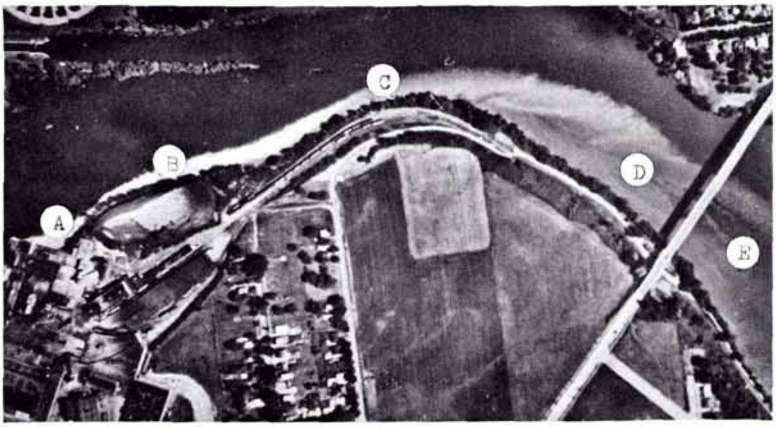

FIG. 1. Photograph of a waste discharging from a paper mill. Samples were taken at *A, B, C, D, E,* and at many other places in the plume. Results from analyzing these samples are shown in Figure 6.

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Water Quality by Photographic Analysis

With proper techniques the image brightness on film can be measured with a microdensitometer to obtain the water-quality parameter of turbidity at any point on the photograph.

(Abstract on next page)

INTRODUCTION

THE UNIVERSITY of Wisconsin Department of Civil and Environmental Engineering has participated since 1968 in a National Aeronautics and Space Administration Grant (No. NGL 50-002-127) for Multidisciplinary Research in Remote Sensing as Applied to Water Quality. In 1968 this project was started (in conjunction with the Wisconsin Department of Natural Resources) to find a more efficient means of monitoring paper-mill waste effluents in Wisconsin's rivers. River surveys within the State of Wisconsin are currently made once every five to seven years. It was hoped that some of the parameters of water quality could be determined from quantitative analysis of aerial photographs or that aerial photography might be used in conjunction with ground surveys to make the water sampling more efficient.

The experience gained from the taking of aerial photographs and sampling over the last five years at the University of Wisconsin has led to new aerial reconnaissance and data extraction techniques[8, 12, 13] A useful and usable system has been developed by the combination of laboratory and field results.

A well-defined paper-mill plume discharging tons of solids a day into a Wisconsin river was chosen for this study.[5] The color of the outfall was white and it was thought that its whiteness and homogeneity would help simplify the analysis.

The whiteness was caused by bleached organic fibrous material and a clay paper coating material suspended in the river water.

The clay coating contains titanium dioxide (Rutile), a material used to add whiteness to the finished paper product.

Various water parameter tests were run on the water samples but it was the parameter of turbidity that correlated best to the image brightness. Turbidity, an optical property, is related to light scattered from suspended material in the water. The suspended material causing the turbidity settles out of the stream forming a thick mat of clay and organic material. The heavy particles naturally settle out first thereby changing the characteristic of the waste along the plume. The waste from the particular site selected had an organic content of 30 percent. The organic portion of the mat creates a high biological oxygen demand (BOD) which causes anaerobic conditions on the stream bottom. At the time of the data collection, 27.5 tons of material per day were entering the stream. This caused a BOD_5 load of 18,300 pounds per day.

ABSTRACT: *Five years of research work has led to workable and practical aerial reconnaissance techniques of correlating water quality parameters to aerial photographs. Positive correlation exists between reflectance of water and the water quality parameter of turbidity. This relationship holds for all times for a particular waste. At particular times other parameters such as suspended solids correlate to turbidity and can also be mapped. To analyze aerial photos properly to obtain water reflectance, a standard reflectance panel is needed somewhere in the frame. For this study color and color-infrared film are used and analyzed with a color microdensitometer which, with certain modifications, is also used to analyze reflectance of water samples. Noise in the analysis includes bottom effects, reflection from the air-water interface, and path luminance, but these can all be dealt with by proper techniques.*

This paper describes how photo brightness can be correlated to the water pollution parameter of turbidity. At a particular time the suspended solids causing the turbidity can also be monitored from the aerial images. It is however, the water pollution parameter of turbidity that correlated to image brightness at all times. Realizing this, the process described can be an effective tool for water pollution monitoring.

