Turbidity Measurement[1]

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ABSTRACT

A quick and reliable method of measurement is necessary to set standard limits on the amount of suspended sediment to be tolerated in streams near land-use operations. Turbidity measurements may be useful if a major portion of the total turbidity is contributed by settleable solids, if a relationship exists between turbidity readings and weight per unit of volume of suspended sediment, and if a reliable meter is available. Water with turbidity readings greater than one JTU (Jackson Turbidity Unit) is generally composed mostly of settleable solids unless distorted by color. Non-filterable and total dissolved solids contribute variable amounts of light penetration reduction. Percentage contribution to turbidity of settleable solids is highly variable from sample to sample and from station to station.

A high correlation exists between turbidity readings and weight for individual sediment types of suspension, but a poor relationship exists when sediment type is varied. Experiments conducted on the Hach model 2100, the Hellige, and the Jackson Candle turbidimeters resulted in a highly significant difference ($\alpha = 0.01$) between readings on the same sample of suspended sediment. Turbidity is a questionable measure of suspended solids in water. A more accurate index would be suspended solids measured gravimetrically.

INTRODUCTION

Harmful effects of suspended sediment on aquatic fauna have been well documented in the literature. Large quantities of suspended sediment are detrimental to aquatic life of salmon and trout streams (Cordone and Kelly, 1961). Peters (1965) reported a 98% successful hatch of trout eggs in a clear area of a stream opposed to none in an area receiving particulate matter in the redds.

Before standard limits can be established on the weight of solids suspended in water, an efficient method of measurement must be available. Direct measurement of settleable solids is difficult and time consuming. Turbidity would be a valuable index in determining amounts of settleable solids in suspension if a relationship exists between the amount of settleable solids by weight and the turbidity reading obtained, regardless of the material in suspension.

Turbidity is an optical expression of finely-divided material suspended in a sample. The standard unit of turbidity is the Jackson Turbidity Unit (JTU). This unit is based on the calibrations of the Jackson Candle turbidimeter using kaolin (American Public Health Association, 1965).

The major objective of our study was to determine the best method of measuring turbidity and settleable solids with commercially available instrumentation. Definite criteria must be satisfied to use water turbidity as an indirect method of measuring settleable solids.

1. a. Total turbidity of a water sample must be comprised mainly of settleable solids.
   b. Non-filterable and total dissolved solids must have a negligible effect on the overall reading.
   c. Percentage contribution of settleable solids must remain constant for determination of the appropriate factor to convert turbidity readings to settleable solids (g/l).
2. A relationship must exist between the turbidity reading and weight per unit volume of suspended sediment regardless of the type of material in suspension.
3. A turbidimeter must give reproducible readings.

MATERIALS AND METHODS

Description of the Study Site

Blue Mesa dam on the Gunnison River near Gunnison, Colorado, was closed in October,

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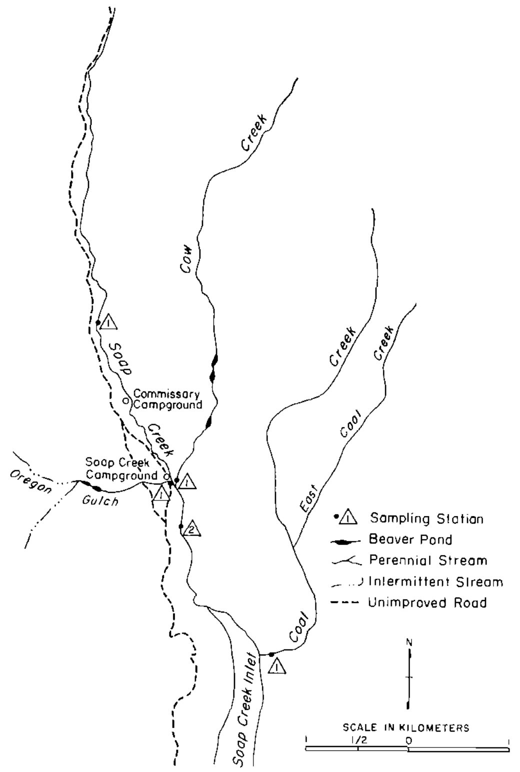

FIGURE 1.—Map of the study area.

