The Use of Color Infrared Photography for the Determination of Sediment Production

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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 conducted on 100 miles of stream over the West Fork of the Madison River in southwestern Montana. The source and magnitude of sediment production during peak snowmelt runoff was analyzed by photo interpretation and the use of carefully located ground control stations.

Regression analysis was used to correlate width to discharge and suspended sediment to turbidity, producing excellent correlations significant at the 99 percent level. Photo density measured by a microdensitometer was correlated with suspended sediment and turbidity, and both produced strong correlations significant at the 99 percent level. These correlations made it possible to determine reliable estimates of sediment production through photo analysis.

The photographic analysis indicated that the majority of the suspended sediment sources were primarily from channel erosion. Fluvial interpretations derived from photo analysis were also presented and discussed.

INTRODUCTION

The use of color infrared photography to locate and quantify sediment production has had limited application in most water quality monitoring programs. This limited application is the result of the resource managers unfamiliarity with the different remote sensing techniques and their application to the work at hand.

Sediment production is one of the most serious water pollution problems of mountainous watersheds. Information is vitally needed about the source, magnitude and long-range consequence of accelerated sediment production, especially in relation to short-term resources management activities.

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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 centered in relatively small watersheds.

In June 1971 a color infrared photographic flight was conducted to provide resource managers with quantitative data of the sources and distribution of suspended sediment in the West Fork of the Madison River in southwestern Montana. This project was conducted on the Beaverhead National Forest, Northern Region of the U. S. Forest Service. The West Fork of the Madison River was chosen because of its disproportionately high sediment contributions during spring snowmelt runoff periods to the Madison River, a nationally renowned fishing stream.

The West Fork of the Madison is a watershed of extremely diverse geology, soils and vegetative associations, coupled with a wide variety of land use activities involving grazing, timber harvest, road construction, wildlife and recreational impacts. The relationship of these land uses and the various hydrophysiographic regimes to the sediment production of the West Fork has caused much concern. The large area (200 square miles) and the inaccessibility of the West Fork has hampered inventory attempts since 1966. Under "traditional" water collection and analysis procedures there were not enough people, funds, time or sediment samplers to meet the objectives of these watershed studies.

It was evident that some type of remote sensing technique was needed in order to overcome these inventory and analysis difficulties and provide timely interpretations for resource management application.

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, 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).

One type of image producing system which appears the most suited for physical water quality studies is color infrared photography or false-color film, so named because objects do not appear on transparencies of prints in the same color they do to the human eye. The film is always 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 micrometers) reach the emulsion. It has a great ability to cut haze, which provides good film resolution. One major disadvantage is that it has poor shadow penetration and needs direct sunlight reflectance for consistent photo images. Thus, on cloudy days, its use is limited for this purpose. There has been a lack of documented research for the specific application of color infrared photography for the quantitative analysis of sediment production. However, some investigators have obtained preliminary results on some practical applications. Logan (1967) had been using color infrared 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 color infrared 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 reflection curves (Figure 1) he reported that the concentration of suspended solids appears to be correlated with the amount of light reflectance.

Another recent large scale study was initiated by Ruff, et al., (1972) in cooperation with the Bureau of Reclamation. They flew the Clarks Fork of the Yellowstone River in Montana using thermal infrared imagery for water temperature interpretation and color infrared photography for sediment and turbidity detection. Ground sampling was conducted concurrent with the flight. Their visual observations of the film where ground control data was available indicated that small changes in suspended material concentrations in water change the reflective characteristics significantly in the wave length recorded on the color infrared film.

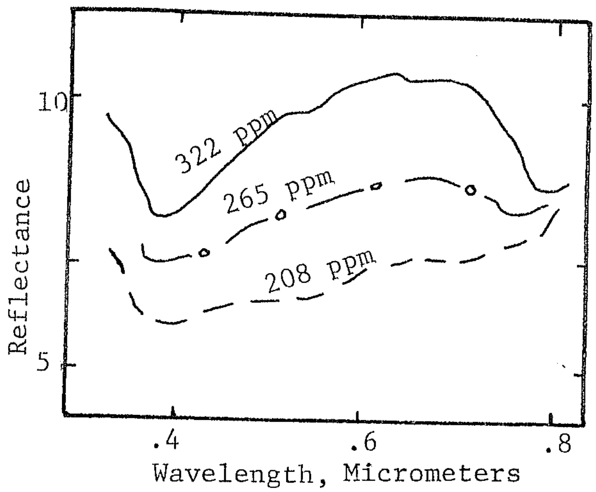

Figure 1. Change in reflectance of steel mill discharge from Chicago area as a function of concentration of solids. (Scherz, 1971)

Factors to consider for maintaining good quality are described by Heller (1970): (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 equpment 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 variable which involves 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 40° the percentage of energy reflected is small and constant (Figure 2). This can be adjusted in the photo analysis procedure.

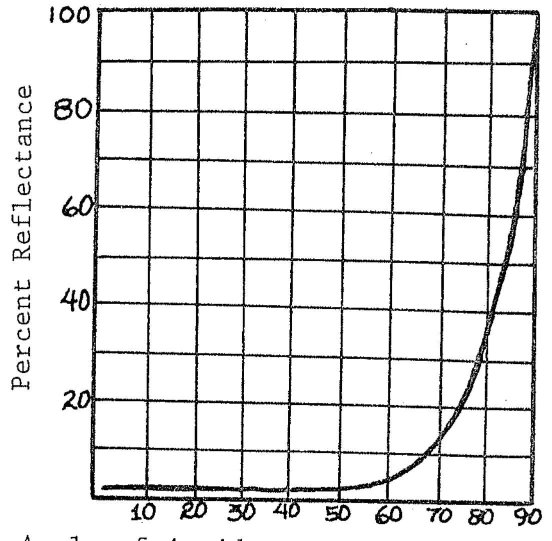

Figure 2. Percentage reflectance of air-water interface as function of angle of incidence, measured from normal direction. (Piech and Walker, 1971)

These and other spectral variability factors must be considered in planning aerial water quality surveys.

