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Light Scattering in Sewage Effluent: A Study of the Effects of Angle of Scatter and Common Light Sources

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LIGHT SCATTERING IN SEWAGE EFFLUENTS: A STUDY OF THE EFFECTS OF ANGLE OF SCATTER AND COMMON LIGHT SOURCES

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EXECUTIVE SUMMARY

Traditionally suspended solids have been measured for consent purposes for effluent discharge. However, conventional measurement techniques are too slow and are not amenable to continuous monitoring. Consequently, it has been recommended in the Discharge Consent and Compliance Policy that turbidity is used as a general surrogate for suspended solids and included into consent policy.

Turbidity is an expression of the optical property of a liquid that causes light to be scattered and absorbed rather than transmitted in straight lines through a sample. There are three main techniques currently used in the measurement of turbidity and the method used, sample condition and instrument design all have an influence on the repeatability of the measurement.

The report describes an investigation into establishing the relationship between light scattered at 90°, 25° and low angles with gravimetric suspended solids for treated sewage final effluent.

The conclusions of the report is that it is possible to predict the suspended solids from the turbidity measurement and there is a link between effluent particle size distribution and turbidity measurement angle. The type of light used in the instrument has been shown to effect the correlation between scattered light intensity and suspended solids with white light having a slight advantage over visible or near infrared. Additionally calibration is important and will vary depending on effluent and instrument parameters such as illuminant wavelength and scatter angle.

The recommendations of the report is that an on-line trial using a range of commercial instruments is carried out on a selection of effluents. Additionally a study should be carried out to investigate the area of calibration for turbidimeters.

KEYWORDS

Calibration, Correlation, Effluent, Evaluation, Particle, Scatter, Suspended Solids, Turbidity.

1. BACKGROUND

The light scattering properties of a water or wastewater have been used for some years as a measure of its basic quality. Instruments which measure scattered light can be calibrated against a standard suspension such as Formazine to give a reading in turbidity units or can be calibrated directly in suspended solids from gravimetric analysis.

Earlier instruments used tungsten filament lamps as light sources and Selenium or photodiode detectors. The current generation of water industry instruments often use near-infra-red (NIR) light-emitting-diodes (LEDS) as light sources and silicon photodiode detectors. Scatter at 90° is commonest though 25° is favoured by at least one manufacturer. 'Low angle scatter' describes an instrument which collects light scattered close to the axis of the incident light, but with the transmitted light excluded. Such an arrangement is widely used in laser diffraction type particle size analysers, but it is not commonly used in turbidimeters or suspended solids meters. For online instruments measuring high suspended solids levels such as are found in mixed liquor, the loss of transmitted light can also be used as a measure of turbidity or suspended solids.

Environmental pressures are leading both regulators and companies discharging to surface waters towards a greater degree of monitoring of the quality of effluents. In particular, the monitoring of gravimetric suspended solids, which has been for most of this century a yardstick of water quality, cannot readily be adapted to continuous monitoring. There is, therefore, a need to identify alternative parameters which can be measured on a continuous basis and can provide a suitable measure of water quality. Turbidity is an obvious candidate for this function. However, it can be measured in many different ways and there is very little published data about its relationship to suspended solids and the mode of measurement. Against this background a study has been undertaken to gather some basic information on the effect of some turbidity measurement parameters on the relationship between turbidity and suspended solids.

This document describes an investigation into the relationship between light scattered at 90°, 25° and 'low angles' and gravimetric suspended solids for treated sewage final effluent. A test rig has been constructed which has allowed light at the different angles to be measured. It has also allowed the source light to be filtered through a coloured glass filter. Effluents from 3 different sewage treatment works have been measured. Particle size distribution measurements have also been carried out on samples of the effluent to characterise their likely light scattering properties.

2. TEST RIG

A diagram of the test rig is shown in Figure 2.1. The light source was a quartz halogen 100 watt lamp in a commercial projector housing. The light was focused on a 1.5 mm diameter pinhole, and an image of the pinhole was projected through the test sample to a detector. A nominal 25 millimetre diameter cylindrical sample cell was used. Detectors at 90° and 25° were arranged around the sample. These detectors use biconvex lenses to focus scattered light onto a photodiode. The transmitted light detector and low angle detector were mounted together by cementing the transmitted light detector to the low angle detector lens.

It is important to reduce stray light within equipment of this kind so that the relatively small amount of scattered light does not have to be detected in the presence of a large and varying background signal. A baffle was mounted just in front of the sample vessel to reduce stray light and to reduce flare around the source light beam. A mask was fitted to the low angle detector lens close to the transmitted light axis to exclude stray light. The cylindrical sample cell was a particular difficulty in obtaining a small spot for the transmitted light, but it had to be retained for the 25° scatter detector. A parallel-sided vessel (A cuvette) would have been better for the low angle measurements. The angle accepted by the 25 degree detector was restricted to ± 3° to exclude some stray light produced by multiple reflections between the detectors and sample cell. All reflective surfaces were painted matt black to minimise stray light.

The amplifier circuit used is shown in Figure 2.2. Each photocell was connected to a chopper-stabilised operational amplifier in the configuration shown. This arrangement gives the best linearity by avoiding any voltage across the diode. Dark current and stray light were offset by feeding current into the amplifier as shown. Four separate circuits were constructed and built into the case shown in Figure 2.3. A 4½ digit panel meter was used to display the output from the amplifiers selected by a switch on the front panel. A simple low pass filter was used on the amplifier output to average the fluctuations which naturally occur in measuring the scattered light from a suspension.

A general view of the test rig is shown in Figure 2.3 and a closer view of the detector arrangement is shown in Figure 2.4. A cover was constructed to exclude ambient light when measurements were being carried out. The projector was fitted with a filter holder and measurements were carried out with unfiltered white light, visible only light using a filter to exclude infrared, and a filter which cut out the visible but transmitted the near infrared. The spectral characteristics are shown in Figure 2.5. The silicon detectors were all of the same type with a spectral sensitivity shown in Figure 2.5. This is a typical spectral response for silicon photodiodes with no special filtering or doping. The combination of the detector response and the visible excluding filter is intended to simulate the infrared LEDs commonly used which generally centre on 880 nm.

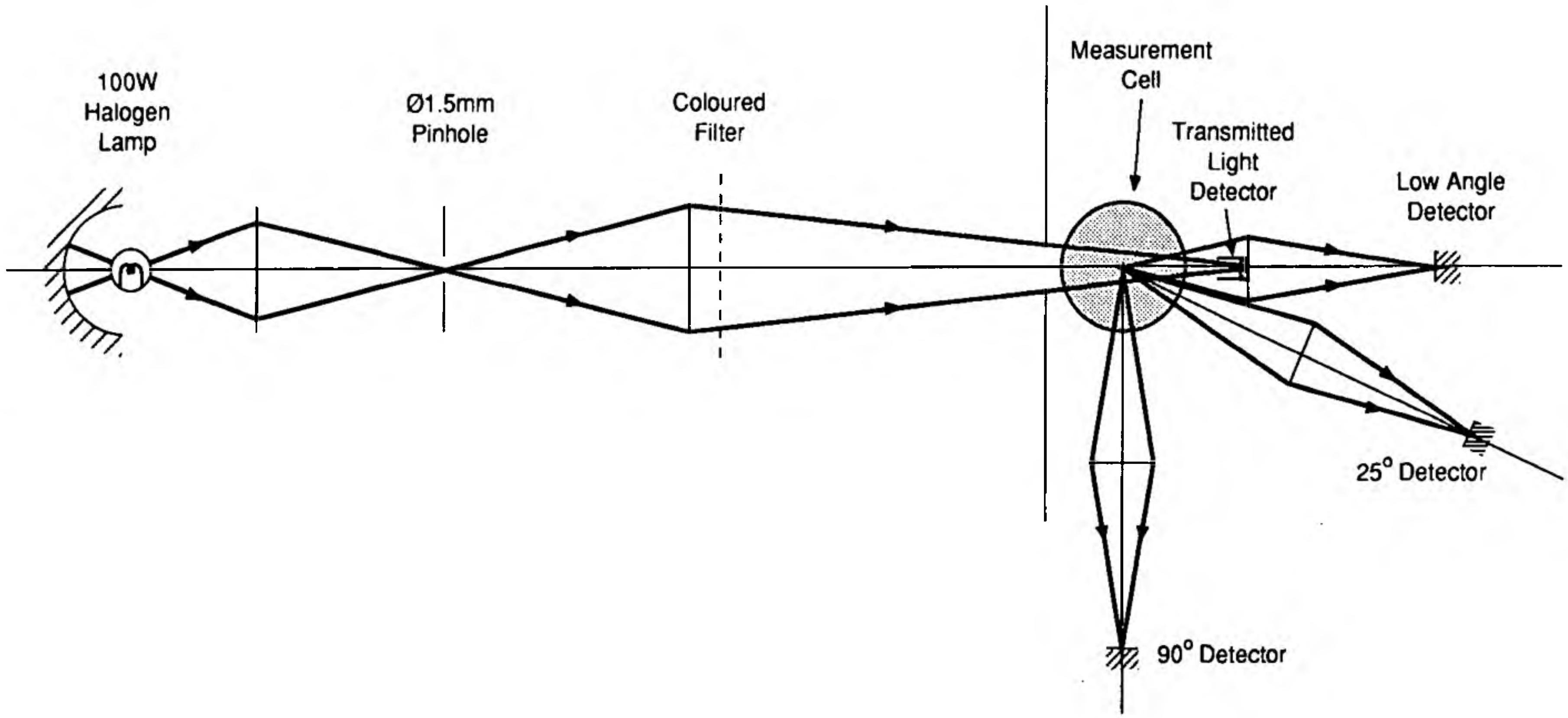
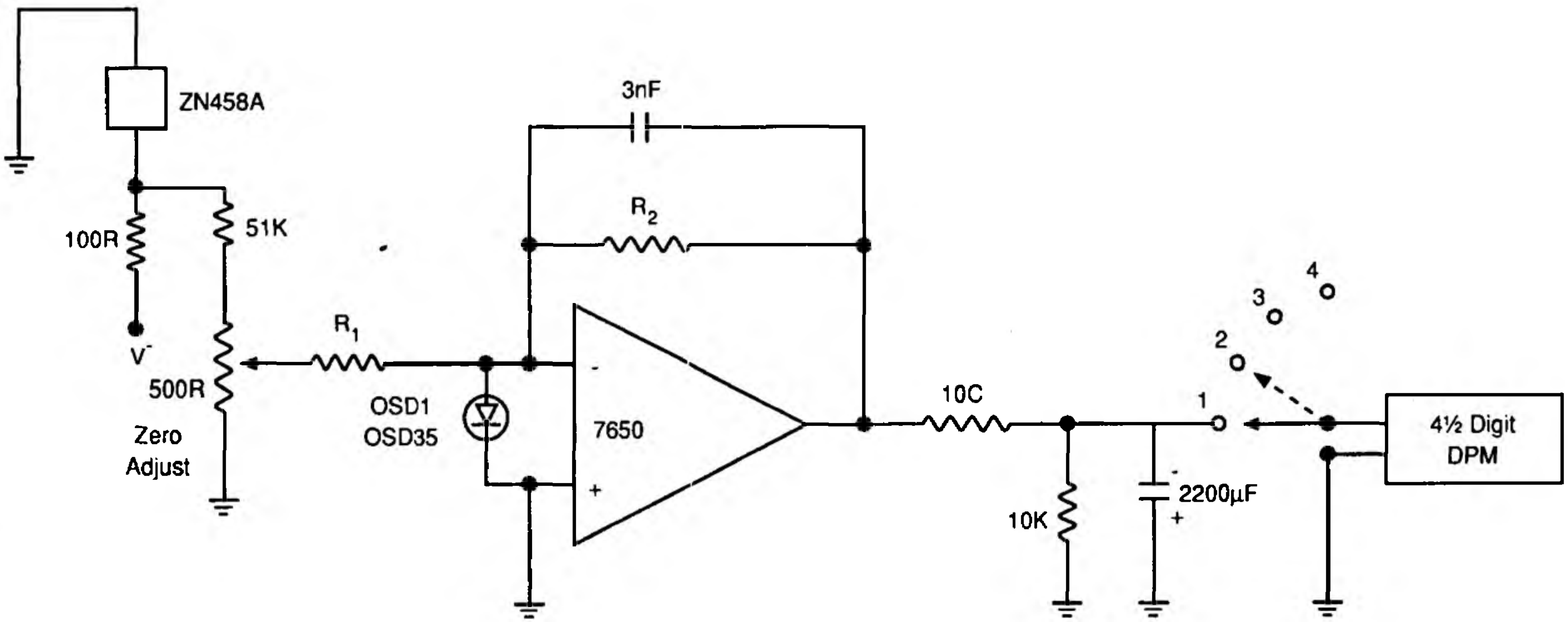


Figure 2.1 Optical arrangement



Note: Four separate circuits as above were built with various values of R_1 and R_2.
The panel meter is switchable between the 4 outputs.