1965 creating Blue Mesa reservoir. The reservoir has been stocked with rainbow trout (*Salmo gairdneri*) and kokanee salmon (*Oncorhynchus nerka*) to establish self-sustaining populations. Soap Creek is one of the best spawning areas for these fish species (Wiltzius, 1967). High suspended sediment concentrations during spring runoff may limit natural production. Soap Creek and three of its major tributaries, Oregon Gulch, Cow Creek, and Coal Creek were selected for study (Figure 1).

Soap Creek originates about 40 km above Blue Mesa Reservoir in Soap Basin, part of the West Elk mountain range. Its water supply is from snow-melt and spring-fed tributaries. Bottom materials consist mainly of rock and rubble. Mean annual discharge is 1.77 cubic meters per second (cms) (Wiltzius, 1966). Oregon Gulch enters Soap Creek from the west about 8 km above Soap Creek Inlet. Oregon Gulch consists mainly of riffle area with only a few pools greater than 0.33 m in depth. Mean discharge between May and September, 1968–69, was 0.033 cms. Cow Creek enters Soap Creek from the east about 91 m below the mouth of Oregon Gulch. Cow Creek has a two to one riffle to pool ratio. Few pools were deeper than 0.33–0.66 m. Mean discharge between May and September, 1968–69, was 0.133 cms. Coal Creek flows into Soap Inlet created by the inundation of Soap Creek's flood plain after the closing of Blue Mesa dam. Coal Creek area is comprised of riffles with few pools greater than 0.33 m deep. Mean discharge was 0.045 cms between May and September, 1968–69 (Duchrow, 1970).

Contribution of Settleable Solids to Total Turbidity

Water samples from the four study streams were collected between May and September, 1969 for analyses of the contribution of settleable solids to the total turbidity of water. Samples were collected at three-week intervals on the three tributaries and two stations on Soap Creek (Figure 1). Each sample was collected using a modified depth-integrating suspended sediment sampler.

Total turbidity of each sample was measured with a Hach model 2100 turbidimeter. One liter of each sample was placed in an Imhoff settling cone for 24 hours. Turbidity of the supernatant water was recorded. Settleable solids were dried at 103 C to a constant weight. All weights were recorded as mg/l (American Public Health Association, 1965). The supernatant water was filtered through a Gooch crucible fitted with an asbestos mat filter. Turbidity of the filtered water was recorded. A 150 ml aliquot of the filtrate was evaporated in 50 ml aluminum moisture dishes under a Fisher Infra-Rediator to determine total dissolved solids (American Public Health Association, 1965). Samples were weighed and converted to mg/l using the appropriate conversion factor (6.667). Non-filterable solids remaining in the crucible were dried at 103 C to constant weight (American Public Health Association, 1965). The percentage contribution of each type of solid to total turbidity was determined.

TABLE 1.—*Physical characteristics of experimental sediments*

Sediment	Color		Sediment size[1] (mm in diameter)	Specific gravity (g/1)
Formazine	White		0.00391	0.37
Kaolin	Cream		0.00391	2.22
Silica	Grey		0.00391	2.59
Bentonite	Yellow		0.00391	1.66
Carbon	Black		0.06250	1.03
Sawdust	Tan		0.12500	0.11
Soap Creek Soil[2]	Brown	33%	0.00391	2.00
		14%	0.06250	
		53%	0.12500	

[1] Sediment diameters correspond with sediment classification in Welch (1949).
[2] Percent values indicate the fraction of the soil consisting of sand, silt, and clay, respectively.

TABLE 2.—*ANOVA table breakdown for testing the null hypothesis regarding similar readings from different meters*

Source	Degree of freedom
Whole plot	
Days	1
Dilutions	8
Error[1]	8
Sub-plot	
Meters	3
Meters versus day	3
Meter versus dilutions	24
Error[1]	24
Total	71

[1] If an F-test indicates no significant difference between whole plot error and sub-plot error, error terms and degrees of freedom can be pooled.

Meter Analysis

Jackson Candle, Hellige, and Hach model 2100 turbidimeters were used to determine the best method of turbidity measurement. The Hach is the most recent addition to the market and, for this reason two Hach turbidimeters were used to determine possible differences in readings between the two meters.

An experiment was designed to determine: (1) if all turbidity instruments in our study would yield similar readings with different materials, and (2) if similar readings were obtained with different materials at the same concentration. The experiment also determined if a numerical relationship existed between turbidity units and the concentration of suspended sediment regardless of the type of material used.