SAMPLING

On August 28, 1972, hundreds of water samples were gathered simultaneous with aerial photography taken by two airplanes and several types of cameras and films. The samples were taken in the outfall of the mill selected and coverage extended downstream until the plume was indistinguishable from the background as observed from the air (see Figure 1). Two-foot white styrofoam panels were anchored in the water prior to sampling to identify the sample points and eliminate the need of triangulation positioning of the sample points or later relocating them photogrammetrically on the film. The white panel also served as a reference standard to eliminate the effects from variations in incident energy. The white panel can also serve as a standard to control effects from radial lens falloff and lens flare; both are factors affecting the image brightness. In all instances, the white panel was used as a known scene reflectance standard.

Bottom effects can also show and interfere with the brightness caused by the plume. A thorough understanding of the bottom effects should be known in the locations where samples are taken. Secchi disc readings were used to find locations where the bottom reflectance is significant. The Secchi disc consists of a white disc which is lowered into the water until it is no longer visible. This depth is known as the Secchi disc reading for that body of water. It is known that only about 1 percent of the returning energy comes from below the depth of the Secchi disc reading.[9, 14] The areas where the Secchi disc reading is greater than the depth to the bottom should be eliminated from the analysis, or analysis in such locations should be restricted to the use of photographic infrared energy, which penetrates but a few inches into water.

Water samples taken simultaneously with the photography were analyzed in the laboratory for total solids, turbidity and color. Replicate samples at each point increased confidence in the sampling results. Random samples were split in the field to check reproducibility of laboratory results and equipment. The samples were refrigerated upon collection and remained so until analyzed. Also, laboratory reflectance and transmittance data was obtained from a larger volume using a 2-ft sample tube and a spectrophotometer as shown in Figure 8.

Photography and Processing

Nine-inch and 35-mm vertical photographs were taken simultaneously with the water samples. Although the 35-mm camera system proved very economical for such work,[7] the better metric quality 9-inch photography was analyzed in this instance. The 9-inch mapping camera was outfitted with a 6-inch focal length lens, Kodak 8443 film, and a No. 12 Wratten filter. Photography was taken in mid-afternoon in order to eliminate sun glitter, although in this particular application the sky was moderately overcast. Color-infrared film was chosen because the infrared energy, showing up as red on this film, penetrates but a few inches into the water.[10,11] Analyzing the red layer of the color-infrared film essentially allows one to sense only the first few inches of water and completely eliminate bottom effects. One can also analyze the blue and green layers, if greater depth penetration is preferred.

Film processing must be done in accordance with sensitometric procedures. A step wedge must be processed with the film because of the variations in the film, exposure, and processing. The film was processed so that the images of the sample points fell on the linear portion of the *D-log E* curve. See Figure 5.

Film Analysis

A Gamma Scientific microdensitometer-spectrophotometer arrangement was used to extract the quantitative information from the film. This microdensitometer (Figure 2) attached to a spectrophotometer can analyze the film at any color or wave length and is herein called the color microdensitometer. One of the authors designed an x-y scanning stage to modify the manufacturer's existing equipment.[3] The stage is capable of holding bulk film up to a 70-mm format and with the addition of a vacuum platen will hold single frames of up to 9-inch imagery.

On the color microdensitometer a collimated light source is focused onto the plane of the film. The apparatus is equipped with various sized apertures. A 50-micrometer spot was used for the analysis. This is equivalent to an area of 0.3m² on the water's surface for the flying height used. The light energy, after illuminating a spot, is focused into a collector which directs the energy into a fiber optic. The fiber optic is coupled to a Bausch and Lomb monochromator. A photomultiplier tube (PMT) is connected to the monochromatic output and the output of the PMT is then displayed on a digital pico-ammeter and the values can be used to measure spectral transmittance and, therefore, density of the film. Density values are computed as follows:

$$Density = log_{10} \frac{1}{T}$$

where

$$T = \frac{Transmitted\ Light}{Incident\ Light} = Transmittance.$$

Dark current readings should be first subtracted from the readings from the film. Some raw outputs (transmitted light) are shown in Figure 3.