Figure 2.2 Amplifier for Photodiodes

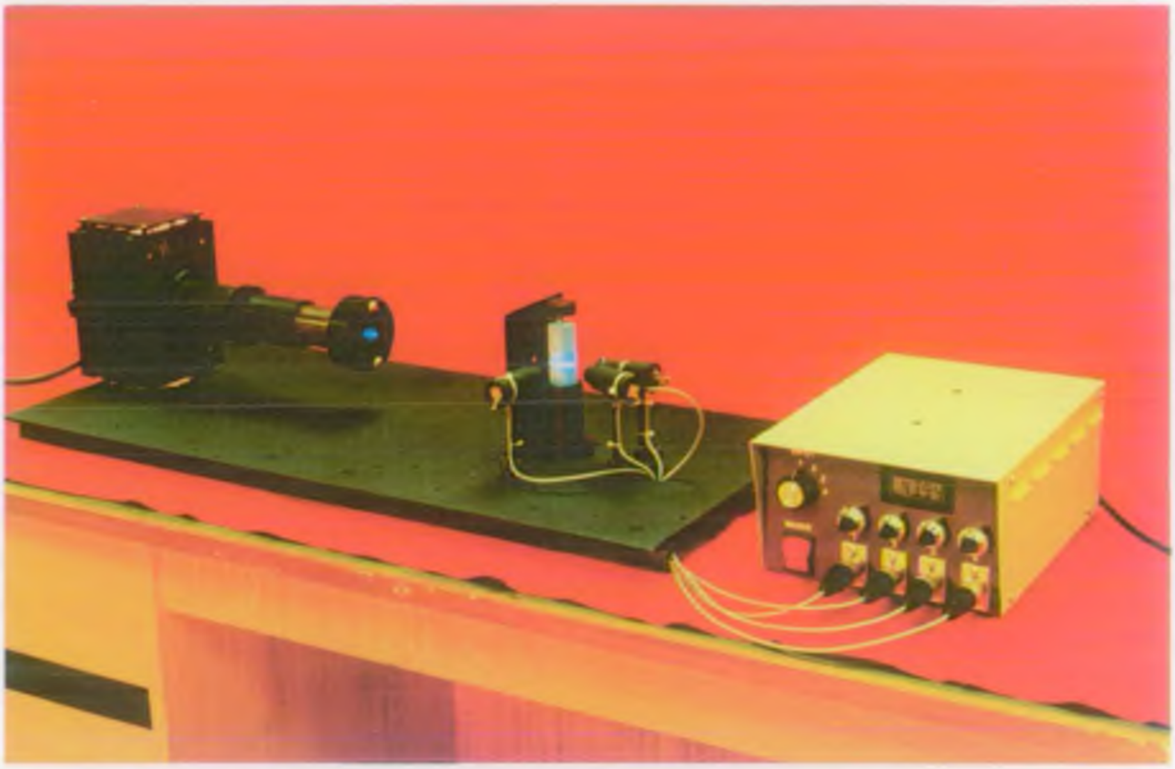


Figure 2.3 General View of Light Scatter Test Rig

Figure 2.4 Light Scatter Detectors

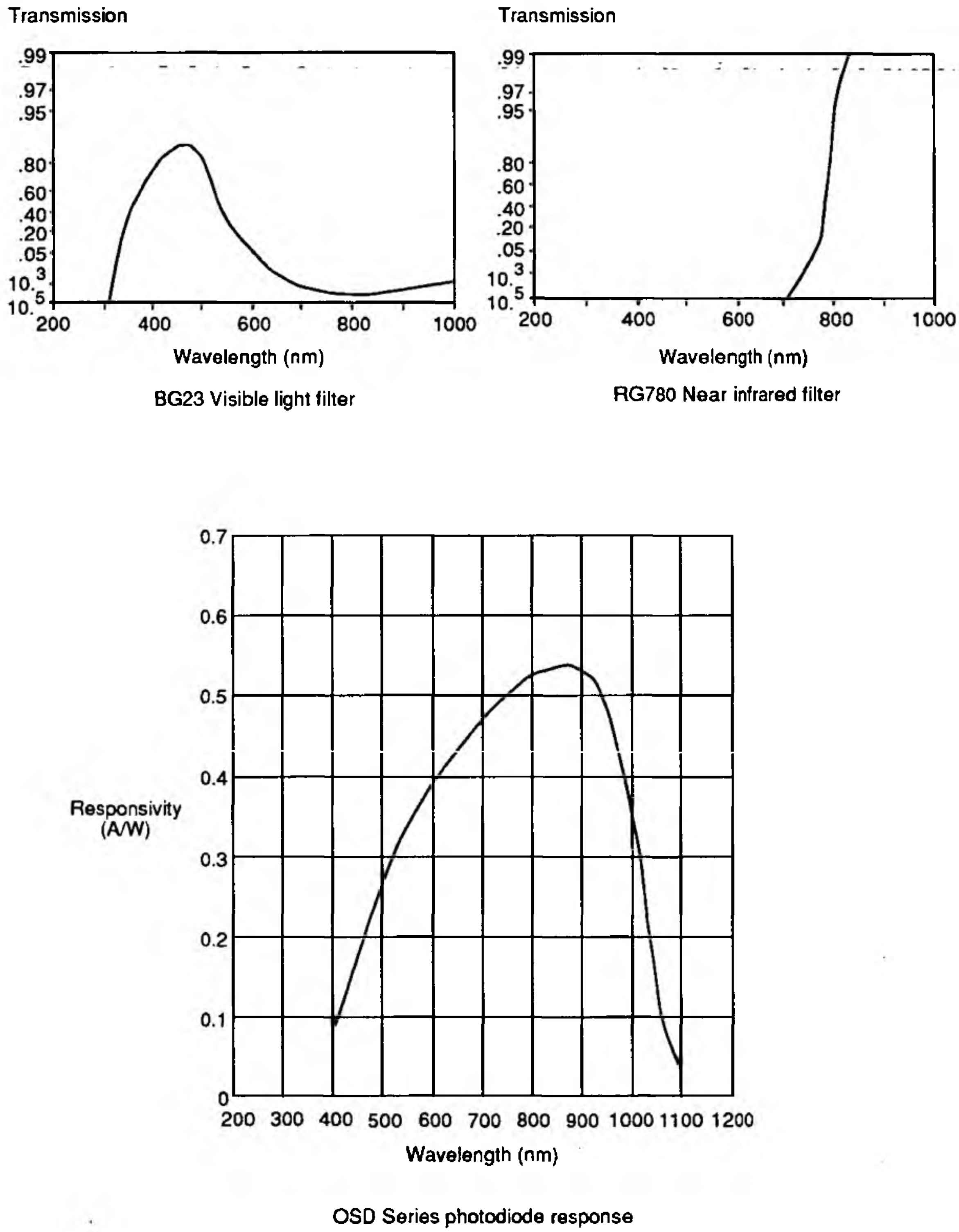


Figure 2.5 Spectral characteristics of filters and detectors

3. EXPERIMENTAL PROCEDURE

3.1 Effluent Sampling

Sewage final effluent was collected from 3 works in 1 litre sample containers. The samples were brought to WRc Swindon within an hour for measurement. The effluents were:

(a) A Reed Bed effluent from a small rural works. The works employs two Rotary Biological Contactors (RBCs or 'Biodiscs') followed by a sand filter and two Reed Beds. The works produces consistently good effluents with suspended solids in the range 1 to 5 mg l^{-1}.

(b) An activated sludge works effluent. The works has conventional aeration of the activated sludge followed by secondary clarifiers with no tertiary treatment. The suspended solids range was typically 10 to 20 mg l^{-1}.

(c) A biological filter works effluent. The works uses conventional Biological filters with secondary clarifiers and no tertiary treatment. The suspended solids range was the most variable of the three ranging from 8 to 30 mg l^{-1}.

3.2 Suspended Solids Determinations

The suspended solids determinations were carried out according to the Standing Committee of Analysts recommendations (Suspended, Settleable, and Total Dissolved Solids in Waters and Effluents 1980) except that a Microwave oven was used for drying the filter papers. For each sample of effluent 3 separate suspended solids determinations were made and the mean used to correlate with light scattering measurements, unless there was a clear reason to discard one of the readings such as a punctured filter paper. Where suspended solids determinations could not be carried out straight-away the sample was chilled. The suspended solids determinations were carried out within 5 hours of the light scattering readings.

3.3 Light Scattering Measurements

The test rig was set up in the laboratory with a voltmeter to monitor the DC lamp supply. The equipment was switched on each morning and left to warm up for at least half an hour. The zero offset potentiometers were then adjusted to give zero output with distilled water in the sample cell. The offset potentiometer readings were then recorded for white light and with each of the two filters on the incident light projector. The zeroing procedure was carried out every day and those settings used for the day in case of drift. The low angle scatter was most prone to zero drift. This was due to the stray light between the sample cell and transmitted light/low angle detectors, rendered more difficult by the cylindrical sample cell.

The effluent sample was then well shaken and the sample cell filled. Care was to taken to avoid bubbles, condensation and settlement with the sample. The sample cell was inverted several times to disperse the suspended material uniformly, and to ensure removal of any bubbles on the sample cell walls. The sample was then inserted in the holder and the readings at the three angles and the transmitted light level recorded. Although the photodiode amplifiers were built with a 20 second time response, the output readings fluctuated so that the maximum reading was a factor of 1.3 times the minimum reading obtained. Twenty readings were therefore taken manually and the mean recorded. The fluctuations were greatest with the activated sludge effluent, presumably due to large particles moving in and out of the measurement volume of the instrument. After each set of angles was measured, the zero offset potentiometers were reset, the light source filter changed and the sample inverted several times to avoid under-reading due to settlement.

3.4 Turbidity Readings

For each sample the turbidity as measured by a HACH XR Ratio bench turbidimeter was recorded as a check on the light scattering measurements.

4. LIGHT SCATTERING RESULTS

4.1 Light Scattering with Formazine

Formazine suspensions were made up from fresh stock 4000 FTU standard suspension to cover the range 0 to 20 FTU which nominally would include a suspended solids range of 0 to 50 mg l^{-1} suspended solids with most turbidimeters. The scattered light intensities at 90°, 25° and low angle were measured and the ratio of scattered light to transmitted light was plotted against the 8 standard suspension FTU values. All the points lay close to straight lines with the least squares fitted line passing close to the origin. The low angle scattered light graph appears to be non-linear on the dilute suspensions particularly with white light. For an instrument manufacturer it would be necessary to consider whether a look-up table were needed to cover this range. The data is shown plotted in Appendix A with the least squares fitted straight line drawn through the data.

It is interesting to note that in all cases the visible light scatters more efficiently than the white light, which in turn scatters more efficiently than the near infrared light. This is in accordance with theory, where shorter wavelengths would be expected to be scattered more than longer wavelengths. The effect would be more marked if the detector had a flat response.

4.2 Correlations with Suspended Solids

A total of 28 samples of each effluent have been collected over a 3 week period from the 3 sewage treatment works with their different effluent types. In many cases there was quite a wide scatter of points on the graphs and so there is a separate graph with its least squares line for the 3 effluents, the 3 angles and the 3 'colours' of incident light making a total of 27 graphs. These are included in Appendix B for reference. The most appropriate figure of merit is the 95% confidence limit for the prediction of suspended solids from turbidity and these are summarised in Table 4.1. The correlation coefficients are similarly summarised in Table 4.2 and the correlation coefficients, gradients and intercepts are given on the individual graphs. The results will be described by effluent.

(a) **Reed Bed Effluent.** The Reed Bed effluent covered an unusually low range of suspended solids values. The effluent was visually difficult to distinguish from tap water with no large particles visible and so the amount of scattered light to be detected is very small.

The best results were obtained with the 90° scattered light though the visible only light graph has two outliers giving a poorer result. The white light gave a 95% confidence limit of ± 1.6 mg l^{-1}. The low angle scatter gave the poorest result on this effluent with 95% confidence limits of ± 1.9 mg l^{-1}. The visible only illuminated results were the poorest.

Table 4.1 Summary of 95% Confidence Limits. All values in mg l^{-1}

	Low Angle	25 Degrees	90 Degrees
A) 95% Confidence Limits for the Prediction of Suspended Solids at the mean from Scattered Light Intensity for the Reed Bed Effluent (Mean suspended = 2.9 mg l^{-1})			
White Light	± 1.87	± 1.69	± 1.63
Visible Light	± 1.92	± 1.81	± 1.88
Near Infrared	± 1.84	± 1.82	± 1.68
B) 95% Confidence Limits for the Prediction of Suspended Solids at the mean from Scattered Light Intensity for the Activated Sludge Effluent (Mean Suspended Solids = 14.1 mg l^{-1})			
White Light	± 6.9	± 7.1	± 7.6
Visible Light	± 6.8	± 6.5	± 7.1
Near Infrared	± 6.8	± 7.2	± 7.6
C) 95% Confidence Limits for the Prediction of Suspended Solids at the mean from Scattered Light Intensity for the Biological Filter Effluent (Mean Suspended Solids = 19.6 mg l^{-1})			
White Light	± 9.0	± 7.9	± 8.0
Visible Light	± 9.4	± 8.3	± 7.7
Near Infrared	± 9.0	± 8.3	± 8.7

Table 4.2 Summary of Correlation Coefficients

	Low Angle	25 Degrees	90 Degrees
A) Correlation Coefficients between Scattered Light and Suspended Solids for the Reed Bed Effluent			
White Light	0.45	0.59	0.63
Visible Light	0.39	0.50	0.44
Near Infrared	0.47	0.49	0.59
B) Correlation Coefficients between Scattered Light and Suspended Solids for the Activated Sludge Effluent			
White Light	0.41	0.37	0.00008
Visible Light	0.44	0.52	0.37
Near Infrared	0.44	0.32	0.074
C) Correlation Coefficients between Scattered Light and Suspended Solids for the Biological Filter Effluent			
White Light	0.55	0.67	0.66
Visible Light	0.48	0.63	0.69
Near Infrared	0.54	0.63	0.58

(a) **Activated Sludge Effluent.** The Activated Sludge effluent was a good quality effluent in suspended solids terms. Visually it contained a small number of quite large particles, but was otherwise clear. Of the 3 effluents, it was the least well settled, so that it was necessary to agitate the sample vessel frequently to avoid low results. This situation presents measurement problems for light scattering instruments because the selection of particles scattering light varies as they drift about the sample vessel requiring extensive averaging. This would be much less of a problem with an online instrument provided there was plenty of flow past the probe.