Seven materials were selected: formazine, kaolin, silica, bentonite, fine carbon, sawdust, and a soil sample from Soap Creek. Physical characteristics of the seven materials are given in Table 1.

Each material was suspended in turbidity free water, *i.e.*, deionized water with an average turbidity of 0.099 JTU ± 0.038. Nine concentrations were used: 0.00, 0.05, 0.20, 0.50, 0.90, 1.5, 2.0, 3.5, and 7.0 g/l. Samples were shaken before each reading to insure all material was in suspension. Turbidity readings were recorded for each concentration with each turbidimeter. Readings were taken in random order. An average of three readings per concentration per meter was taken to assure a better estimate of the turbidity of each concentration. Each set of three readings comprised one data cell. The same procedure was followed for each material. The entire experiment was replicated once.

Data were analyzed first for homogeneity of cell variances with Bartlett's test (Sokal and Rohlf, 1969).

Data from each material were analyzed with a split-plot analysis of variance (ANOVA) to test the hypotheses that the meters yield similar readings. Split-plot ANOVA was also used to determine whether the two Hach meters gave similar readings for each material. An example of the ANOVA table breakdown is shown in Table 2. The breakdown according to source remained constant. Degrees of freedom varied with the hypothesis being tested.

Regression analyses were calculated to determine the relationship between turbidity readings (JTU) and concentration of suspended sediment (g/l) regardless of the material. Similar regressions were calculated for individual sediments.

Human Error Analysis

An experiment was designed to determine the most reliable commercial turbidimeter with different operators. Preliminary studies had indicated two problems. First, procedures were not available to prepare suspensions with known JTU values without using one of the test meters to calibrate the suspension. To alleviate this problem formazine was selected for the suspended solid. Formazine can be synthesized with a reproducibility within 1%

(Hach Chemical Company, no date). Formazine, properly prepared, has particles of uniform number, size, and shape. Second, operator error causes erroneous readings. Consideration of this problem developed the criterion that the turbidimeter with the lowest coefficient of variation, *i.e.*, human error or manipulative error, regardless of the operator, would be the best meter. The coefficient of variation considers the reliability of readings of the same suspension.

Human error data were collected from the four turbidimeters. One inexperienced and two experienced operators were selected for our experiment. Six concentrations were prepared, two each for the low, medium, and high ranges of each meter. Within each range, two similar suspensions were used to test each meter's capability to distinguish between suspension.

The three operators read the concentrations at random with no knowledge of what concentration they had received. Each concentration was read five times by each operator. This procedure was followed for each meter. The experiment was replicated once.

Split-plot ANOVA was used to calculate coefficients of variation for each meter. The ANOVA table breakdown used for these calculations is illustrated in Table 3. This ANOVA design provided another opportunity to test the hypothesis that there was no significant difference between each meter's reading of similar suspensions.

TABLE 3.—*ANOVA table breakdown used in coefficients of variation calculations*

Source	Degree of freedom
Whole plot	
Days	1
Concentration	4
Error[1]	4
Sub-plot	
Operators	2
Day versus operators	2
Concentration versus operators	8
Error[1]	8
Total	29

[1] If an F-test indicates no significant difference between whole plot error and sub-plot error, error terms and degrees of freedom can be pooled.

RESULTS

Contribution of Settleable Solids to Total Turbidity

Data collected on the two Soap Creek stations and at the mouth of the three tributaries indicated most of the total turbidity of these streams consisted of settleable solids. This was true except during periods when the water was colored by dissolved substances carried into the stream by runoff from the watershed. Total dissolved solids and color contributed to most of total turbidity at very low readings, *i.e.*, usually less than one JTU. Non-filterable solids contributed a negligible amount of light penetration reduction. Table 4 illustrates the contribution of each type of solid and emphasizes the variation in percentage contribution of settleable solids with time as sediment type changes. The Oregon Gulch data in Table 4 were typical of data collected at the other sampling stations.

