzed. The microdensitometer produced abrupt "peaks" in these portions, quickly identifying the high reflections areas (Figure 10).

The ability to readily detect this reflection helps avoid unnecessary detailed microdensitometer analysis. Reaches of steep gradient streams with super-critical flow also created very high surface reflectance. Thus, density readings were avoided in these reaches. As explained earlier, CIR has poor shadow penetration which directly affects optical density. When high cumulus clouds would create shadows, the helicopter had an added advantage over fixed wing aircraft by being able to land and wait for more consistent sky conditions. In some reaches, stream-side vegetation caused shadows affecting photo density. Quantitative analysis from photo density could not be obtained in these areas.

Where stream depths were less than 0.3 of a foot combined with sediment concentrations of less than 20 mg/l bottom materials were reflected, causing unrealistic density readings. Since the .7 to 1.0 micrometer wave lengths are adsorbed by the first few inches of water there were penetration problems on these types of very shallow streams. It is the blue-forming layer of the CIR that captures the penetrating wave lengths (Kiefer and Scherz, 1971). Thus for future studies a filter combination eliminating the blue layer for density analysis of very shallow streams may provide a better representation. Most of the streams on the West Fork drainage had adequate depth and/or sufficient sediment concentrations to overcome this problem.

Over 98% of the total sediment production at the mouth of the West Fork is suspended load (Lisle, 1972). This factor and the fine texture of the material in suspension (silts and fine sands), contributed significantly to the high correlation of the suspended sediment/turbidity and to the good correlation of photo density (based on the reflective characteristic of sediment-laden waters) to suspended sediment concentration. These relationships will vary by streams and should be established concurrent with the photographic flights.

A regression equation may be regarded as a satisfactory predictor if the "F" value should exceed the selected percentage point of the F-distribution by a factor of four times the selected percentage point (Draper and Smith, 1966). The F values derived from Steel and Torrie (1960) for turbidity/density and sediment/density of 36.2 and 29.8, respectively, exceed the F value of 6.51 at the 99% level by over four times.

From this relationship density readings may be obtained to determine sediment concentrations throughout the watershed if the CIR transparencies are used with due regard to the spectral variabilities involved. Thus, direct interpretations of sediment concentrations and turbidity can be made where field data was not obtained. This technique presents an approach to solving an age-old problem in sediment studies, that of obtaining enough sample points within the watershed during a runoff event to determine sources and spatial distribution.

Not only is access limiting in wildland watersheds, but obtaining enough people, equipment, and dollars to determine source areas and distribution of sediment is not feasible (as evidenced by the lack of such data). With a densitometric analysis "thousands" of data points throughout the watershed become available to the interpreter as the runoff event is uniformly captured.

The total cost of this project, involving helicopter time, film, and film processing, field data collection and analysis, and the photo analysis was approximately \$2,200, or \$14/km (\$22/mile).

Sediment Sources and Interpretations

Through the photo scale control stream widths can be measured by photo analysis. From the excellent correlation of the width to discharge reliable estimates of discharge can be obtained. Once discharge is determined the density readings to estimate suspended sediment concentrations can be combined to quantify total sediment production (tons/time/area) for various stream reaches.

To determine sediment source areas photo density readings were taken on headwater streams where problems in direct sediment introduction by overland flow, rilling and gulying were occurring. Very low density readings (indicating very high sediment concentrations) occurred on many headwater streams from these direct sources. The concentrations were reduced in a very short distance downstream due to the low stream discharge and the "depositional" type channels draining these areas. Thus, a low percentage of the introduced sediment appeared to be transported to the larger order streams. The low stream discharges from these headwater areas resulted in low sediment production compared to the total at the mouth of the West Fork during this snowmelt runoff period.

In many instances on both large and small streams incised in material of low "erosional resistance", density readings became progressively lower (higher concentrations of suspended sediment) with increasing width and associated discharge downstream. This increase as determined from density readings, would occur between contributing tributaries, indicating sediment sources were predominantly from channel erosion. This did not occur on stable channels incised in coarse angular material.

As the sediment concentrations were traced throughout the stream system, it was evident that during this runoff event the bulk of the total sediment production at the mouth of the West Fork was derived primarily from channel sources. The majority of the subdrainages appeared to owe the bulk of their sediment load to channel erosion processes. The sediment/discharge relationships of the various tributaries also provides some interpretation as to stream equilibrium conditions in relation to the downwasting rates of the various combinations of landtype within the subdrainages.