(b) The low angle measurements gave the best correlation with suspended solids with a 95% confidence limit of ± 6.8 mg l^{-1} with infrared light. The 90° results were poor with little correlation apparent. The 25° results were better than the 90° results with a definite positive correlation. Visible only light appeared to give slightly better results than the other illuminants. Overall these results were the poorest as correlations, though the 95% confidence limits are actually better than the filter effluent results in terms of mg l^{-1} solids rather than percentage reading or correlation coefficients. It is unfortunate that the spread of values was so small, though this is of course a healthy situation for the works.

(a) **Biological Filter Effluent.** The Filter effluent was typical of many small to medium sized works. Visually it was the worst-looking effluent with a wide range of particles sizes visible. The works did not have very much holding capacity and so the effluent quality varied with hydraulic loading leading to a greater variation in suspended solids than with the other effluents.

(b) The 90° and 25° results were better than the low angle results with the best 95% confidence limit of ± 7.7 mg l^{-1} recorded for visible light at 90°. The low angle results were between ± 9.0 to ± 9.4 mg l^{-1}. The Filter effluent gave the best correlation coefficients and the graphs look relatively respectable.

(c) **All three effluents.** It is interesting to note that all the intercepts are positive values except for 4 of the Reed Bed results. It may be that a curve rather than a straight line model would give better results over a wide range of suspended solids values.

4.3 Results with the Hach XR

The Hach XR is a laboratory turbidimeter which is essentially a 90° white light scatter instrument. Measurements were made on each effluent as a check on the performance of the test rig. The correlations between the Hach turbidity and the suspended solids follow a very similar pattern to that of the 90° white light scattering measurements. The result for the Reed Bed effluent is near identical, with the Hach giving slightly better results for the Activated Sludge and Filter effluents. 95% confidence limits of 1.6 mg l^{-1}, 7.0 mg l^{-1} and 6.9 mg $\cdot l^{-1}$ were obtained for the reed bed, activated sludge and filter effluents respectively. The results are shown plotted in Appendix C.

A further check can be made on the quality of the test rig measurements by examining the correlation between the Hach turbidity and the 90° white light scattered light and these are shown in Appendix D. There is a good correlation between these parameters for the Reed Bed and Filter effluents with correlation coefficients of 0.94 and 0.89 respectively. This is a very much better correlation than was obtained between any of the scattered light measurements and suspended solids, indicating that the observed uncertainty in predicting suspended solids from the scattered light measurements is not attributable to shortcomings in the scattered light equipment. The correlation between Hach turbidity and the 90° scattered light for the activated sludge effluent is very poor. This indicates that there is an inherent variability in measuring scattered light from this effluent with this kind of equipment.

It should be noted that the gradients of the least squares fit lines in the relationship between turbidity calibrated on Formazine and suspended solids for the 3 effluents range from 0.12 to 0.32 FTU mg l^{-1}. It is clear therefore that the relationship between turbidity and suspended solids will vary from effluent to effluent besides being instrument dependent.

5. PARTICLE SIZE DISTRIBUTION

5.1 Introduction

A Malvern Mastersize X was used to measure the particle sizes in the effluents. There is a difficulty with particle sizing in effluents in that the particle concentration falls between two classes of sizing equipment. The Malvern Laser Diffraction type is designed for higher concentrations but will work down to at least 10 mg l^{-1} solids on effluents quite reliably. For a very good effluent it is probably more appropriate to use a Laser particle counter or a Coulter counter, but these instruments use a capillary or orifice which is liable to blockage on more concentrated effluents. The Malvern was considered the best instrument for the purpose, but the results for the Reed Bed effluent were rather variable.

The Mastersizer X produces a standard report which includes a histogram of the data and the percentages of particles in the different range 'bins' of size. The data has been presented in this form as it provides a good summary. The Mastersizer X is designed to show the relative amount of solid material in suspension on a volume basis. The percentages shown in the tables therefore indicate the percentage of the volume of suspended material within a given range. This should be the best guide as to how the different size ranges contribute to the suspended solids of the suspension. If the histogram were drawn on the basis of the number of particles, the peak would usually be at the low size end of the range. However, because the volume varies as the cube of the linear dimensions of a particle, these many small particles contribute only a small proportion of the volume of material.

The treatment of a sample may have a profound effect on the particle size distribution. These samples were collected from the works outfall and measured within 1 hour. They were stirred sufficiently to keep the material in suspension and pumped through the measurement cell as gently as possible. This care was exercised to avoid high shear rates which may break delicate flocs. It was found that even with this care some change occurred between successive measurements, but this was only a slight shift towards the small size end of the distribution. Some floculation is in any case likely to occur between sampling and measurement.

5.2 Results

The Reed Bed effluent results are shown in Figures 5.1 and 5.2. It may be seen from Figure 5.1 that there are flat peaks at a few microns and at around 30 microns with a sharper peak at around 200 microns. The results in Figure 5.2 were measured after a few minutes of stirring and circulation. Most of the samples had histograms in the form of Figure 5.1, with varying proportions of material in the 200 micron peak. The form of the histogram indicates that there is a negligible volume of suspended material outside the measured 0.5 to 600 micron range.

MALVERN INSTRUMENTS MASTERSIZER X

Version 1.1 | Wed, Jan 27, 1993 2:45PM

Reed bed :Run Number 1

Effluent from Reed bed works. 27/1/93.

Sample File Name: UWIST2 , Record: 35 | Source: Analysed
Measured on: Wed, Jan 27, 1993 2:40PM Last saved on: Wed, Jan 27, 1993 2:41PM

Presentation: (2$$D) 1.330, 1.540 + i 0.10000
Polydisperse model | Volume Result | Focus = 300 mm.

Residual = 3.887 % | Concentration = 0.005 % | Obscuration = 1.30 %
d (0.5) = 167.70 µm | d (0.1) = 13.14 µm | d (0.9) = 228.54 µm
D [4, 3] = 150.13 µm | Span = 1.28
Sauter Mean (D[3,2]) = 25.72 µm | | Mode = 184.15 µm
Specific Surface Area = 0.0944 sq. m. / gm | | Density = 2.47 gm. / c.c.

Size (Lo) µm	Result In %	Size (Hi) µm	Result Below %
0.50	0.03	1.32	0.03
1.32	0.39	1.60	0.42
1.60	0.74	1.95	1.16
1.95	1.05	2.38	2.21
2.38	1.26	2.90	3.47
2.90	1.38	3.53	4.86
3.53	1.34	4.30	6.20
4.30	1.14	5.24	7.34
5.24	0.80	6.39	8.14
6.39	0.54	7.78	8.68
7.78	0.40	9.48	9.08
9.48	0.51	11.55	9.59
11.55	0.66	14.08	10.25
14.08	0.90	17.15	11.16
17.15	1.29	20.90	12.44
20.90	1.77	25.46	14.21

Size (Lo) µm	Result In %	Size (Hi) µm	Result Below %
25.46	2.12	31.01	16.33
31.01	1.73	37.79	18.06
37.79	0.12	46.03	18.19
46.03	0.00	56.09	18.19
56.09	0.01	68.33	18.20
68.33	0.98	83.26	19.18
83.26	2.22	101.44	21.40
101.44	4.55	123.59	25.95
123.59	11.41	150.57	37.36
150.57	25.34	183.44	62.70
183.44	25.34	223.51	88.04
223.51	9.79	272.31	97.82
272.31	2.04	331.77	99.87
331.77	0.13	404.21	100.00
404.21	0.00	492.47	100.00
492.47	0.00	600.00	100.00

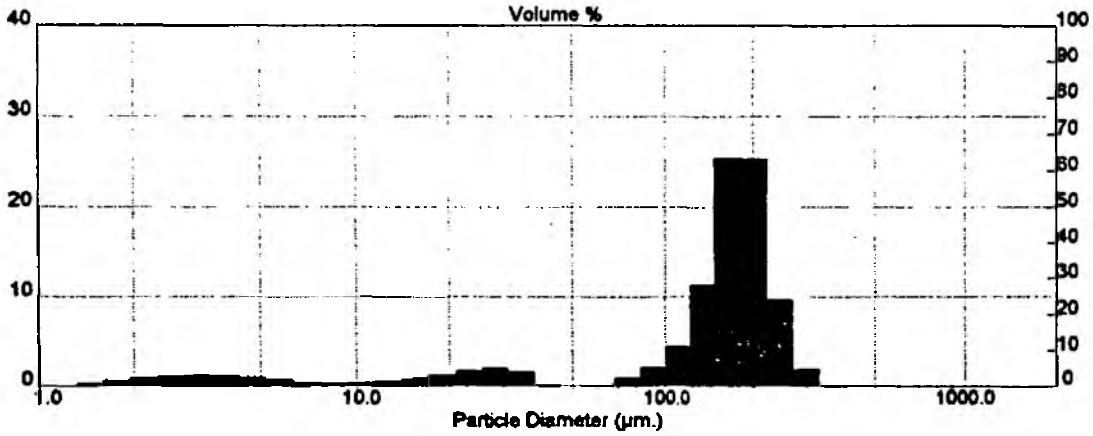


Figure 5.1 Reed bed effluent particle size distribution

MALVERN MASTERSIZER X

Version 1.1 Thu, Jan 28, 1993 10:53AM

Reed bed :Run Number 4

Effluent collected at 9-00 am on 28/1/93

Sample File Name: UWIST2 , Record: 47 Source: Analysed
Measured on: Thu, Jan 28, 1993 10:49AM Last saved on: Thu, Jan 28, 1993 10:50AM

Presentation: (2$$D) 1.330, 1.540 + i 0.10000
Polydisperse model Volume Result Focus = 300 mm.

Residual = 2.750 % Concentration = 0.001 % Obscuration = 2.22 %
d (0.5) = 4.66 µm d (0.1) = 2.01 µm d (0.9) = 71.71 µm
D [4, 3] = 22.36 µm Span = 14.96
Sauter Mean (D[3,2]) = 4.25 µm Mode = 3.34 µm
Specific Surface Area = 0.5716 sq. m. / gm Density = 2.47 gm. / c.c.

Size (Lo) µm	Result In %	Size (Hi) µm	Result Below %
0.50	0.27	1.32	0.27
1.32	3.02	1.60	3.29
1.60	5.61	1.95	8.90
1.95	7.83	2.38	16.73
2.38	9.45	2.90	26.18
2.90	10.23	3.53	36.41
3.53	9.92	4.30	46.33
4.30	8.52	5.24	54.85
5.24	6.51	6.39	61.36
6.39	4.65	7.78	66.01
7.78	3.34	9.48	69.35
9.48	2.42	11.55	71.77
11.55	1.89	14.08	73.66
14.08	1.72	17.15	75.38
17.15	1.76	20.90	77.14
20.90	1.77	25.46	78.92

Size (Lo) µm	Result In %	Size (Hi) µm	Result Below %
25.46	1.74	31.01	80.66
31.01	1.83	37.79	82.49
37.79	2.02	46.03	84.51
46.03	2.33	56.09	86.83
56.09	2.55	68.33	89.38
68.33	2.48	83.26	91.86
83.26	2.33	101.44	94.19
101.44	1.85	123.59	96.04
123.59	1.20	150.57	97.24
150.57	0.94	183.44	98.18
183.44	0.93	223.51	99.11
223.51	0.69	272.31	99.80
272.31	0.20	331.77	100.00
331.77	0.00	404.21	100.00
404.21	0.00	492.47	100.00
492.47	0.00	600.00	100.00

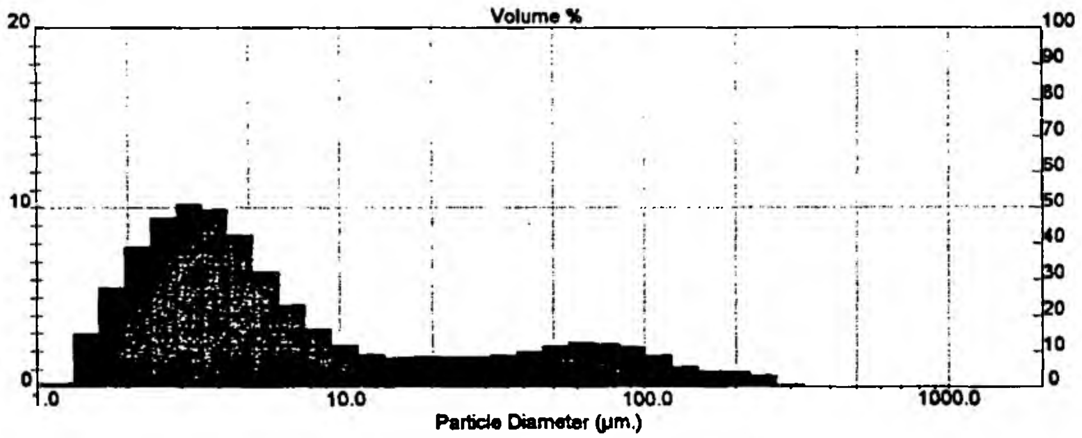


Figure 5.2 Reed bed effluent particle size distribution

The Activated Sludge works effluent results are shown in Figures 5.3 and 5.4. Figure 5.3 shows that the majority of the volume is contributed by particles greater than 10 microns in size with a peak at about 150 microns. A smooth and broad distribution like this is typical of suspensions of particles which have been allowed to interact and floculate or break over a period of time. There is some sign of a subsidiary peak at 10-20 microns but this is not significant in volume terms. The distribution tails off at both ends indicating that very little material is present outside the 0.5 to 600 micron range. Figure 5.4 is similar in form at the low size end, but does not tail off at 600 microns in the same way. This suggests that there may be some material greater than 600 microns in size, though visual inspection indicated that no great amount of such material can be present. The majority of the activated sludge samples produced histograms of the form of Figure 5.3.