AERIAL PHOTOGRAPHY AND GROUND CONTROL PROCEDURE

Photography

The author conducted the flight using a hand held 70 MM Maurer P-2 camera fitted with a 3-inch lens and a Wratten 12, minus blue filter. Kodak Aerochrome color infrared (type 2443) film was used. This camera system is described by Heller, et al., (1959). The film was loaded in three separate 50-foot rolls. The photographs were taken vertically from the door of a helicopter, with a flying height of 300 feet, which provided a 1:500 photo scale. Photo scale control was obtained by placing 4' x 6' markers at certain stream junctions. This was supplemented by actual stream width measurements at selected locations throughout the flight. The photographs were taken within 10 minutes of the actual field sampling and measurements of the stream.

The flight was conducted two hours before and after local apparent noon. If sky conditions changed significantly, such as cloud shadows, etc., the helicopter would land and wait for favorable light conditions. The aerial flight was timed to coincide with the high elevation snowmelt generated runoff peak of the West Fork. The hydrograph of the West Fork in relation to the flight is shown in Figure 3. The selection of the day to fly was closely coordinated with sky conditions and runoff peaks. Over 100 miles of stream were flown and photographs taken intermittently using over 150 feet of film.

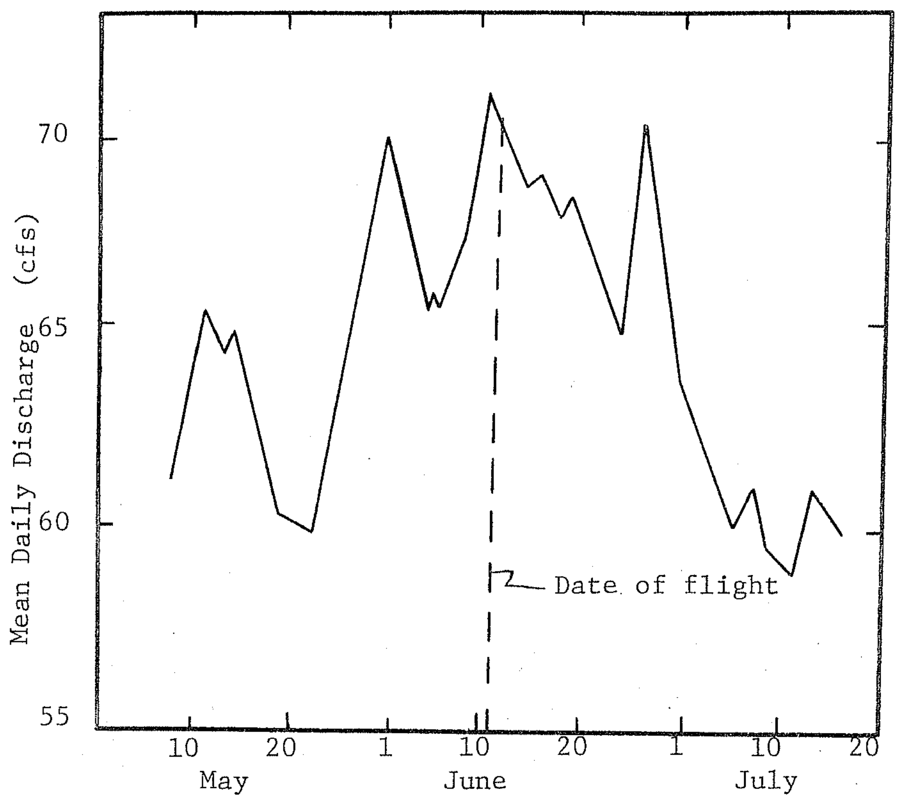

Figure 3. Hydrograph of the West Fork of the Madison River, Montana. 1971

Field Sampling

In order to correlate the photo density with various water quality characteristics, a network of water sampling stations were selected (Appendix I). Stations were stratified by hydro-physiographic units where sediment concentrations per unit discharge relationships were expected to be different. These stations were also selected to provide a range in stream gradient, velocity, depth, width, and sediment types and concentration. Differences in elevation which might affect light attentuation were also included in the selection.

Suspended sediment samples were obtained using a D.H. 48 depth-integrating hand sampler (Guy and Norman, 1970). Additional samples were obtained for turbidity. Temperature, pH and specific conductance were also determined.

Stream width, depth and velocity were also measured at each site. This was done to determine their interrelationships and to provide stream discharge to quantify sediment production.

The helicopter enabled this 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 control data at a few selected stations 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.

After the infrared 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 infrared film transparencies at the exact location where the water samples were obtained.

Density readings were obtained with clear, red, green, and blue filters. Multiple regression analysis was used to determine which filter or filter combinations provided the best correlations with the field variables.

Regression analysis was then used to determine the relationships between the water quality data and optical or photo density. Tests of the residuals for linearity indicated the particular form of the relationship and whether additional analysis was needed.

Once relationships were determined, photo density and stream width measurements could be obtained by photo analysis to determine sources and spatial distribution of sediment and other water quality characteristics.

Density readings were also obtained for the streams in each major hydrophysiographic regime to determine the sediment production/per unit discharge as a function of erosional rates and channel morphological conditions.