Raw readings show relative values of light intensity or image brightness and also the electrical response of the equipment. These values can be expressed in percent reflec-

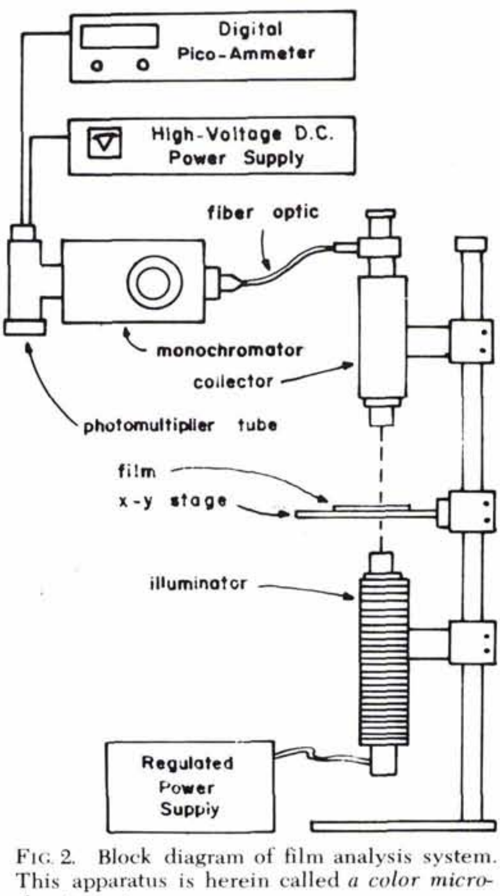

FIG. 2. Block diagram of film analysis system. This apparatus is herein called *a color microdensitometer.*

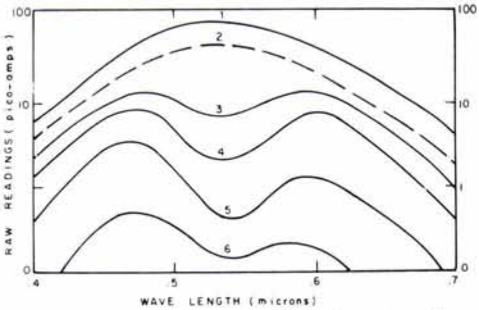

FIG. 3. Raw readings from the color microdensitometer. *1*. Open-air setup showing system response. 2. Theoretical response of image of white panel on perfect color film. *3*. Typical response of image of white panel on color film. *4*. Image of high-effluent concentration on color film. 5. Image of low-effluent concentration on color film. *6*. Image of background river water on color film.

tance only if converted to densities and compared to a scene standard of known reflectance.

A white surface reflects equally in all parts of the spectrum. A white panel showing on the film should theoretically have a response following that of the film analysis system. Instead it was found to have a *double-humped* nature as shown in Figure 3. This is explained by the inability of the color film's dyes to reproduce faithfully the full spectrum. This limitation occurs because of the limited spectral bandwidth of each of the three dyes making up the emulsion. The relative performance of three dyes and their integrated effect is shown in Figure 4.

White light is composed of equal amounts of red, green and blue light. Greys or neutral densities are gradations of white. The *humpback* effect of the film (Figures 3 and 4) at different wavelengths confirms the need for white reflectance standards if using color films. Changes in intensity at different wavelengths can be caused by the film characteristics as well as the material being photographed. The white reflectance panel allows one to correct for changes in intensity caused by the film. A multi-spectral scanner which has a near-linear response and gives absolute values referenced to skylight would eliminate the need for reflectance panels. To use films for quantitative reflectance analysis one must work with standard reflectance panels and the *D-Log E* curve for the film.

The *D-Log E* curve is computed from a step wedge photographed or directly contact printed on the film. The relative densities or exposing brightness caused by the wedge is plotted against the resulting densities of the image of the wedge on the film. This plot is the *D-Log E* or *Density-Log Exposure* curve for that film. For color film there is also a different *D-Log E* curve for each wavelength so if one analyzes color film, care should be taken to do it at the same wavelength for which the *D-Log E* curve was made. By measuring the film density and by use of the *D-Log E* curve one can compute the relative intensities of light which caused the original exposure (see Figure 5).