Meter Analyses

Data cell variances for each meter were significantly different ($\alpha = .01$) as indicated by Bartlett's test between data cell variances for each meter. Adjusted Chi-square values ranged from 749.25 with 49 degrees of freedom (d.f.) for the Jackson Candle to 1,539.68 with 62 d.f. for the Hellige turbidimeter. Even though these results indicated a violation of a major

TABLE 4.—*Contribution of various solids to the total turbidity of Oregon Gulch, 1969*

		Total turbidity (JTU)	Settleable solids (%)	Non-filterable solids (%)	Total dissolved solids (%)
3 May	1969	8.5	22.3	8.2	69.5
17 May	1969	9.1	18.7	6.6	74.7
3 June	1969	7.9	44.3	22.8	32.9
22 June	1969	6.9	53.6	7.3	39.1
8 July	1969	6.2	43.5	8.1	48.4
31 July	1969	5.9	76.3	1.7	22.0
15 August	1969	5.1	60.8	15.7	23.5
3 September	1969	3.6	50.0	8.3	41.7

assumption governing analysis of variance models, *i.e.*, equality of cell variances, analysis of variance with heterogeneous variances is a valid test providing highly significant results are obtained (Scheffé, 1956). Further examination of cell variances indicated an increasing variance between readings with an increase in turbidity. This relationship existed in all four turbidimeters tested.

Split-plot ANOVA indicated a highly significant difference ($\alpha = .01$) between the three meters with the seven materials tested. Nonsignificance was observed in all but one test between the two Hach turbidimeters. The significant difference ($\alpha = .05$) with silica was probably due to a high variance between readings since silica settles rapidly and accurate readings were difficult to obtain.

Highly significant differences ($\alpha = .01$) were also present between readings obtained on the seven materials for each meter. F values for the first Hach, second Hach, Hellige, and Jackson Candleturbidimeters are: $F_{6,56} =$ 13,124.44, $F_{6,48} =$ 9,218.67, $F_{6,56} =$ 438.92, $F_{6,49} =$ 855.10, respectively.

Regression analyses indicated a high correlation between turbidity readings and the weight of suspended sediment for each material used. The range of coefficients of determination (r^2) for each meter are:

Hach #1	95.25	(Sawdust)
	to 99.87	(Kaolin)
Hach #2	96.27	(Sawdust)
	to 99.81	(Kaolin)
Hellige	94.63	(fine carbon)
	to 98.42	(Kaolin)
Jackson	96.17	(fine carbon)
	to 99.80	(Bentonite)

The relationships between turbidity and sediment concentration for each meter using formazine are shown in Figure 2.

Regression analysis indicated a poor correlation between turbidity readings and suspended sediment concentrations for all materials tested. Coefficients of determination varied from 38.19 for the Hellige to 42.17 for the Hach #1 turbidimeter. Regression equations describing the relationship between turbidity and sediment concentrations for the seven materials using the Hach #1 turbidimeter are given in Figure 3.

TABLE 5.—*Coefficients of variation for each meter*

	Low range (%)	Middle range (%)	High range (%)
Hach #1	4.35	3.84	3.75
Hach #2	5.40	2.94	3.53
Hellige	16.41	15.03	18.37
Jackson Candle	5.51	5.31	10.15

Bartlett's test yielded no significance between cell variances for each meter in the second experiment.

Coefficients of variation indicated the Hach model 2100 turbidimeter was the most reliable followed by the Jackson Candle and Hellige turbidimeters, respectively. Coefficients of variation for each meter are listed in Table 5. Further analyses indicated no significant difference between readings obtained by operators using the two Hach turbidimeters ($F_{2,15} = 0.76$ and $F_{2,10} = 0.19$, respectively). Significance was detected between operators using the Hellige and Jackson Candle turbidimeters.

Similar suspensions could be differentiated in all scale ranges for the two Hach meters. The Hellige meter could separate similar suspensions only in the low range and the Jackson Candle could distinguish similar suspensions in the low and middle ranges. High coefficients of variance caused the inability to distinguish similar suspensions in the other ranges.

DISCUSSION

There is ample documented evidence in the literature that high concentrations of suspended solids have fatal effects on aquatic life. The exact concentration and exposure time that can be tolerated by an organism before death occurs are variable depending on the species and its life history stage.