Results

The suspended sediment concentrations at the sampling stations varied from 22 mg/1 to 660 mg/1. Turbidity levels varied from 15 JTU's to 202 JTU's.

Regression analysis of the field data indicated the following correlations: (Figures 4 and 5).

Variable	Correlation Coefficient (r)	Level of Significance
Suspended sediment/turbidity	.96	99%
Stream width/discharge	.95	99%
Depth/discharge	.81	99%

The linear regressions used to determine the correlation of sediment to photo density and turbidity to photo density produced correlation coefficient (r) values of .72 and .68 respectively, both were significant at the 99% level. The relationship of suspended sediment and turbidity to photo density is shown in Figures 6 and 7.

The simple linear model indicated a strong relationship (^{F} Prob. 15 = 15.69) significant at the 99% level. The X, Y observations and the plot of the residuals, however, indicated that the model should either be curvilinear or that separate regression equations be established for high and low sediment concentrations, (Norick, Personal communication, 1973). Although the sample size does not lend itself for more complex models, a simple curvilinear regression model was used to investigate this trend. This regression produced an r value of suspended sediment to photodensity of 0.94 and an r value of 0.96 of turbidity to photodensity, both being significant at the 99% level (figures 8 and 9).

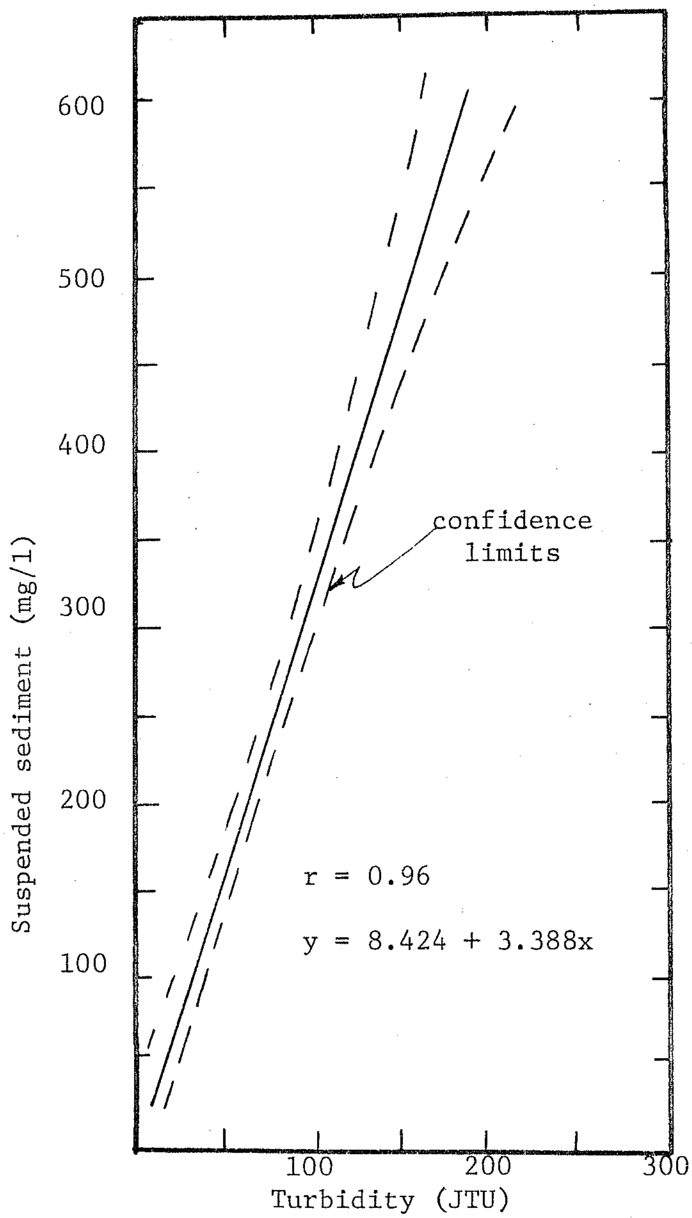

Figure 4. Linear regression of suspended sediment to turbidity.

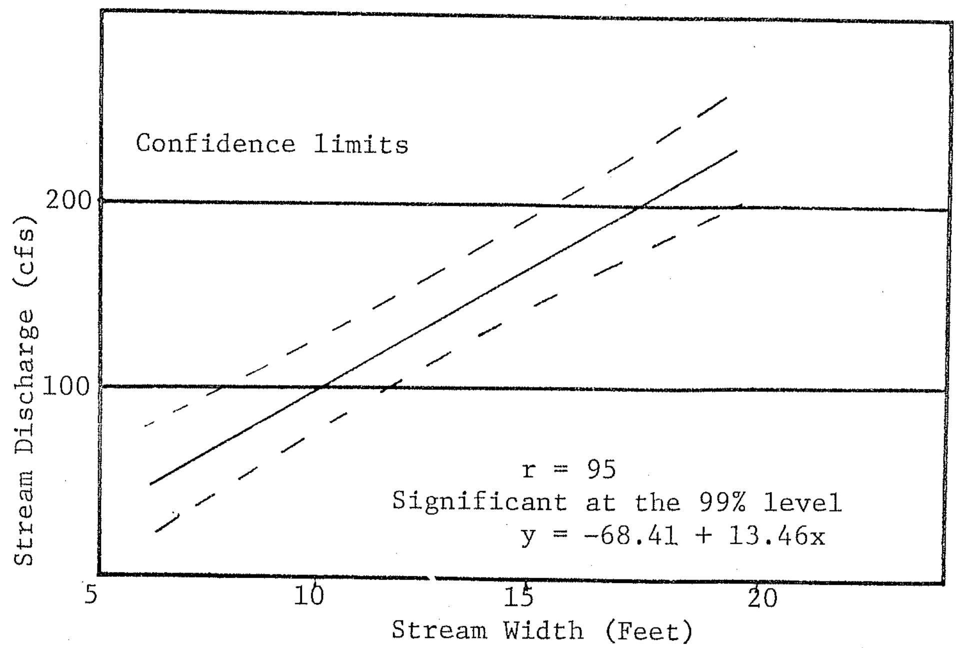

Figure 5. Regression of discharge as a function of width.