Zero density units on the film correspond to 100 percent transmission and three density units correspond to 0.1 percent transmission. The density or transmission values from the film are plotted on the ordinate or y-axis and the relative amounts of light causing these densities or transmittance values are shown on the abscissa or x-axis.

The white panel on the film is assumed to

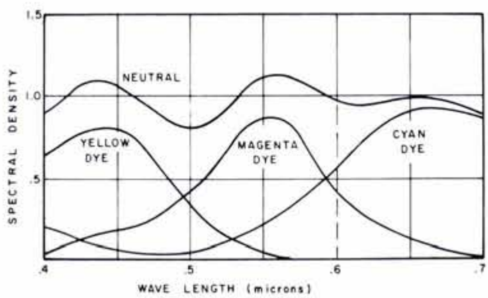

FIG. 4. Spectral dye density curve for Kodak color film. Kodak Publication Number M-61.

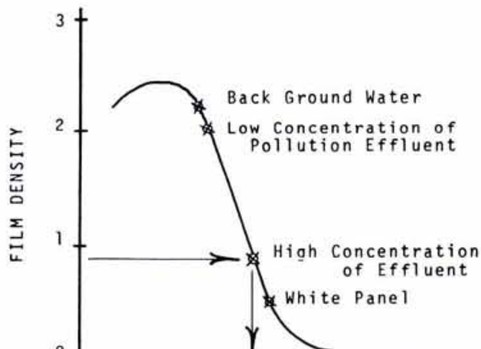

FIG. 5. Film density *vs.* relative exposure (*D-Log E* curve) for Kodak color reversal film type 8443. The relative exposure is derived from a step wedge exposed onto the film. The curve shows the relationship for the color green (0.55 micrometers) on the film.

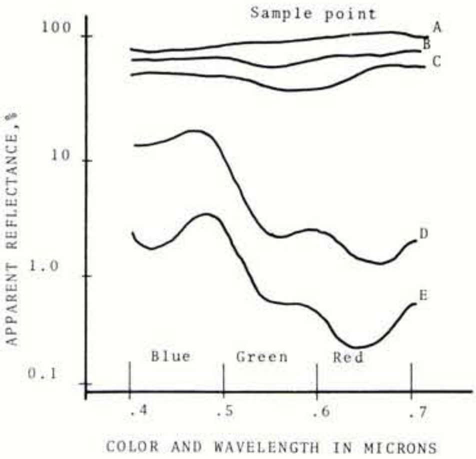

FIG. 6. Apparent reflectance of water at various points in the pollution plume shown in Figure 1. (See Table 1).

have 100 percent reflectance, and the reflectance values from the effluent are compared to it. Figure 6 shows resulting reflectance curves of various points in the plume shown in Figure 1. One will note that near the outfall (sample *A*) that the reflectance as well as the values for turbidity and solids are high. As one moves down the plume towards sample point *D*, the reflectance, turbidity, and suspended solids decrease. There is, therefore, a good positive correlation of reflectance to turbidity and suspended solids for this set of data. These values are obtained by analyzing color film with the microdensitometer and comparing the reading on the water with that of a standard styrofoam panel. The values of turbidity and suspended solids associated with the water sample points are shown in Table 1. One will note that there is indeed a good correlation between apparent reflectance and the values of turbidity and suspended solids.

LABORATORY REFLECTANCE ANALYSIS

If one replaces the microscope of the color microdensitometer of Figure 2 with a telescope, the resulting apparatus can be used to analyze the brightness of a sample of water. The water sample can be illuminated from either the top or the bottom to obtain respective values of water reflectance or transmittance. The resulting apparatus is shown in Figure 8.

Laboratory reflectances of water samples were obtained by attempting to duplicate field conditions in the laboratory. The styrofoam panels used in the field had reflectance almost identical to the reflectance of the laboratory standard of barium sulfate. (See Figure 7). For laboratory analysis the barium sulfate standard was placed over the sample tube and a light reflectance reading was taken from it. The standard was then removed and a reading taken on the water sample. The ratio of the two is the percent reflectance of the lab sample.