Our study showed that settleable solids are the greatest contributors to light reduction in turbidimetric measurements except at turbidities less than one JTU or when the water is highly colored. The percentage contribution of settleable solids was highly variable and an exact value would be difficult to obtain. Varying size, shape, specific gravity, and refractive index of sediment held in suspension by turbulence of the stream contribute to this variation. Since the contribution of settleable solids to total turbidity analyses was conducted on wa-

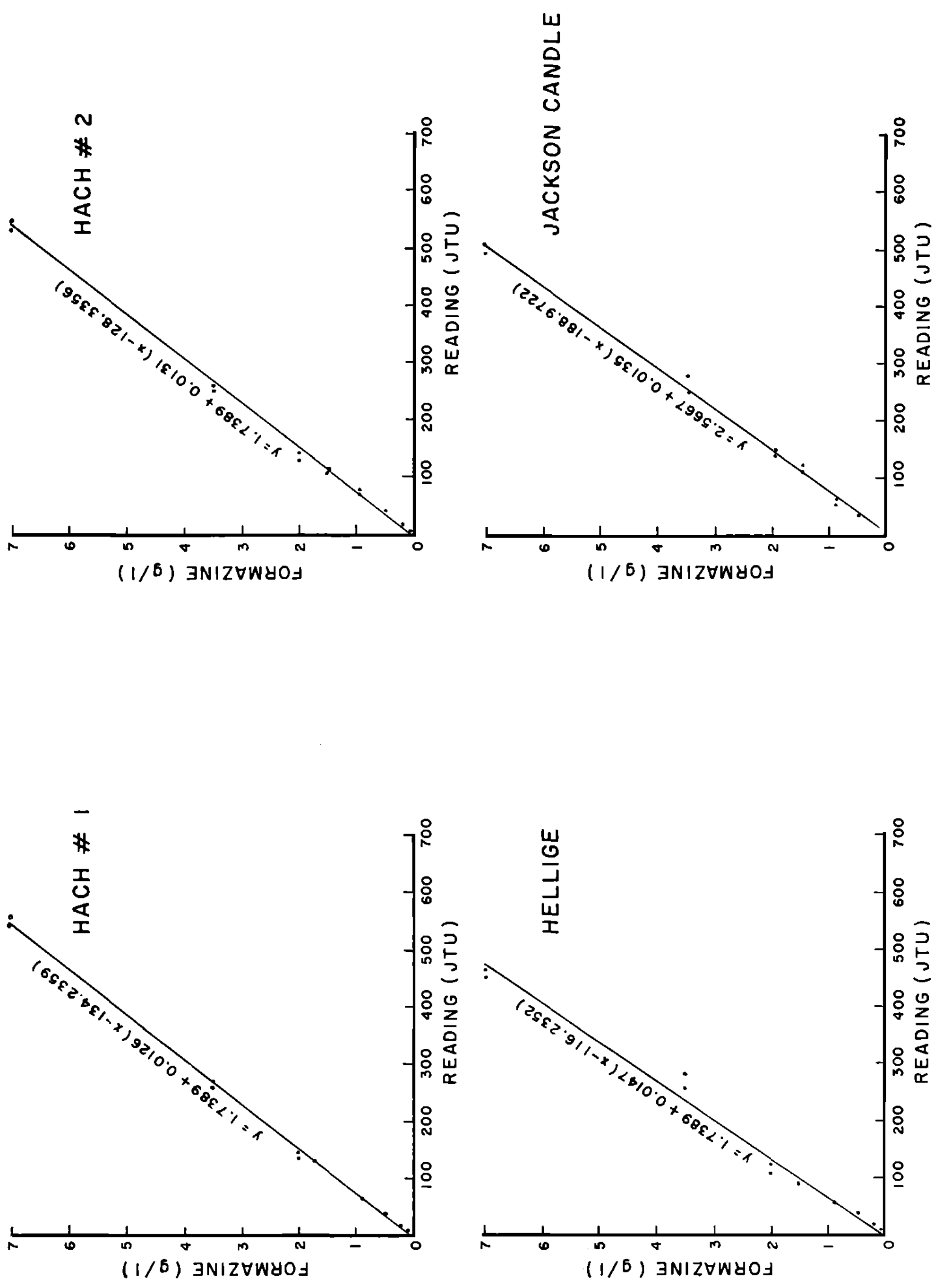

FIGURE 2.—Numerical relationship between turbidity readings (JTU) and weight of sediment (g/l) for four turbidimeters using formazine.