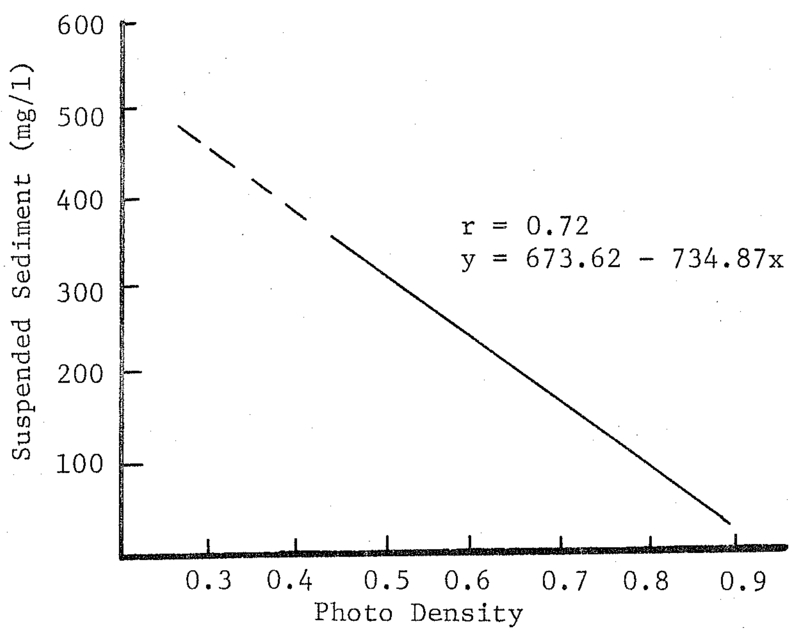

Figure 6. Linear regression of suspended sediment to photo density.

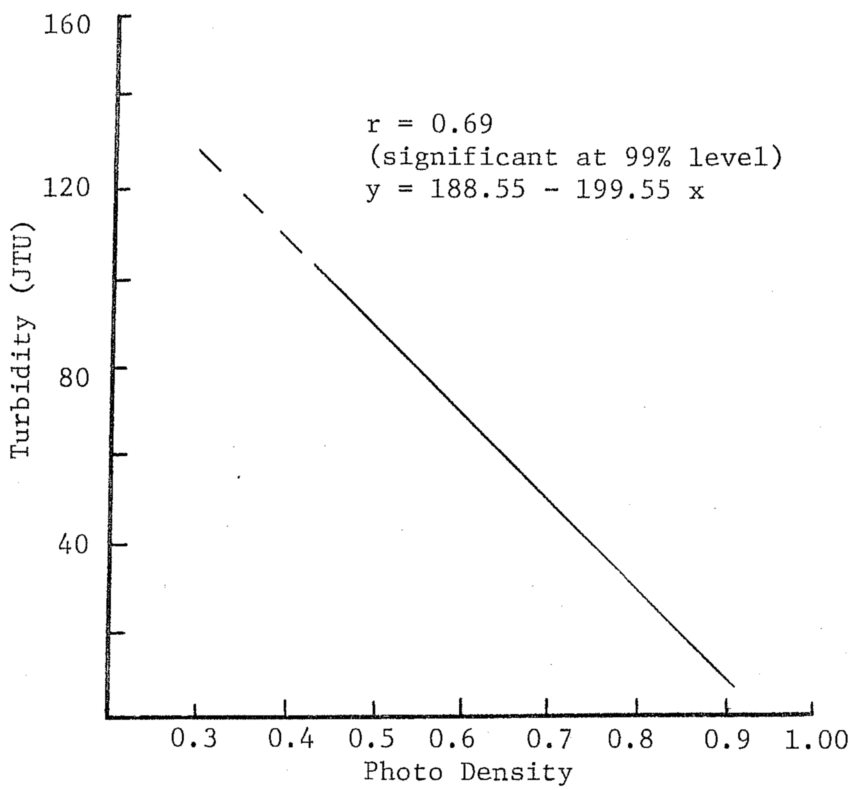

Figure 7. Linear regression of turbidity to photo density.