The construction of the tube that holds the water samples is critical. Although diameter does not have an important effect, the length, side material and bottom materials play important roles. Secondary reflections occurred off a plain glass bottom. A flat black bottom was added to make bottom effects negligible.

For the paper-mill waste of Figure 1, reflectance was measured on dehydrated waste effluent to achieve 1,000,000 ppm solids and also measured on dilutions of the waste that extended to that of tap water (0 ppm total suspended solids). Measurements were also made starting with tap water and adding measured amounts of titanium oxide (Rutile) until a saturation effect was achieved. The laboratory reflectance of high concentrations of the waste (Figure 8) corresponded to values given in the Thermal Radiative Properties handbook for titanium oxide. This helped to confirm the laboratory procedure.

TABLE 1. VALUES OF TURBIDITY AND SUSPENDED SOLIDS ASSOCIATED WITH THE WATER SAMPLE POINTS OF FIGURE 6

Water Sample Point	*Turbidity JTU*	*Suspended Solids mg/l*
A	110	172
B	75	100
C	40	50
D	18	23
E	11	8

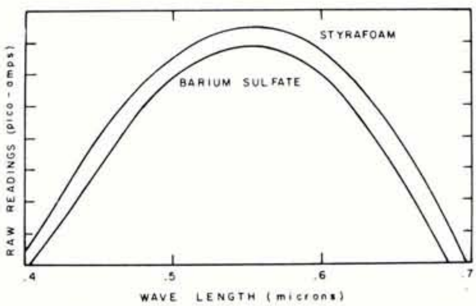

FIG. 7. Comparison of reflectance standards. The styrofoam panel is used as a reflectance standard in the field, the barium sulfate is used as a reflectance standard in the laboratory.

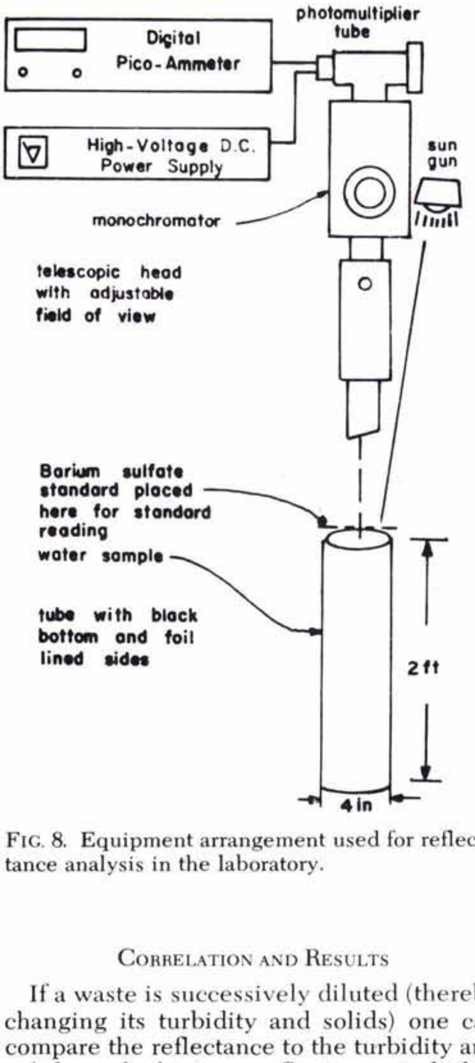

FIG. 8. Equipment arrangement used for reflectance analysis in the laboratory.

CORRELATION AND RESULTS

If a waste is successively diluted (thereby changing its turbidity and solids) one can compare the reflectance to the turbidity and solids and obtain a reflectance-turbidity curve for any desired wavelength. Figure 10 shows a reflectance-turbidity curve for the waste shown in Figure 1.

It was found that increases of turbidity or suspended solids caused increased reflectance. Turbidity is an optical property associated with scattered light, and is related only to suspended material and does not correlate to dissolved substances. Turbidity depends on the wavelength used, the size and shape of the particles present and their reflectance qualities.[15]

Turbidity cannot be universally correlated to suspended solids, but for one type of effluent at a particular day and at a constant flow rate, a correlation can be made. This is done by obtaining values from a standardized laboratory turbidimeter and corresponding values from solids analysis from many sample points within the outfall (See Figure 9). The curve of turbidity versus reflectance in Figure 9 changes from day to day and from mill to mill.