The Biological Filter works effluent results are shown in Figures 5.5 and 5.6. The histogram of Figure 5.5 is typical of the results from this works with a smooth form peaking at around 60 microns. There is no significant material greater than 300 microns at the high size end, or below 1 micron at the bottom end. As with the activated sludge results this form of histogram is typical of a suspension that has been allowed to interact over a period as one would expect during settlement at a sewage treatment works. Experience suggests that the difference between the activated sludge effluent and the filter effluent has more to do with settling conditions in the clarifiers than the treatment process. During the turbidity measurements the activated sludge effluent tended to settle more quickly than the filter effluent. Figure 5.6 shows another sample with a much broader peak, but otherwise very similar to Figure 5.5.

The Filter and Activated Sludge works effluent results are much as expected. The Reed Bed effluent is quite different. It may be that the sand filter which precedes the Reed Bed is effective in removing most of the larger sized material and that the peaks which are observed are caused by floculation in the Reed Bed or after sampling of the effluent.

5.3 Effects on Light Scattering

From a light scattering point of view it is significant that most of the material is above 10 microns in size. In this situation the particles are much greater in size than the wavelength of light and the scattered light can be considered as the sum of two contributions:

(a) A strong forward-scattered lobe of diffracted light very close to the transmitted light axis. The angle made with the transmitted light axis is smaller for larger particles in accordance with the laws of diffraction.

(b) A general illumination over the full 360° caused by reflection and refraction of light by the particles. For particles with irregular surfaces such as bacterial floc there will be many multiple reflections around the surface of the particles contributing to this illumination.

MASTERSIZER X

Version 1.1 Wed, Jan 27, 1993 10:48AM

Activated 1 :Run Number 2

Effluent from activated sludge plant 27/1/93 collected at 08-50.

Source: Analysed

Measured on: Wed, Jan 27, 1993 10:45AM

Presentation: (2$$D) 1.330, 1.540 + i 0.10000
Polydisperse model

Volume Result

Focus = 300 mm.

Residual = 1.027 %
d (0.5) = 97.96 µm
D [4, 3] = 114.03 µm
Sauter Mean (D[3,2]) = 29.06 µm
Specific Surface Area = 0.0836 sq. m. / gm

Concentration = 0.015 %
d (0.1) = 13.13 µm
Span = 2.30

Obscuration = 3.71 %
d (0.9) = 238.92 µm

Mode = 152.47 µm
Density = 2.47 gm. / c.c.

Size (Lo) µm	Result In %	Size (Hi) µm	Result Below %
0.50	0.04	1.32	0.04
1.32	0.22	1.60	0.26
1.60	0.37	1.95	0.62
1.95	0.47	2.38	1.09
2.38	0.54	2.90	1.63
2.90	0.59	3.53	2.21
3.53	0.65	4.30	2.86
4.30	0.76	5.24	3.63
5.24	0.95	6.39	4.57
6.39	1.18	7.78	5.75
7.78	1.40	9.48	7.15
9.48	1.64	11.55	8.79
11.55	1.92	14.08	10.71
14.08	2.22	17.15	12.93
17.15	2.47	20.90	15.40
20.90	2.65	25.46	18.05

Size (Lo) µm	Result In %	Size (Hi) µm	Result Below %
25.46	2.86	31.01	20.91
31.01	3.21	37.79	24.13
37.79	3.77	46.03	27.90
46.03	4.50	56.09	32.40
56.09	5.32	68.33	37.71
68.33	6.26	83.26	43.97
83.26	7.44	101.44	51.41
101.44	8.73	123.59	60.14
123.59	9.64	150.57	69.79
150.57	9.63	183.44	79.42
183.44	8.26	223.51	87.68
223.51	6.09	272.31	93.77
272.31	3.91	331.77	97.68
331.77	1.98	404.21	99.66
404.21	0.34	492.47	100.00
492.47	0.00	600.00	100.00

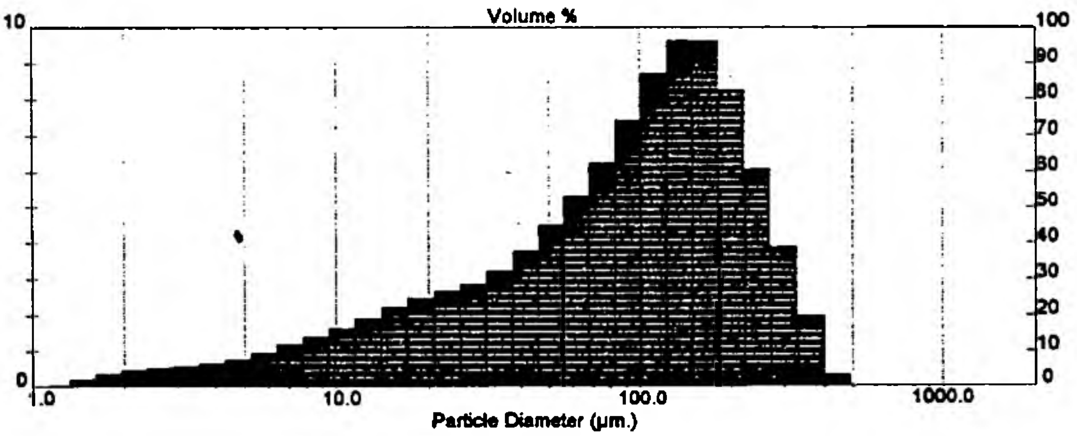


Figure 5.3 Activated sludge works effluent typical particle size distribution

MALVERN MASTERSIZER X

Version 1.1 | Thu, Jan 28, 1993 4:29PM

Activated Sludge :Run Number 1

Sample of effluent from activated sludge works. 28/1/93.

Sample File Name: UWIST2 , Record: 53 | Source: Analysed
Measured on: Thu, Jan 28, 1993 4:28PM | Last saved on: Thu, Jan 28, 1993 4:29PM

Presentation: (2$$D) 1.330, 1.540 + i 0.10000
Polydisperse model | Volume Result | Focus = 300 mm.

Residual = 0.805 % | Concentration = 0.009 % | Obscuration = 1.62 %
d (0.5) = 148.80 µm | d (0.1) = 17.57 µm | d (0.9) = 456.93 µm
D [4, 3] = 189.06 µm | Span = 2.97
Sauter Mean (D[3,2]) = 38.29 µm | | Mode = 190.49 µm
Specific Surface Area = 0.0634 sq. m. / gm | | Density = 2.47 gm. / c.c.

Size (Lo) µm	Result In %	Size (Hi) µm	Result Below %
0.50	0.02	1.32	0.02
1.32	0.15	1.60	0.17
1.60	0.25	1.95	0.43
1.95	0.33	2.38	0.76
2.38	0.38	2.90	1.14
2.90	0.43	3.53	1.57
3.53	0.48	4.30	2.04
4.30	0.56	5.24	2.60
5.24	0.70	6.39	3.30
6.39	0.87	7.78	4.17
7.78	1.05	9.48	5.22
9.48	1.25	11.55	6.47
11.55	1.51	14.08	7.98
14.08	1.78	17.15	9.77
17.15	2.02	20.90	11.79
20.90	2.20	25.46	13.99

Size (Lo) µm	Result In %	Size (Hi) µm	Result Below %
25.46	2.36	31.01	16.35
31.01	2.56	37.79	18.91
37.79	2.84	46.03	21.75
46.03	3.20	56.09	24.95
56.09	3.58	68.33	28.52
68.33	4.05	83.26	32.57
83.26	4.83	101.44	37.41
101.44	5.94	123.59	43.35
123.59	7.11	150.57	50.46
150.57	8.05	183.44	58.50
183.44	8.23	223.51	66.73
223.51	7.60	272.31	74.33
272.31	6.51	331.77	80.84
331.77	5.67	404.21	86.51
404.21	5.70	492.47	92.21
492.47	7.79	600.00	100.00

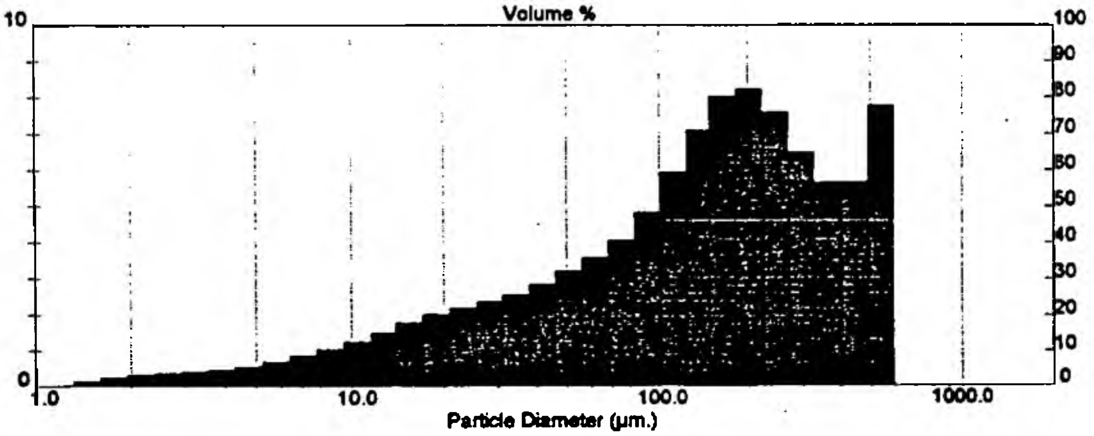


Figure 5.4 Activated sludge works effluent particle size distribution

MALVERN INSTRUMENTS MASTERSIZER X

Version 1.1 Thu, Jan 28, 1993 11:12AM

Filter Effluent :Run Number 1

Effluent collected at 8-30 am on 28/1/93

Sample File Name: UWIST2 , Record: 49 Source: Analysed
Measured on: Thu, Jan 28, 1993 11:09AM Last saved on: Thu, Jan 28, 1993 11:09AM

Presentation: (2$$D) 1.330, 1.540 + i 0.10000
Polydisperse model
Volume Result
Focus = 300 mm.

Residual = 0.397 %
d (0.5) = 48.53 μm
D [4, 3] = 58.72 μm
Sauter Mean (D[3,2]) = 23.88 μm
Specific Surface Area = 0.1017 sq. m. / gm

Concentration = 0.015 %
d (0.1) = 10.82 μm
Span = 2.32

Obscuration = 4.38 %
d (0.9) = 123.21 μm

Mode = 58.86 μm
Density = 2.47 gm. / c.c.