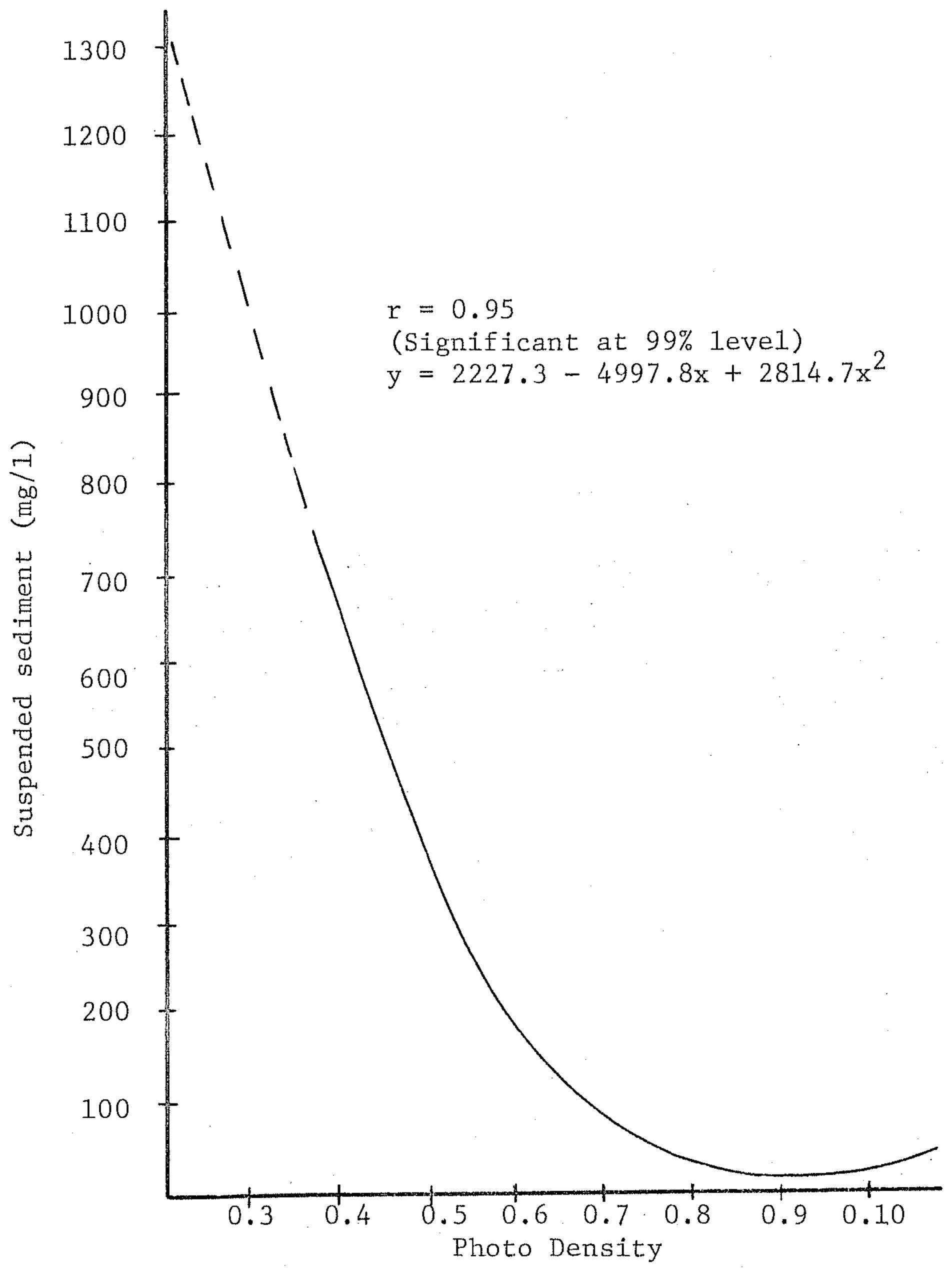

Figure 8. Curvilinear regression of suspended sediment to photo density.