The correlation between turbidity and reflectance seems to be consistent for a particular waste regardless of time. Therefore, if the correlation curve between turbidity and image brightness is known for a set of photos, the turbidity of an entire water body can be mapped by measuring the brightness of the photos with the microdensitometer and going to the reflectance-turbidity curve. On a particular day, if one also knows the relation of suspended solids to turbidity, suspended solids can also be so mapped. The correlation of reflectance to suspended solids changes from day to day as the size and shape of the suspended materials change; the correlation of reflectance to turbidity remains constant.

Turbidity is a measure of scattered light. The effluent in Figure 1 was white and reflected well in all of the colors. In this instance there was a good correlation between turbidity and reflectance or image brightness at all the wavelengths analyzed.

Figure 10 shows the plot of reflectance versus turbidity and suspended solids for 0.55 micrometers on color-IR film. A curve similar to that shown in Figure 10 could be derived for any wavelength. Figure 10 shows this correlation from both analyzing the film and from the lab analysis.

In the laboratory the reflectance increases as more solids are added; however, a point was reached where increases in solids brought very little increase in the amount of scattered light returned to the sensor. (Point A on Figure 10.) To the right of Point A, further increases of solids caused no significant increases in reflectance. A similar flattening of the curve, if obtained from the film, was also occurring very near the outfall. Solids and turbidity associated with values to the right of Point A on Figure 10 are also in the range where turbidity measurements are no

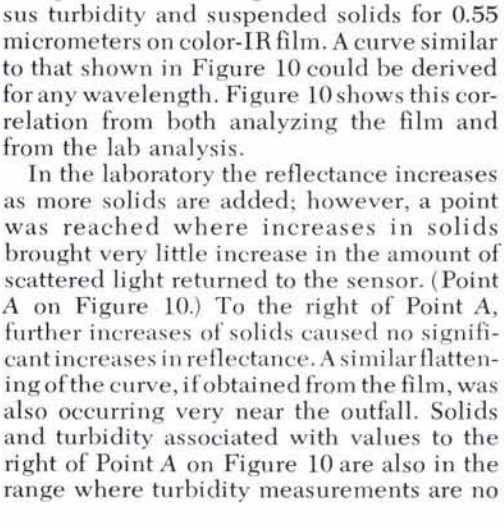

FIG. 9. Relationship of turbidity to suspended solids (mg/l) for a particular day.

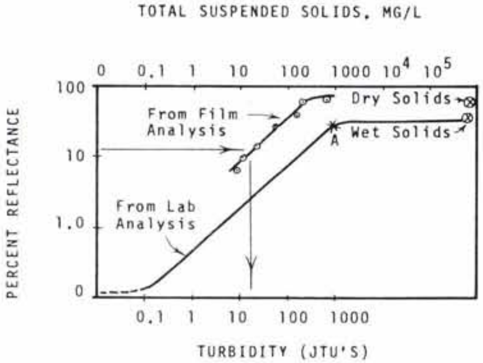

FIG. 10. Curve of reflectance versus turbidity and suspended solids for paper mill waste shown in Figure 1. The particular relationship here is for 0.55 micrometer on color-IR film.

longer obtainable with standard laboratory equipment.

At first it was thought that the curve to the right of Point *A* in Figure 10 was flat due to saturation of the film or the photo multiplier tube. However, both were checked and found to be in the linear range. This flattening phenomena can be best explained by the fact that at Point *A* the sample changes in characteristic (as far as light penetration is concerned) from a transparent liquid to an opaque, mud-like substance. To the left of Point *A*, some of the light penetrates through a certain distance of water where it is attenuated before it strikes a suspended particle and is reflected back. To the right of Point *A* the particles are so thick that light rays travel no appreciable distance before they strike a particle and are reflected back. Therefore to the right of Point *A* (as far as light penetration is concerned) the solution is saturated and increases in solids content cause no significant increase in reflectance. Most real-life situations of industrial plumes discharging into streams will be for values to the left of Point *A* in Figure 10 and in the portion of the straight-line relationship between reflectance and turbidity.