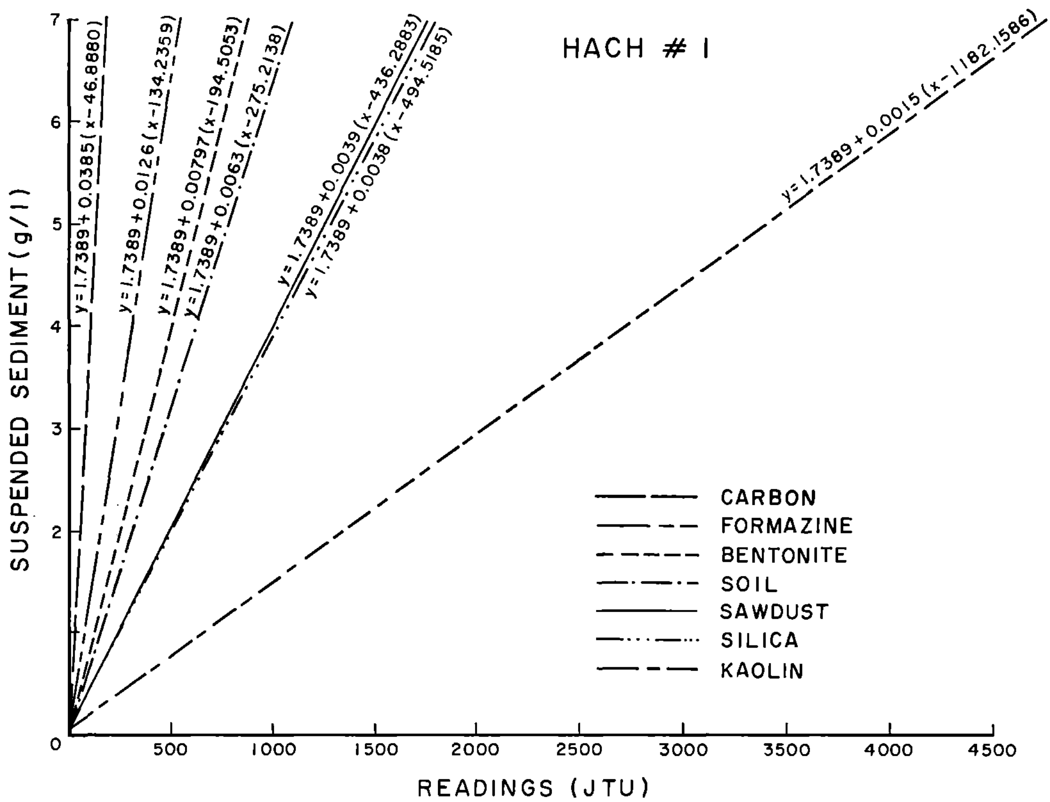

FIGURE 3.—Regression equations giving the relationships between turbidity readings (JTU) and weight of suspended solids (g/l) of seven materials for the first Hach model 2100 turbidimeter.

ter with less than 20 JTU, it is difficult to speculate about higher turbidity values. Turbidities greater than 20 JTU caused by sediment in suspension can only be achieved with an increase in discharge or with an increase in clay size particles. Greater rates of flow can carry larger quantities of sediment so it is feasible to assume that settleable solids contribute the greatest light reduction to the total turbidity of the water.

Turbidity may be a useful parameter as an index to suspended sediment source in individual water systems if the sediment source remains constant. Each stream must be calibrated and the resulting curve could only be applied to that stream. Calibration curves for the four study streams are given in Figure 4. Care should be exercised in using these relationships not to extrapolate beyond the limits of existing data. A single curve cannot be set up to apply to all streams because the type of sediment received by each system is potentially different in size, shape, color, specific gravity, and refractive index.

Experimental evidence indicates the Hach model 2100 turbidimeter was the most reliable of the three tested. Samples should be read as soon as possible after being collected. An average of three readings per sample should be taken as the turbidity of the sample. Because variation between readings within a sample increases with higher turbidities, samples with turbidities greater than 50 JTU should be read by dilution. Our study verified the standard procedures recommended in the Federal Water Pollution Control Administration (1969) report.