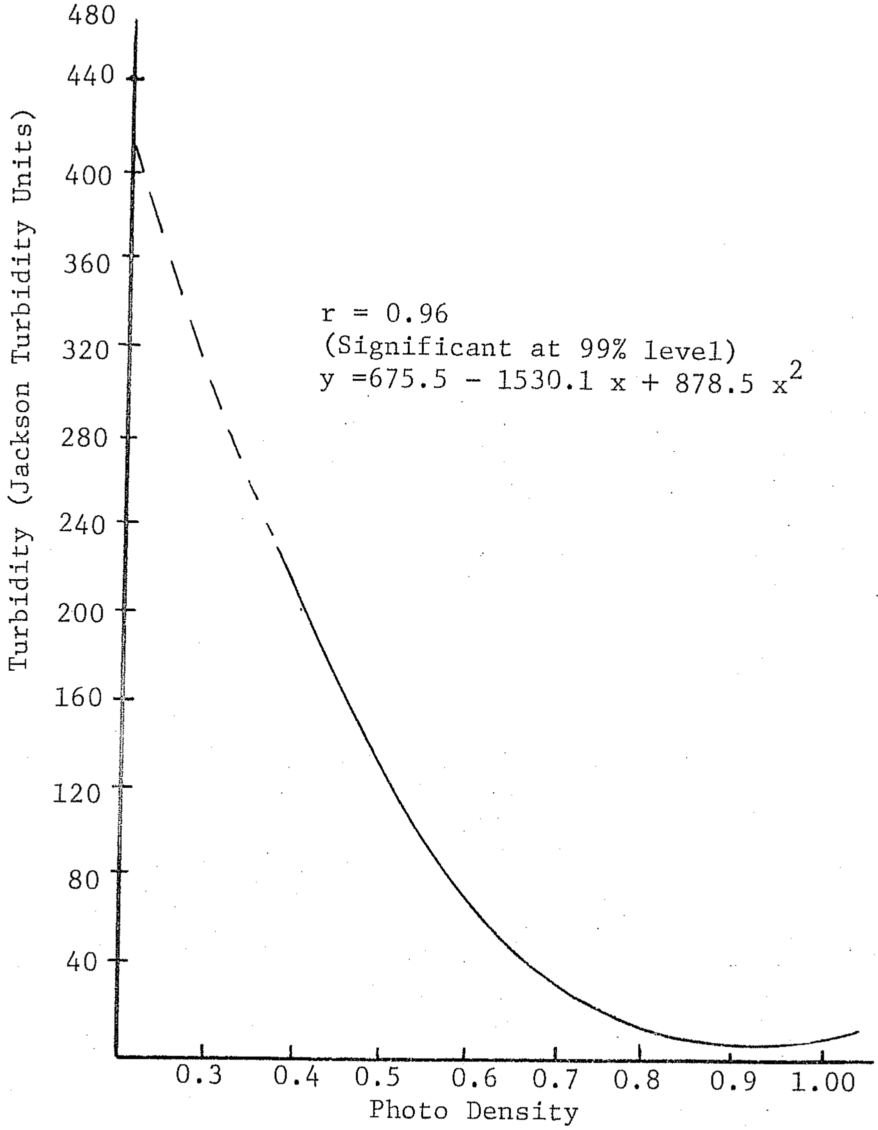

Figure 9. Curvilinear regression of turbidity to photo density.

DISCUSSION

Variables in Photo Analysis

There are many spectral variables involved when taking direct photo density readings for quantitative analysis. Since this was not a true "research" study many of these variables could not be isolated and studied for their own degree of influence. They were, however, anticipated and integrated into the photography and ground control procedures. High surface reflections occurred on many photographs due to sun angle changes as discussed earlier. However, this only occurred in portions of the photograph, allowing the remaining areas to be analyzed. The microdensitometer produced abrupt "peaks" in these portions, easily marking their identity (Figure 10).

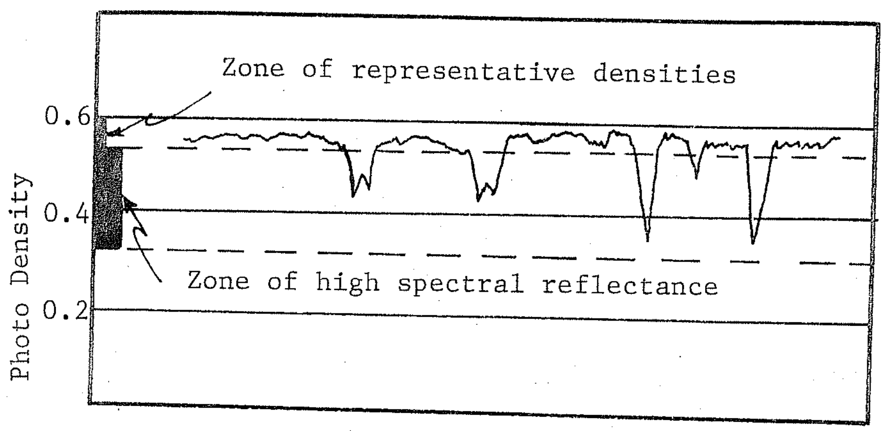

Figure 10. Chart trace of printout of microdensitometer readings indicating zone of representative densities and a zone of high spectral reflectance as a result of supercritical flow, sun angle, etc.

This ease of detection helps avoid unnecessary detailed microdensitometer analysis. Reaches of steep gradient streams with supercritical flow also created very high surface reflectance. Density readings were obtained where velocities were reduced, such as pools, etc. As explained earlier, color infrared film has poor shadow penetration which seriously affects the optical density. When high cumulous clouds would create shadows, the helicopter had an added advantage over fixed wing aircraft by being able to land and wait for satisfactory sky conditions. In some reaches, stream side vegetation caused shadows affecting photo density. Quantitative analysis from photo density could not be employed in these areas.

Over 98% of the total sediment production at the mouth of the West Fork is suspended load (Lisle, 1972). This and the fine texture of the material in suspension contributed significantly to the high correlation of suspended sediment/turbidity and 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 photo analysis. The excellent correlation of suspended sediment to turbidity will reduce the time and expense of future water quality monitoring in these streams as turbidity values which are easily obtained may be used as an indication of suspended sediment concentrations.

In the initial regression analysis of sediment to photo density there was an outlier which did not appear to fit the trend of the data. This was on Cascade Creek where the stream depth reading was approximately 0.3 foot. Apparently changes in energy reflectance from the bottom materials in this shallow depth stream caused this variation. Subsequent regression analysis did not include Cascade Creek. Shallow depth streams observed on the transparencies having the same observed reflectance characteristics were not quantitatively analysed.

The simple linear regression appears to be most representative at low sediment concentrations. As the concentrations increase beyond 300 mg/1, however, the curvilinear relationship appears to fit better with the higher concentrations as observed during the flight. Additional studies should provide for sampling of concentrations up to 800 - 1000 mg/1 to test this portion of the photo density to sediment relationship. The number of observations should be increased to permit use of more complex statistical tests.

The correlation and confidence limits of the photo density to suspended sediment and turbidity were reliable enough for the purpose of this study to allow direct interpretation from micro-densitometer readings on the transparencies in reaches where field data was not obtained.

The cost of the project involving the helicopter flight, film and film processing, field data collection and analysis, and photo analysis was approximately $2200. This averaged approximately $22/mile of stream for this project. Additional studies will also utilize the photography, offering additional savings by providing a permanent record for future analysis. This not only reduces the required cost and time, but is invaluable for determining changes in channels with time.

Sediment Sources and Fluvial Interpretations

Through the photo scale control stream widths can be measured by photo analysis and 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 gullying were occurring. Density readings at several locations increased downstream (reduction in sediment concentrations) in many of these small streams, which may indicate stream aggradation. In many instances the carrying capacity or the sediment transporting energy of the stream was reduced because of high introduced concentrations of sediment. Usually, in these cases the volume or discharge at these headwater streams was low, as was "total" sediment production at that point in the stream system.