Another type of interpretation provided by the densitometric analysis was on the distribution of high concentrations of sediment from direct source areas. On one reach, density readings were obtained upstream,

at the source, and within three meanders downstream of a very high unstable streambank. Although the average stream velocities in this reach exceeded 1.8 m/second (6 feet/second) and the material was composed of noncohesive fine sands, over 95% of the suspended load that was contributed from these areas was deposited within 400 yards downstream (Figure 11).

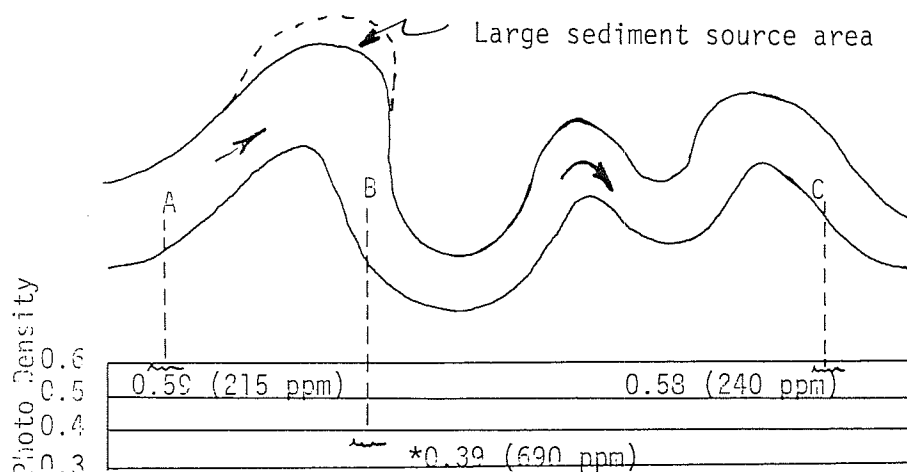


Figure 11. Sediment concentrations and distribution from direct source as determined by photo microdensitometer analysis and strip chart readout for respective stream points A, B and C. *Densities averaged across stream width at selected reach.

Due to the very high concentrations of the sands in suspension deposition occurred. The densitometric analysis provided the ability to determine downstream change in concentration from the sources. On-site field tests verified this interpretation of concurrent scour and deposition at this site. The net result is a prevalence of channel migration. Hydrodynamic studies conducted on the West Fork have shown that the stream is migrating at the mouth at the rate of 5 cm/year (2 inches/year) (Lisle, 1972).

A detailed analysis of the sediment study of the West Fork is beyond the scope of this paper; however, the CIR photography flight and analysis made it possible to pinpoint the sources and spatial distribution of sediment. The analysis also assisted in the water quality characterization of the various subdrainages within the West Fork watershed.

Application

Some of the more obvious advantages of using some form of remote sensing technique in sediment studies are:

1. Coverage of an entire stream system during short-term sediment producing events;
2. Establishment of permanent bench mark records for later detailed quantitative analysis and comparison;
3. Supplementation of detail and interpretation beyond limits of the human eye;
4. Minimum expenditure/unit area for data collection and analysis.

The use of photo analysis can also provide a key in the analysis of stream channel processes in a reach. Subsequent aerial photographs can also indicate rates of bar formations, channel widening, riffle-pool ratios, delta formations and other fluvial features.

Through proper interpretation and analysis of this data, answers can be provided to the following questions:

1. What are the sources and spatial distribution of sediment.
2. What are differences in the sediment producing characteristics between the various subdrainages for short-term hydro-meteorological events.
3. What management criteria is needed to protect or enhance the physical water quality.

The use of CIR photography coupled with a well-planned network of ground truth data should provide a very reliable, fast and inexpensive means of obtaining water quality data in large remote areas. With proper attention to the controls necessary to minimize spectral variability in photographic procedures and microdensitometer analysis, reliable sediment concentrations may be obtained through photo analysis. The overall view provides a sound basis for determining sediment production within a watershed during runoff producing events.

Acknowledgment

The author wishes to express appreciation to Robert C. Heller, Professor, University of Idaho and retired Project Leader, Remote Sensing Unit, Pacific Southwest Forest and Range Experiment Station, for his technical assistance, and for the contributions made by the research station staff, especially Mrs. Nancy Norick and Bob Thomas, for their statistical analysis assistance. The Madison Ranger District personnel also provided valuable assistance in carrying out the project.

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