Size (Lo) μm	Result In %	Size (Hi) μm	Result Below %
0.50	0.02	1.32	0.02
1.32	0.14	1.60	0.16
1.60	0.24	1.95	0.40
1.95	0.33	2.38	0.72
2.38	0.42	2.90	1.14
2.90	0.52	3.53	1.66
3.53	0.66	4.30	2.32
4.30	0.89	5.24	3.21
5.24	1.27	6.39	4.48
6.39	1.74	7.78	6.22
7.78	2.14	9.48	8.36
9.48	2.50	11.55	10.87
11.55	2.85	14.08	13.72
14.08	3.29	17.15	17.01
17.15	3.91	20.90	20.92
20.90	4.77	25.46	25.68

Size (Lo) μm	Result In %	Size (Hi) μm	Result Below %
25.46	5.92	31.01	31.60
31.01	7.27	37.79	38.88
37.79	8.63	46.03	47.50
46.03	9.59	56.09	57.09
56.09	9.78	68.33	66.87
68.33	9.11	83.26	75.97
83.26	7.86	101.44	83.83
101.44	6.25	123.59	90.08
123.59	4.52	150.57	94.60
150.57	2.92	183.44	97.52
183.44	1.62	223.51	99.14
223.51	0.71	272.31	99.85
272.31	0.15	331.77	100.00
331.77	0.00	404.21	100.00
404.21	0.00	492.47	100.00
492.47	0.00	600.00	100.00

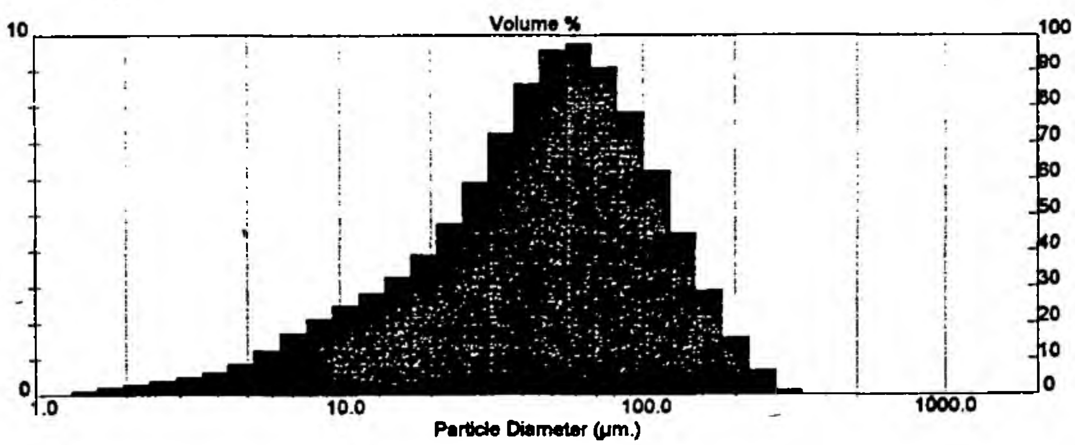


Figure 5.5 Biological filter works effluent typical particle size distribution

MASTERSIZER X

Version 1.1 Wed, Jan 27, 1993 6:33PM

Filter 27/1 :Run Number 3

Filter works effluent. 27/1.

Source: Analysed

Measured on: Wed, Jan 27, 1993 6:11PM

Presentation: (2$$D) 1.330, 1.540 + i 0.10000
Polydisperse model

Volume Result

Focus = 300 mm.

Residual = 0.935 %
d (0.5) = 66.54 µm
D [4, 3] = 92.77 µm
Sauter Mean (D[3,2]) = 30.71 µm
Specific Surface Area = 0.0791 sq. m. / gm

Concentration = 0.011 %
d (0.1) = 14.79 µm
Span = 2.98

Obscuration = 2.59 %
d (0.9) = 213.23 µm

Mode = 59.81 µm
Density = 2.47 gm. / c.c.

Size (Lo) µm	Result In %	Size (Hi) µm	Result Below %
0.50	0.01	1.32	0.01
1.32	0.12	1.60	0.13
1.60	0.20	1.95	0.34
1.95	0.28	2.38	0.61
2.38	0.34	2.90	0.95
2.90	0.41	3.53	1.36
3.53	0.50	4.30	1.86
4.30	0.64	5.24	2.50
5.24	0.87	6.39	3.37
6.39	1.16	7.78	4.53
7.78	1.40	9.48	5.93
9.48	1.64	11.55	7.57
11.55	1.90	14.08	9.48
14.08	2.26	17.15	11.74
17.15	2.79	20.90	14.52
20.90	3.55	25.46	18.07

Size (Lo) µm	Result In %	Size (Hi) µm	Result Below %
25.46	4.57	31.01	22.64
31.01	5.76	37.79	28.39
37.79	6.94	46.03	35.33
46.03	7.76	56.09	43.09
56.09	7.97	68.33	51.06
68.33	7.60	83.26	58.67
83.26	7.04	101.44	65.70
101.44	6.59	123.59	72.29
123.59	6.41	150.57	78.71
150.57	6.47	183.44	85.18
183.44	6.24	223.51	91.42
223.51	5.02	272.31	96.44
272.31	2.81	331.77	99.24
331.77	0.75	404.21	100.00
404.21	0.00	492.47	100.00
492.47	0.00	600.00	100.00

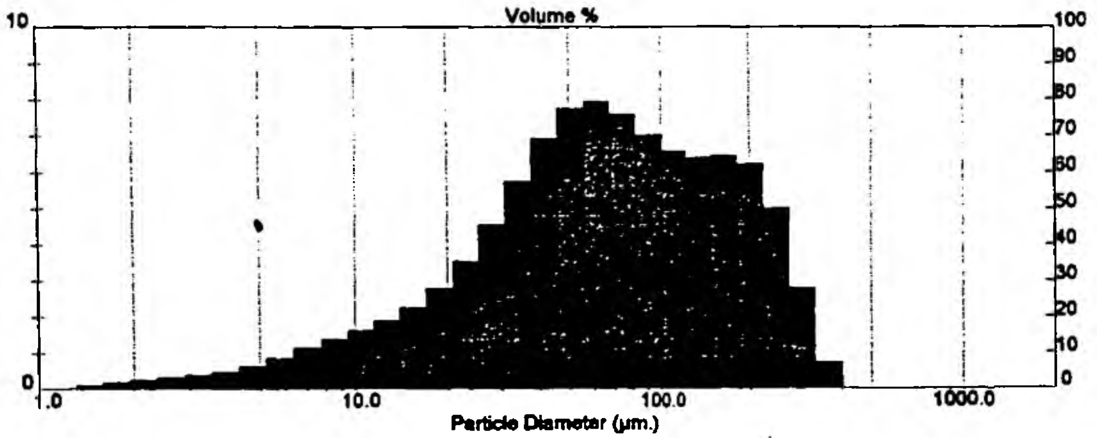


Figure 5.6 Biological filter works effluent particle size distribution

Since there are present in sewage effluents particles of size approaching the wavelength of light, the forward scattered lobe is quite broad. Hence the scattered intensity at 25 degrees is typically 10 times the intensity at 90 degrees for sewage effluent.

6. DISCUSSION

The most unexpected result from the data collected is that the activated sludge effluent results are significantly poorer than the filter effluent results. Activated sludge treatment is a more controlled process than biological filter treatment and a more consistent effluent would be expected.

The particle size measurements confirm the visual impression that the activated sludge effluent contained a relatively high proportion of the solids as larger particles. This is consistent with the poorer result from the 90° scatter correlation with suspended solids, since 90° scatter is the least sensitive of the 3 angles to large diameter particles. The 90° channel also showed greater fluctuation in reading than the other channels, presumably because it is receiving light from a smaller volume of sample. The low angle scatter channel gave the best results on the activated sludge effluent. This is consistent with the above remarks since the low angle geometry will register light from larger particles more effectively than the other 2 channels.

Looking at the reed bed effluent results, the opposite trend can be observed. The reed bed effluent has a high proportion of its solids as small particles and these are detected efficiently by the 90° geometry which gave the best results. Similarly the low angle detector was least sensitive to the changes in small particle numbers and gave the poorest correlation with suspended solids. The 25° detector has produced reasonable results on all 3 effluents as a 'compromise' geometry.

Varying the illuminant spectrum with the filters has had little effect on the results. If there is an observable trend it is that white light gave the best results overall, but it is a less significant factor than angle in this data.

It is clear that the light scattering measurements on the activated sludge effluent would have improved with more effective averaging. This requirement is best addressed by measuring turbidity in a flow situation, or by circulating a large effluent sample through a flowcell. The volume of effluent scattering light on a typical bench turbidimeter such as the Hach range fluctuates far too much to obtain a good estimate of the turbidity without digital averaging. Analogue first order low-pass filtering, with a 10 second time constant is not sufficient to obtain a good estimate. One way to alleviate the problem is to use a larger sample cell. The sensitive volume is also increased by simple geometry with a 25° or low angle instrument which appear to be less troubled by fluctuations than the 90° geometry. Homogenising is another approach to this difficulty, though it may create submicron particles or entrain air if carried out without care.

The presence of large amounts of sub-micron particles is a potential source of error in using scattered light as a surrogate for suspended solids. Such particles would scatter efficiently over a wide range of angles interfering with the light scattered by particles which would be collected as suspended solids on a GF/C filter. In this situation there would be some merit in measuring scattered light at or close to the low angle geometry, as the scattered light from the sub-micron particles would be negligible compared with the high intensity of the diffracted light of the larger suspended solids. There is no evidence from the particle sizing measurements or from the correlations with suspended solids of such an effect.

During the construction of the test rig it was observed that the 90° geometry was much the easiest to build. Although less light is scattered at 90°, it is relatively easy to reduce stray light to a negligible proportion of the signal. Further, the sensitivity of the output to small changes in detector position or angle of acceptance is small. It is therefore not necessary to employ a highly rigid construction or to be careful about restricting the aperture of the detector. By contrast the low angle detector requires a high standard of mechanical construction, since the light intensity as a function of angle is changing rapidly close to the 0° axis. Eliminating the stray light from the transmitted beam is problematic, and requires special provision to absorb this light without multiple reflections occurring between detectors and sample vessel. The 25° detector also required some care, but this was due to the crowded reflective surfaces when measuring transmitted light, low angle and 25° all together and should not arise in a 25° only instrument.

The actual values of the 95% confidence limits obtained from the data are consistent with previous WRc work. Previous results have generally been better, but they have been carried out in a simulated flow situation, so that settlement and averaging problems were minimised. The results with the bench Hach instrument were better than the test rig results by 0.5 to 1.0 mg l^{-1} 95% confidence limits on the activated sludge and filter effluents. This is probably due to the better stability of the commercial instrument where greater effort has been applied to minimising stray light and hence stray light variations.

7. CONCLUSIONS

The following conclusions may be drawn:

1. There is some evidence of a link between effluent particle size distributions and most suitable turbidity measurement angle. 90° scatter is best suited to high quality effluents with few particles in the 100 micron region. Low angle scatter is best suited to effluents with a high proportion of the solids in the 100 micron region. 25° scatter appears to be a good compromise for this parameter if one angle has to be chosen.

2. There is little evidence that the use of white light, visible only light or near infrared light has a marked effect on the correlation between scattered light intensity and suspended solids. White light appears to have a slight advantage.

3. Effective averaging is essential to obtain reliable light scattering results.

4. The suspended solids of a sample may be predicted from the turbidity of a sample to within ± 2 mg l^{-1} at suspended solids levels below 5 mg l^{-1}, and to ± 7 mg l^{-1} at effluent suspended solids of 10-30 mg l^{-1}. These figures are based on a small data set gathered over a 3 week period carried out under good laboratory conditions. They are consistent with other WRc data.

5. The actual relationship between suspended solids and turbidity using formazine for calibration will vary widely depending on effluent and instrument parameters such as illuminant wavelength and scatter angle. A linear model is generally satisfactory though some non-linearity may occur at low suspended solids levels.

6. The variations observed in the correlations between light scattered and suspended solids are probably due to changes in the particle size distribution and changes in the light scattering qualities of the particles. There is no evidence that the variations are due to submicron particles.

7. Particles in sewage effluents are generally within the range 2 to 500 microns, though occasionally larger particles are found.

8. RECOMMENDATIONS

8.1 On-line Evaluation Work

The next step in the process of the investigating the relationship between turbidity and suspended solids is to carry out some online work. It is recommended that an on-line trial is carried out with a range of commercial instruments and on a range of effluents. No clear front-runner has emerged from the study amongst the range of geometry and light source combinations. An online trial would provide:

- A measure of the correlation between suspended solids and turbidity under online conditions.
- Data on the maintenance requirements of on-line turbidimeters with a range of effluent types.
- Further data on the relative merits of particular geometry/light source combinations.

8.2 Standards

Consideration should be given to the way in which present suspended solids consent limits are converted into turbidity consents. If they are expressed in the usual Formazine units (FTU), implying calibration on Formazine, this will lead to wide discrepancies in the effluent turbidities measured, since a range of instruments calibrated on Formazine will give FTU readings varying by up to 50% on the same effluent sample. There are a number of ways to resolve this situation:

- The instrument measurement parameters can be specified in great detail to remove the instrument dependence. This would eliminate many existing instrument designs.
- A table can be drawn up to convert suspended solids to FTU values incorporating the variations for the different angles, wavelengths and perhaps effluent types.
- A new scale could be produced using a standard material whose light scattering properties mimicked those of sewage effluent. A solid material like the Hach 'Gelex' would probably be best. This would bring the instrument outputs into line regardless of measurement geometry and wavelength. Bodies like NPL could advise on suitable materials with the necessary stability and optical properties.
- The instruments can be individually calibrated in suspended solids on each works, but this is really preserving the role of suspended solids.

Some of these options will take time to implement. It would be desirable to work out the preferred option at this stage to avoid delays later in the programme of online monitoring implementation.