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.

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 by channel erosion.

Even the tributaries to the main stream owe the majority of their sediment load to channel erosion processes. The sediment to discharge relationships of the various tributaries also provides some interpretations of the stream equilibrium conditions in relation to the downwasting rates of the various hydrophysiographic regimes. In some streams, sediment concentrations were present in excess of the stream's carrying capacity which not only indicated accelerated development of point and central bars, but also increased localized channel scour.

An important stream morphological condition was determined from the distribution of high concentrations of sediment from direct source areas. Density readings were obtained upstream, at the site and within three meanders downstream of a very high unstable streambank. Although the average stream velocities in this reach exceeded 5 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).

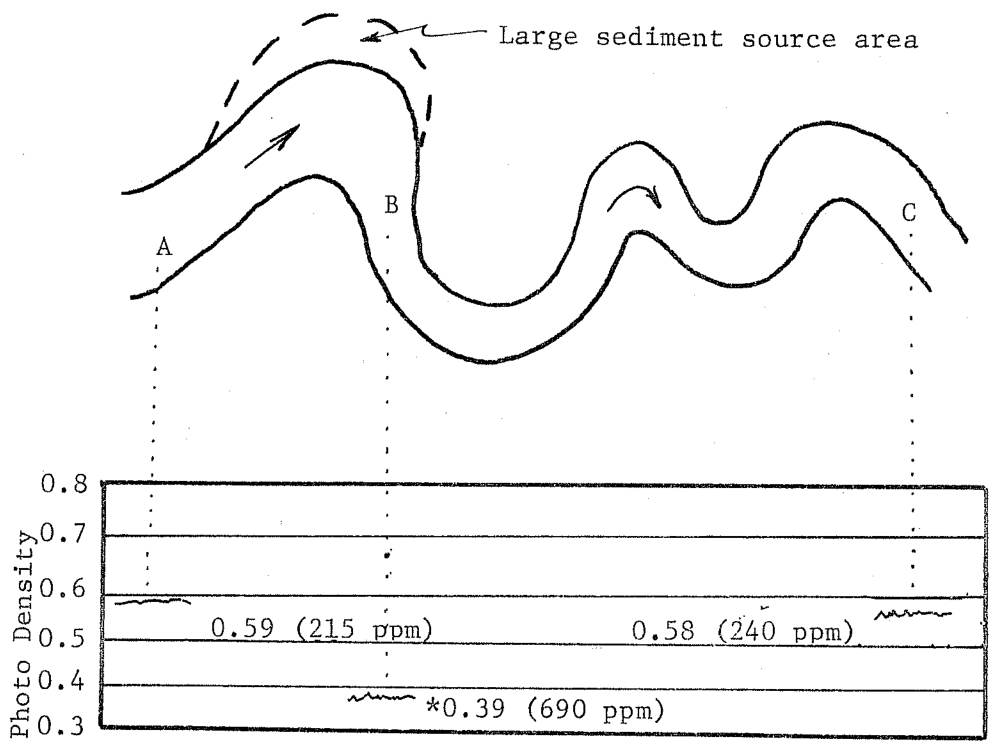

Figure 11. Sediment concentrations and distribution from direct source as determined by photo microdensitometer analysis and strip chart readout for respective stream points A, B and C.

* Densities averaged across stream width at selected reach

This indicated the phenonemon of concurrent scour and fill during a runoff event. As indicated by Lisle's work (1972) the stream is widening at the mouth at the rate of 5 cm/year. This is due to the aggrading condition of the stream, creating lateral channel extension. The carrying capacity of the stream is closely correlated with the sediment concentration and size of sediment debris in addition to velocity, discharge, width/ depth ratio, gradient, etc.

A detailed analysis of the sediment study of the West Fork is beyond the scope of this paper; however, the color infrared photography flight and analysis made it possible to pinpoint the sources and spatial distribution of sediment. It also helped establish sediment/discharge curves to further characterize each major hydrophysiographic regime 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. A permanent record for later detailed quantitative analysis and comparison.

3. Detail and interpretation beyond limits of the human eye.

4. Inexpensive in cost/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 will 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 of sediment?

2. What are the natural or geologic versus accelerated sediment production sources?

3. What are differences in the sediment producing characteristics of the various subwatersheds or hydrophysiographic regimes?

4. What management criteria is needed to protect or enhance the physical water quality?

The use of color infrared photography coupled with a well planned network of ground control 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 for various short-term runoff events.