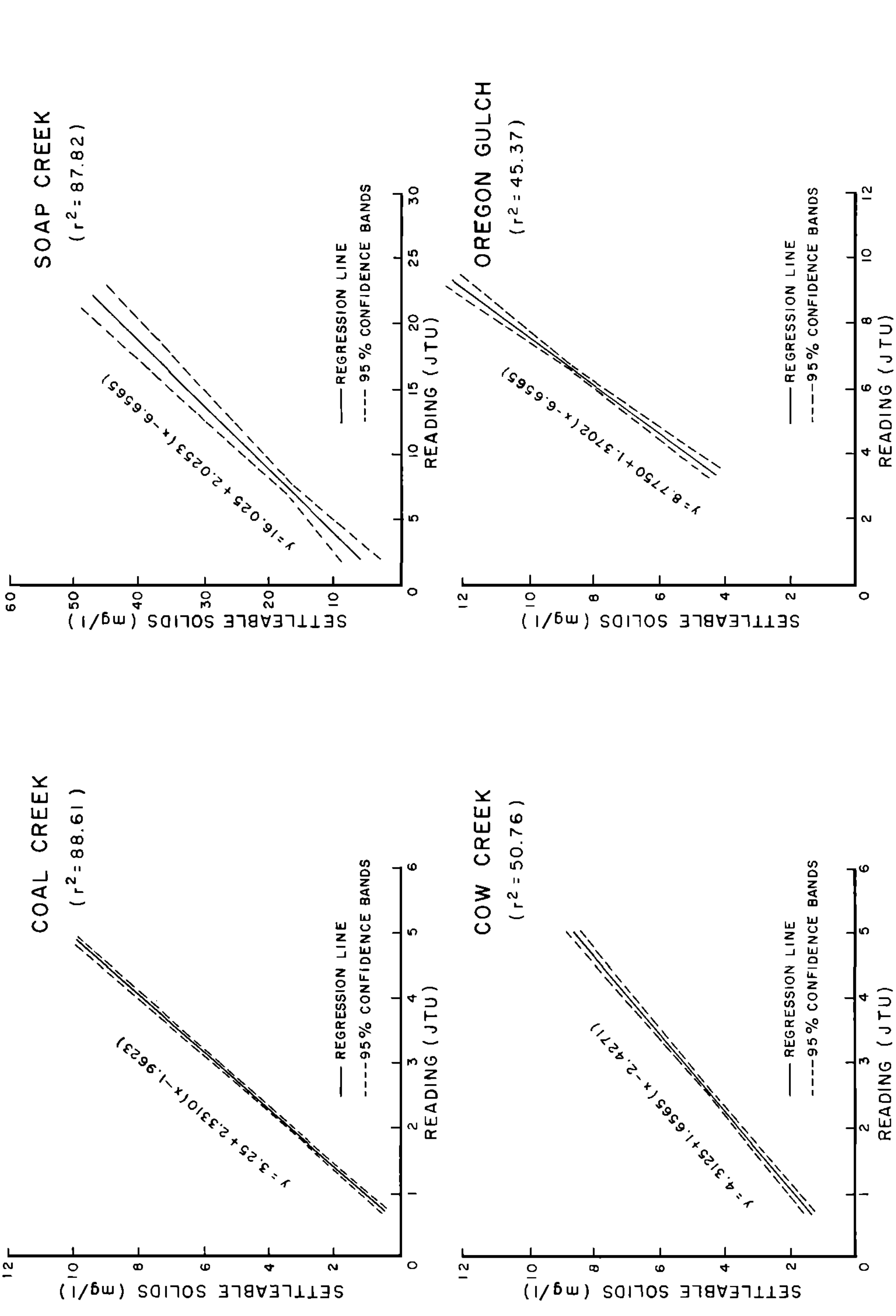

FIGURE 4.—Regression equations giving relationships between turbidity readings (JTU) and weight of settleable solids (mg/l) for the four study streams.

CONCLUSIONS

Turbidity of water is a questionable parameter for establishing water quality standards because too many factors must remain constant before a Jackson Turbidity Unit can be converted to a corresponding suspended sediment concentration.

The main concern with regard to the protection of aquatic fauna from lethal sediment concentrations is the amount of solids in suspension that can potentially settle out as flow decreases, *i.e.*, settleable solids. The type of solid in suspension varies the effect on aquatic fauna. Specific water quality standards for settleable solids must be established for each specific situation. Sediment type and aquatic fauna will probably be different at each site.

Standard techniques for measuring settleable solids using Imhoff settling cones should be used to check and enforce these standards, once standards have been set.

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