APPENDIX A FORMAZINE RESULTS

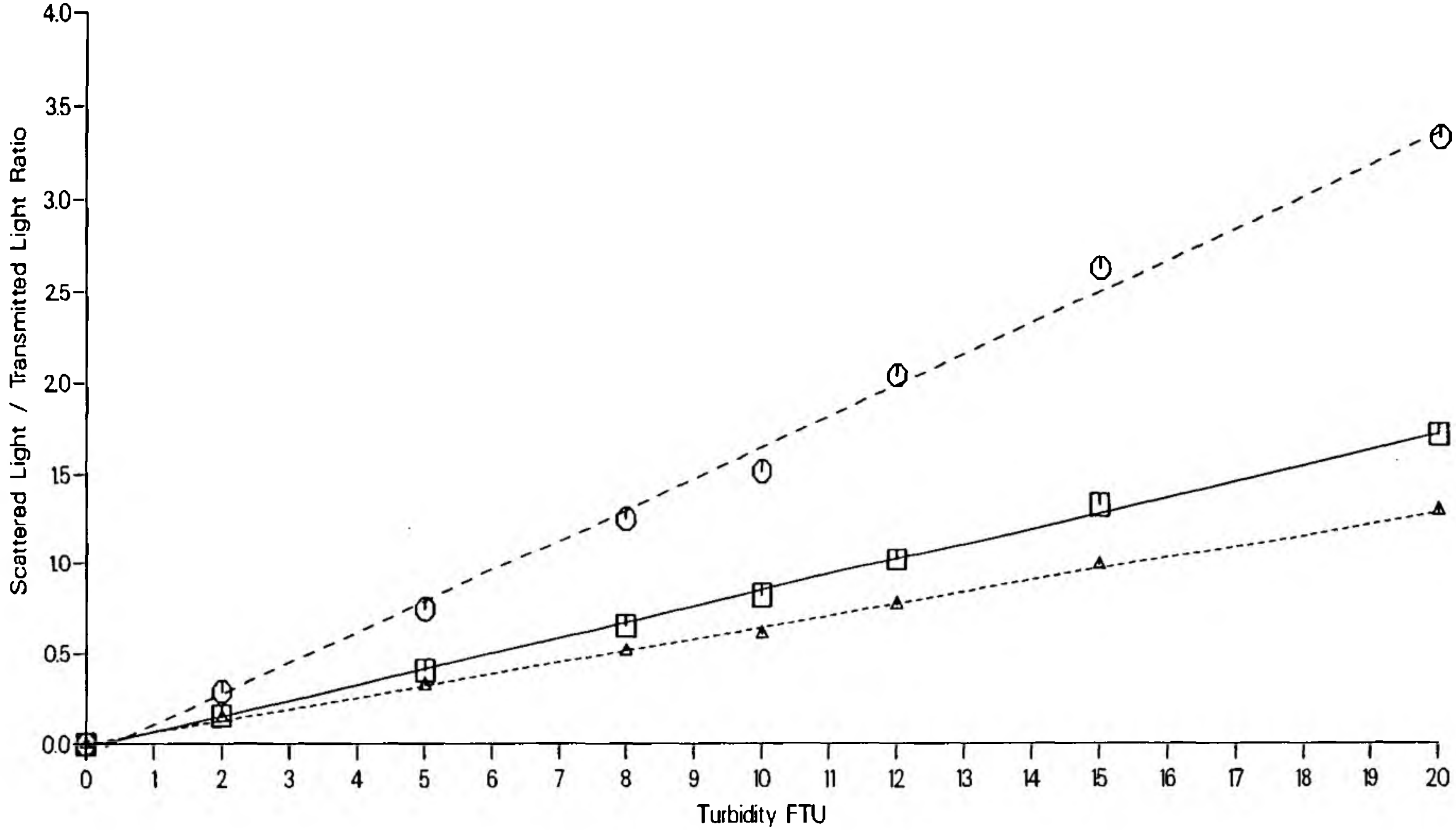


Figure A1 90 Degree Scattered Light Formazine Calibration

White Light
Visible Only Light
Near Infra Red Light

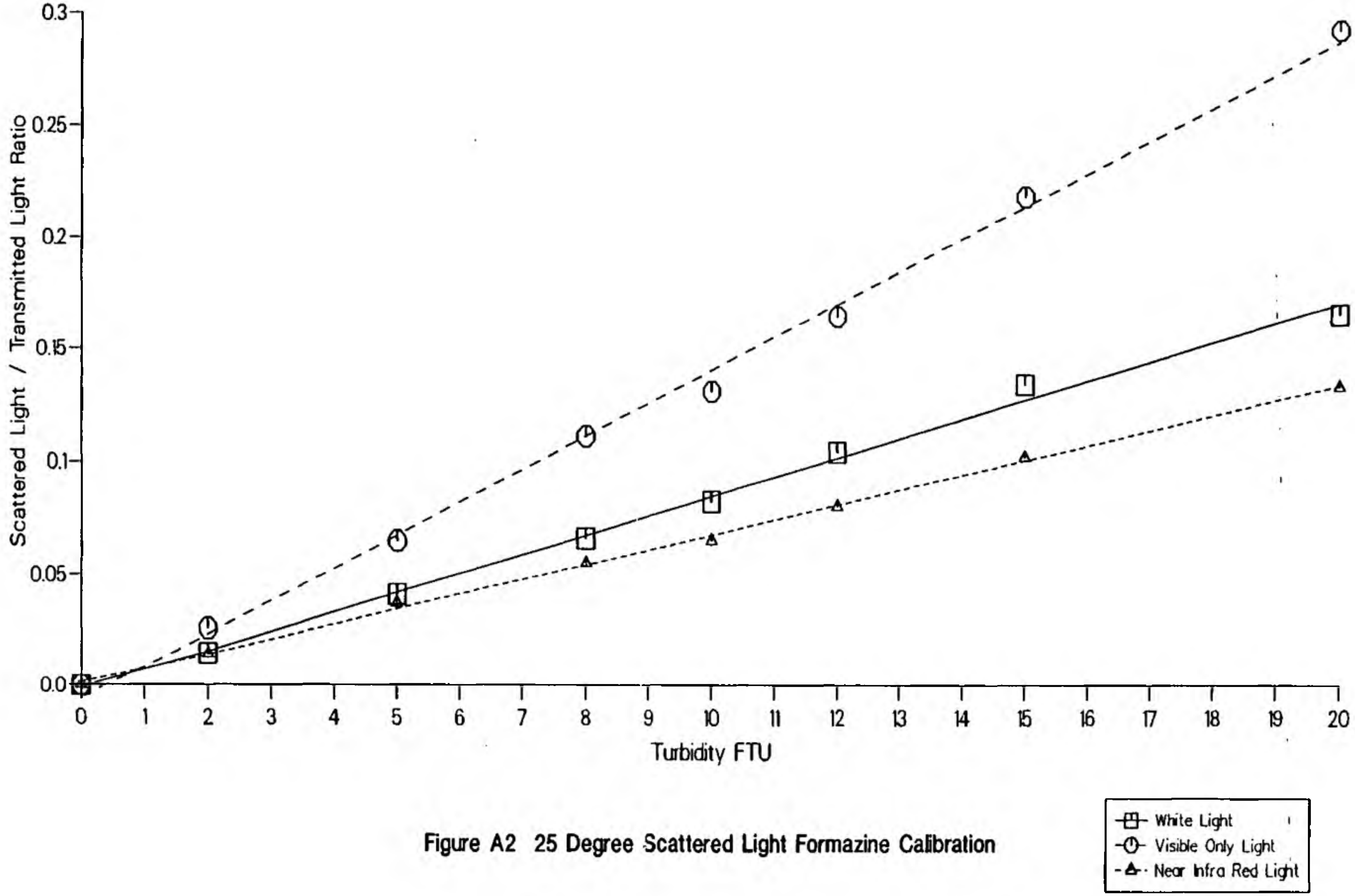


Figure A2 25 Degree Scattered Light Formazine Calibration

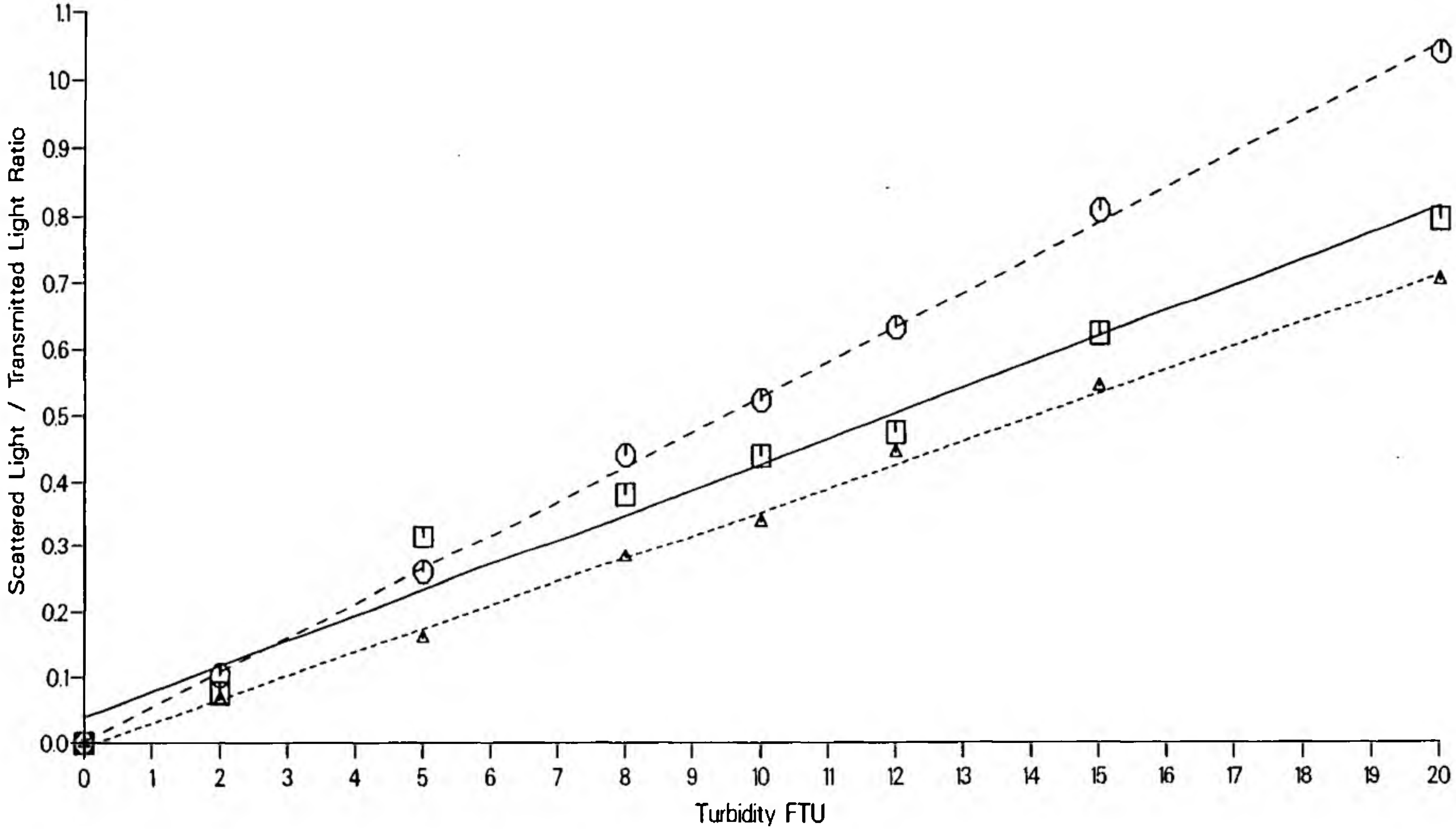
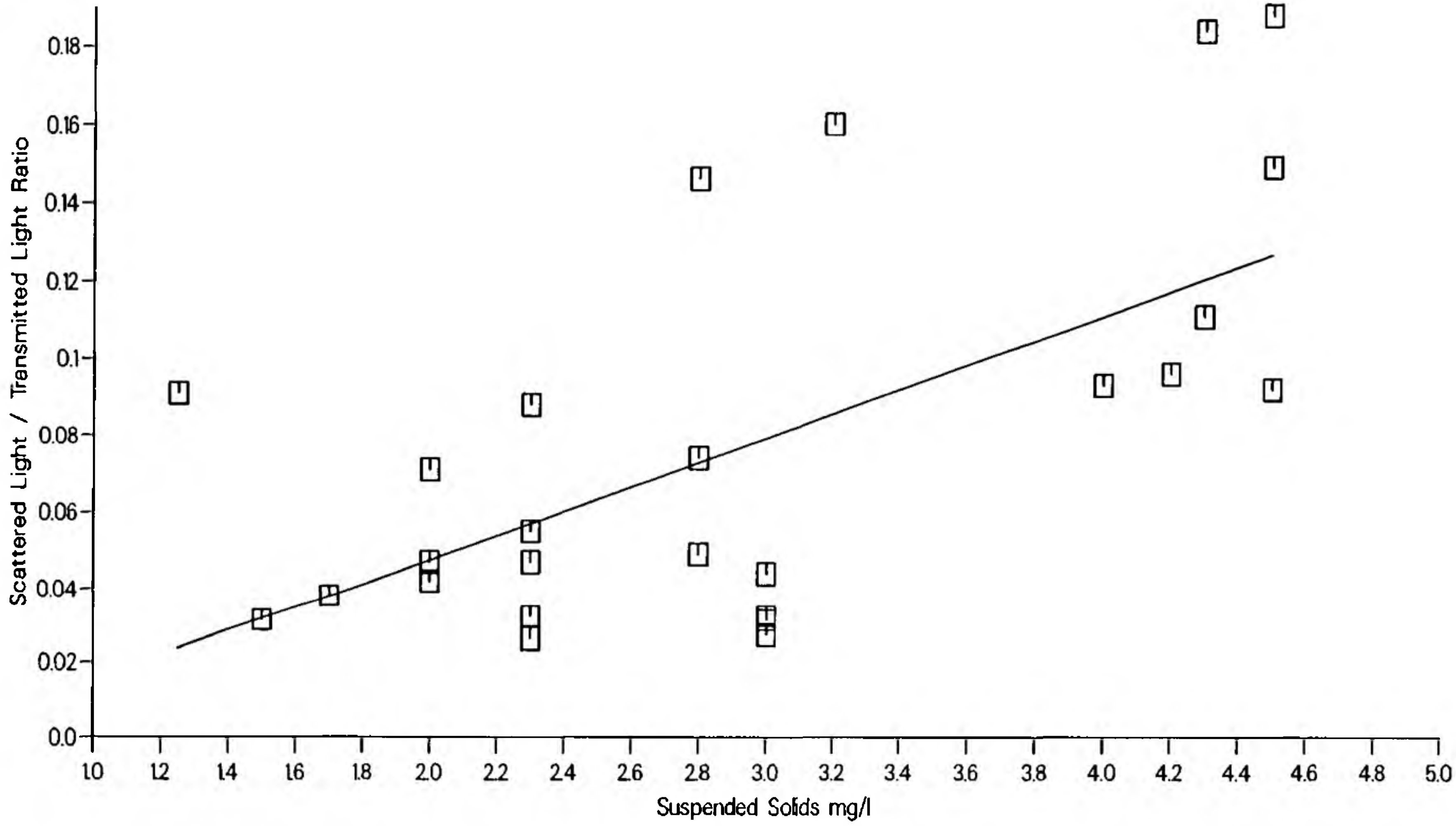