Acknowledgment

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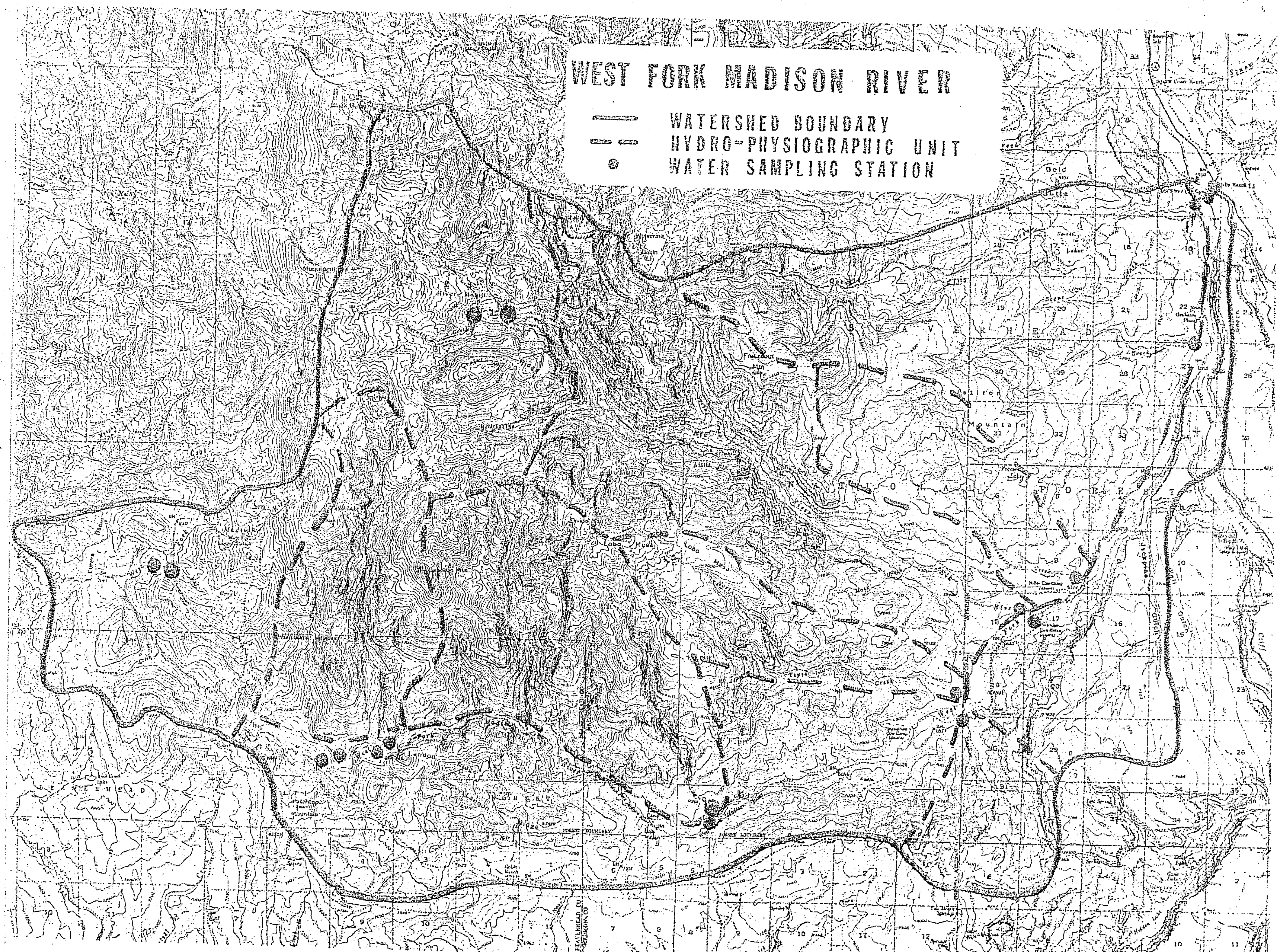
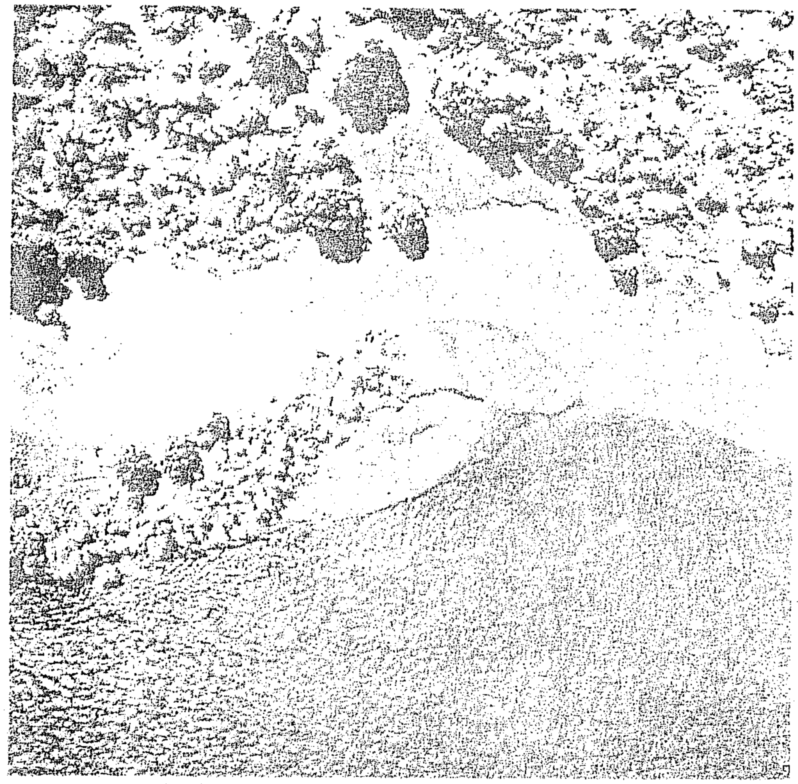

WEST FORK MADISON RIVER
WATERSHED BOUNDARY
HYDRO-PHYSIOGRAPHIC UNIT
WATER SAMPLING STATION
FOREST BOUNDARY
Jackpine
Gulch
Cliff
Lobo Mesa
Mountain



Appendix II. Mouth of the West Fork of the Madison at confluence of the Madison River. Copy of color infrared photograph.

Appendix III. Mouth of Fox Creek at confluence of the Upper West Fork. Copy of a color infrared photograph.

Appendix IV. Mouth of Meridian Creek at confluence with the West Fork. Copy of a color infrared photograph.

Appendix V. Mouth of Fossil Creek at confluence with the West Fork. Copy of a color infrared photograph.