It is interesting to note that the reflectance-turbidity curve from the film analysis shown in Figure 10 is higher than the curve obtained from the analysis of the water sample in the lab. By increasing the side reflectance of the sample tube, the curves can be made to move closer together but there is always a separation between the field curve and the laboratory curve. The field curve derived from analyzing the film is always higher than the laboratory curve. In other words, the reflectance as sensed by the film, is always higher than the reflectance as measured from analyzing the water samples in the laboratory. This is partially caused because the aerial photos, in addition to showing volume reflectance, also show reflection of skylight from the water surface and contain some path luminance while the laboratory results do not. Pending work at the University of Wisconsin focuses on this area.

It can be concluded that if one wishes to map the turbidity or suspended solids of a plume, as shown in Figure 1, what is needed are a few water samples obtained simultaneously with the imagery. From this data, the reflectance-turbidity curve for the film can be obtained as shown in Figure 10. Thereafter, the reflectance of any point on the photo can be obtained by the microdensitometer. From the reflectance-turbidity curve, one can then obtain the corresponding turbidity and solids. These few points of simultaneous ground truth samples are analogous to ground control in photogrammetric topographic mapping where the position of innumerable points can be determined by use of a few ground control points and proper photogrammetric techniques.

LIMITATIONS, NOISE AND ERRORS IN THE SYSTEM

With any technique or new tool, there are potential errors which must be understood and properly dealt with. This is also true when mapping water turbidity using aerial photographs.

SUN GLITTER

One obvious limitation in using photos is possible sun glitter. For the technique herein described there can be no sun glitter present in the part of the photo being analyzed. Sun glitter can be eliminated by taking vertical photos either very early in the morning or late in the afternoon or on a completely overcast day. Handheld oblique photos can be taken at any time of the day as long as the cameraman orients the direction of the camera such that sun glitter does not show on the photo in the area of interest. About 3% of the sunlight reflects from the air-water interface and can cause sun glitter.

SKYLIGHT REFLECTION

In addition to a theoretical 3 percent of the sun's energy reflecting from the air-water interface to cause the sun glitter problem, the same 3 percent of the energy from the sky illumination also reflects from the same water surface.[6] This sky illumination can be any combination of blue sky and white clouds. As one looks into a store window he sees not only what is in the shop but also his own face or a street scene looking back at him. So it is with the water surface. In looking at the water a portion of the sky is always also looking back at the aerial observer or the camera. This is partially the cause of the shift between the film and lab analysis curves shown in Figure 10. As long as the sky conditions are uniform, this effect will be constant and can be uniformly subtracted out. Therefore for water quality work, photos should be taken only on completely clear or uniformly overcast days, but never on days where there are both patches of blue sky and bright cumulus clouds.

ANGLE EFFECTS

Piech has shown that the effects of skylight reflection are quite uniform for angles from the vertical out to about 45°.[6] Beyond 45° the skylight reflection increases very significantly and any analysis at such angles will undoubtedly be in error unless proper corrections are made. Photographs should therefore be taken as near the vertical as possible with a narrow angle lens yet avoiding the sun glitter.

Work has shown that the amount of apparent reflectance of water compared to a white panel will vary depending on whether one is looking toward or away from the sun. One must be careful to keep the same relative orientation between the sun and the direction in which the camera is pointed. The best situation is to have the sun to one's back and to photograph away from the sun.

Conclusions

Anyone observing a plume of industrial waste discharging into a stream intuitively realizes that there is an inherent correlation between the brightness of the plume and the concentration of the waste. This relation can be photographed and measured on film. The results of this work show that by proper techniques the image brightness on the film can be analyzed by a microdensitometer to obtain the water-quality parameter of turbidity at any point in the photograph. Suspended solids can likewise be mapped to whatever extent they correlate to turbidity at that particular instant. Here it is assumed that noise effects are insignificant or have been accounted for. Because of changing skylight and atmospheric effects from day to day, it is necessary to obtain a few simultaneous water samples at the exact time of the overflight to determine the reflectance-turbidity curve for that set of photos. This reflectance-turbidity curve (provided one analyzes the data using a reflectance standard and the *D-Log E* curve for that film) seems to be a straight-line relationship for the values of turbidity encountered in all but the most intense industrial plumes.

Acknowledgments

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