Figure A3 Low Angle Scattered Light Formazine Calibration

APPENDIX B CORRELATIONS BETWEEN SCATTERED LIGHT AND SUSPENDED SOLIDS

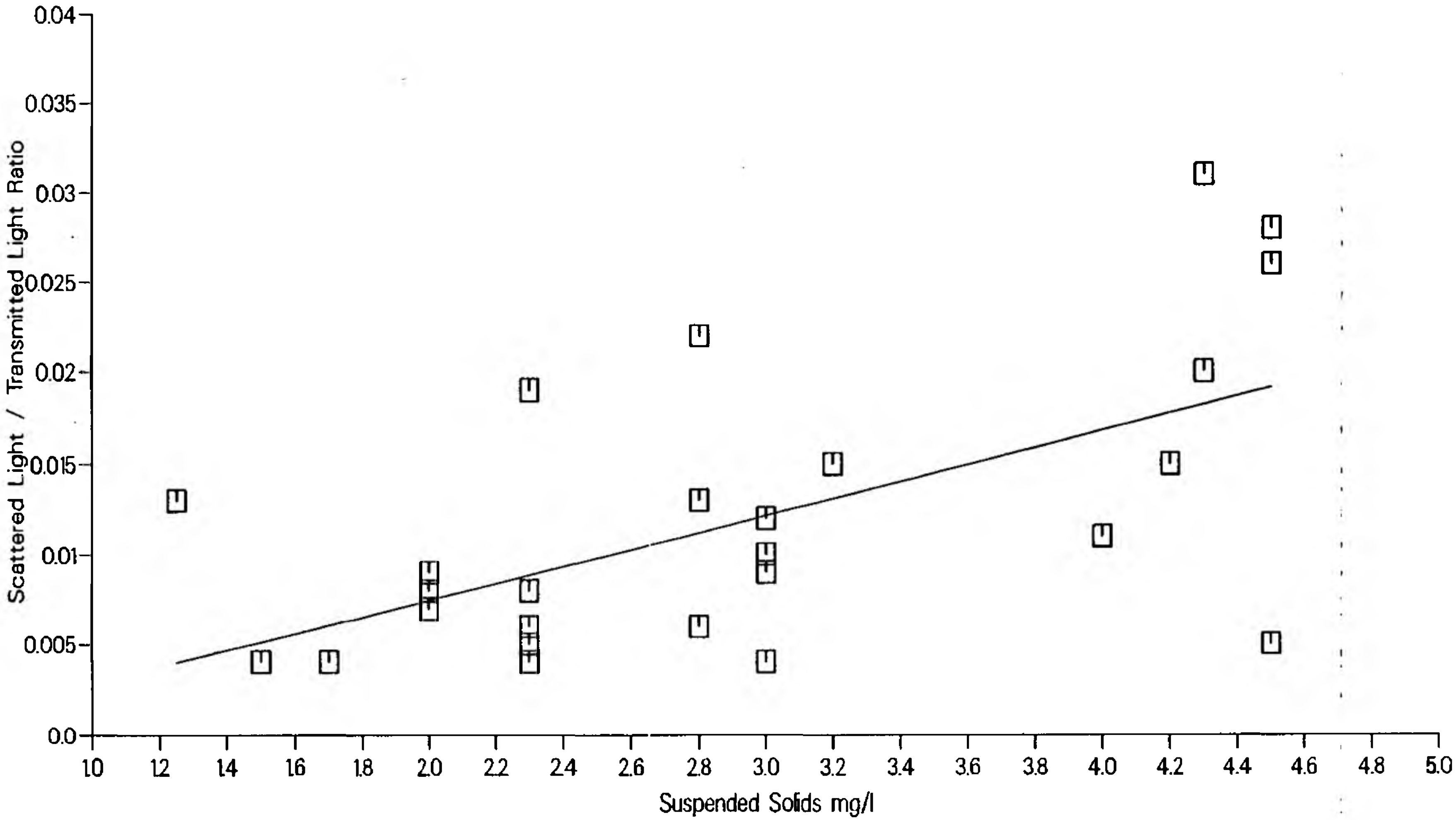


Correlation Coefficient = 0.63

Figure B1 Reed Bed White Light 90 degrees

Slope = 0.032 l/mg

Intercept = -0.016

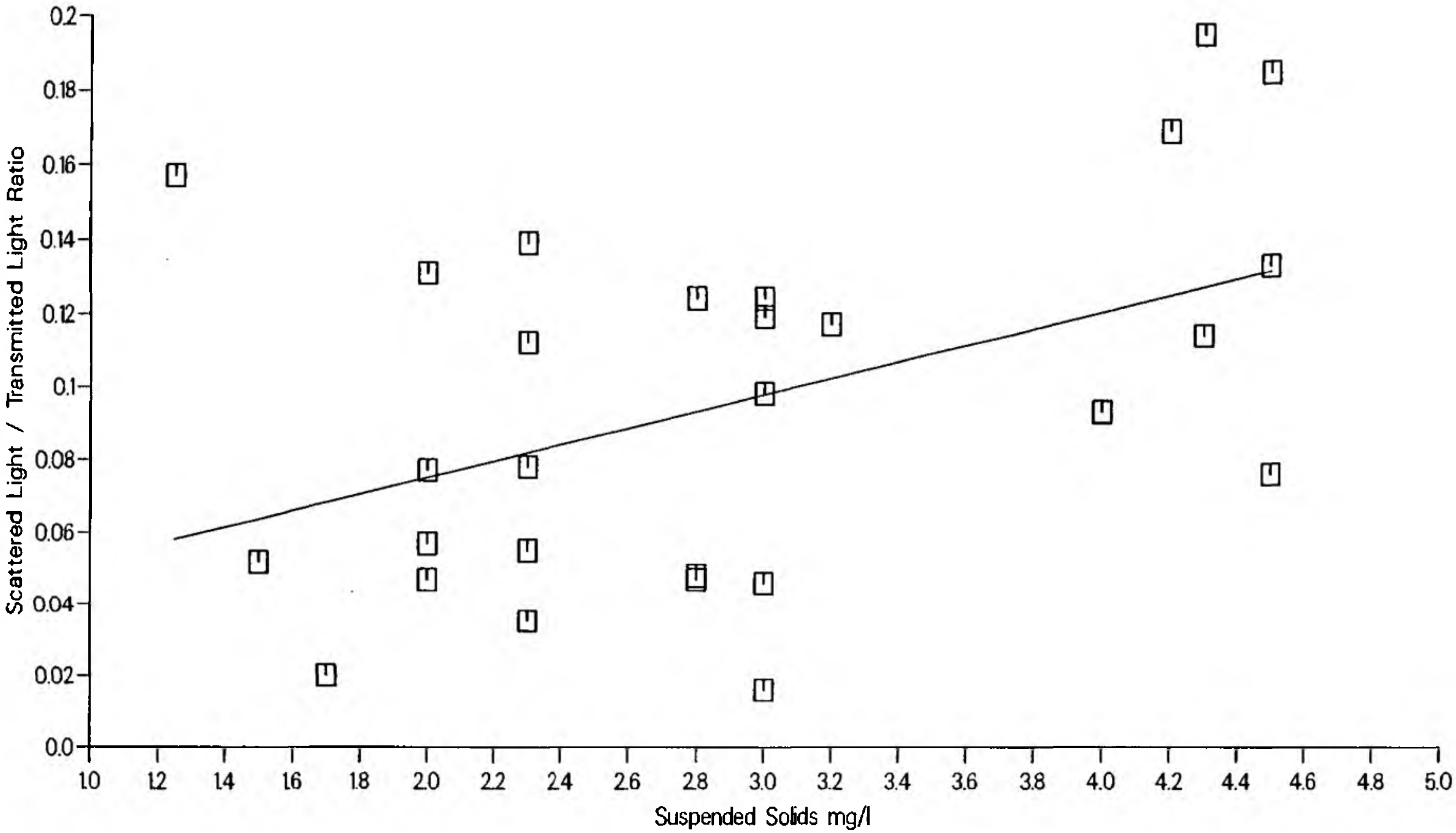


Correlation Coefficient = 0.59

Slope = 0.0047 l/mg

Intercept = -0.0019

Figure B2 Reed Bed White Light 25 degrees

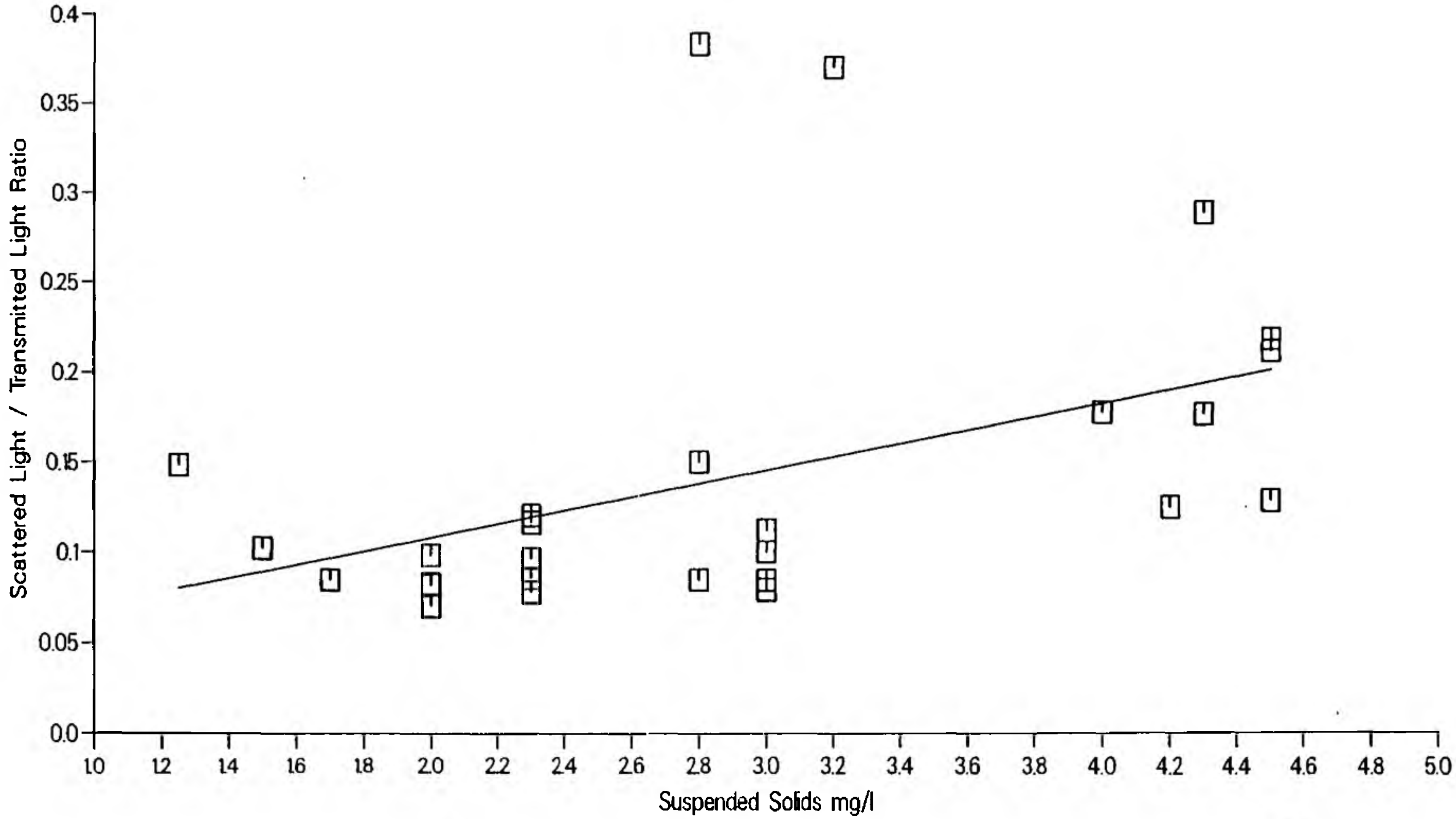


Correlation Coefficient = 0.45

Slope = 0.023 l/mg

Intercept = 0.030

Figure B3 Reed Bed White Light Low Angle

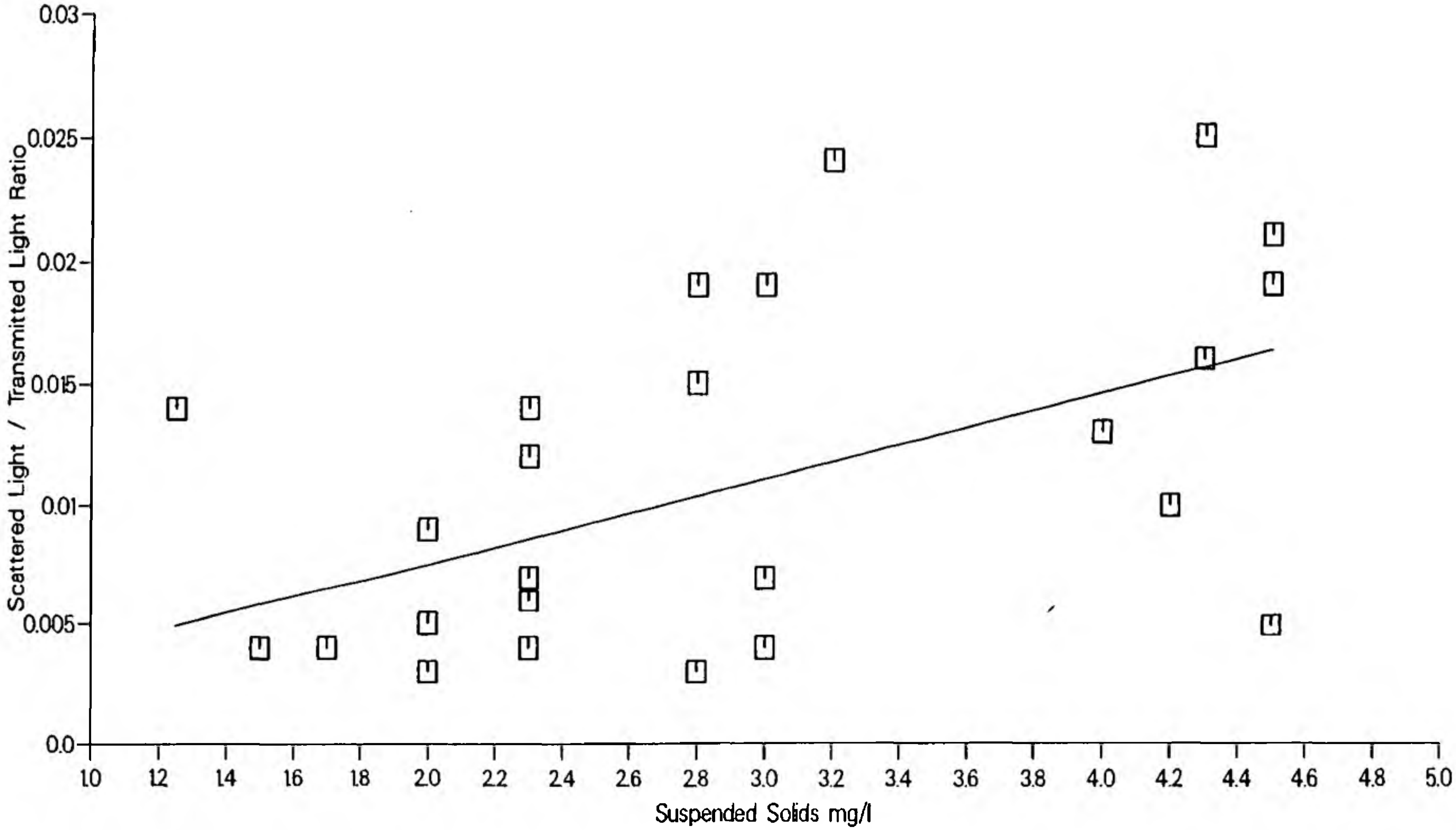


Correlation Coefficient = 0.44

Slope = 0.038 l/mg

Intercept = 0.033

Figure B4 Reed Bed Visible Light 90 degrees

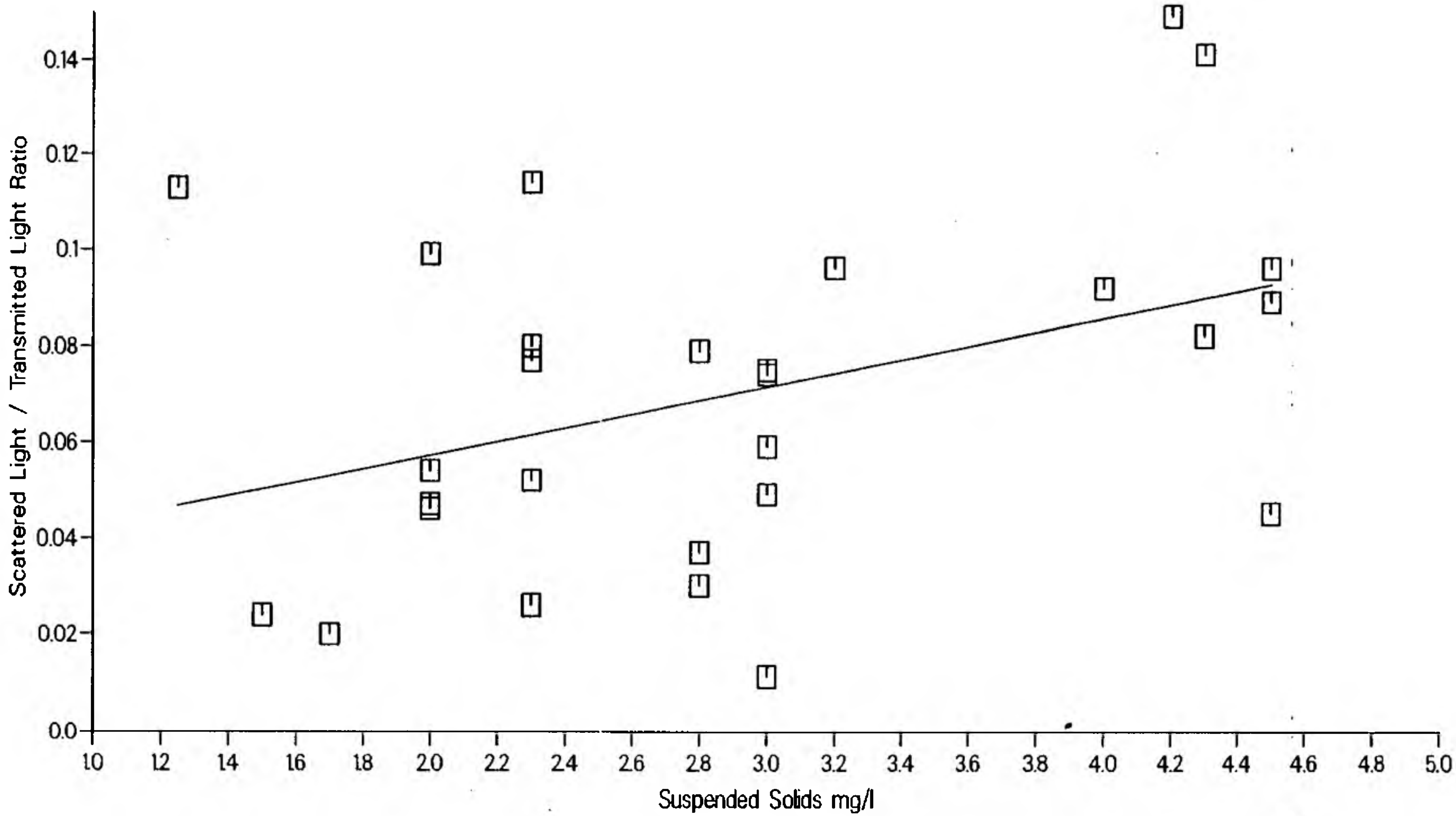


Correlation Coefficient = 0.50

Slope = 0.0035 l/mg

Intercept = 0.00050

Figure B5 Reed Bed Visible Light 25 degrees

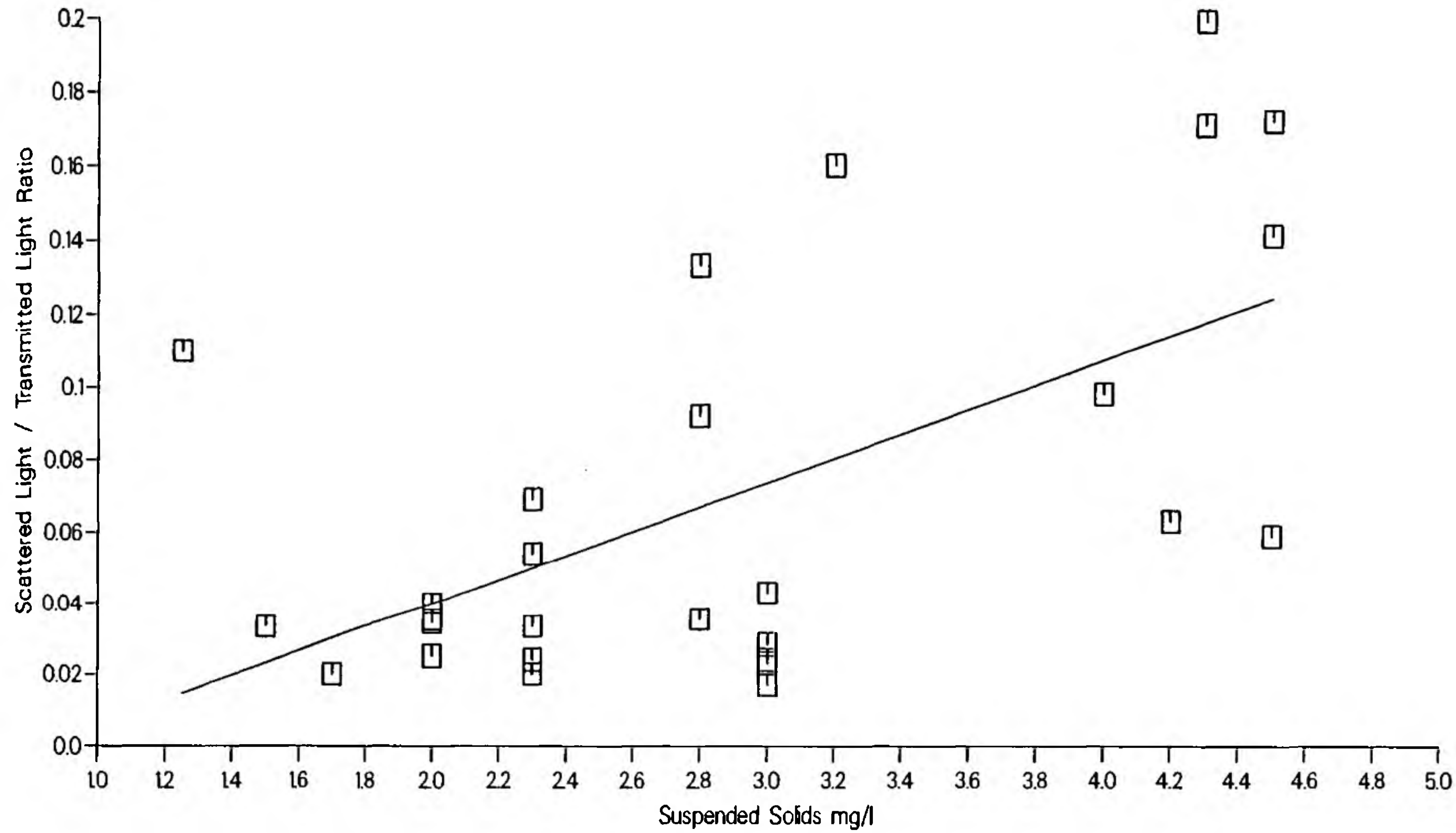


Correlation Coefficient = 0.39

Slope = 0.014 l/mg l

Intercept = 0.029

Figure B6 Reed Bed Visible Light Low Angle

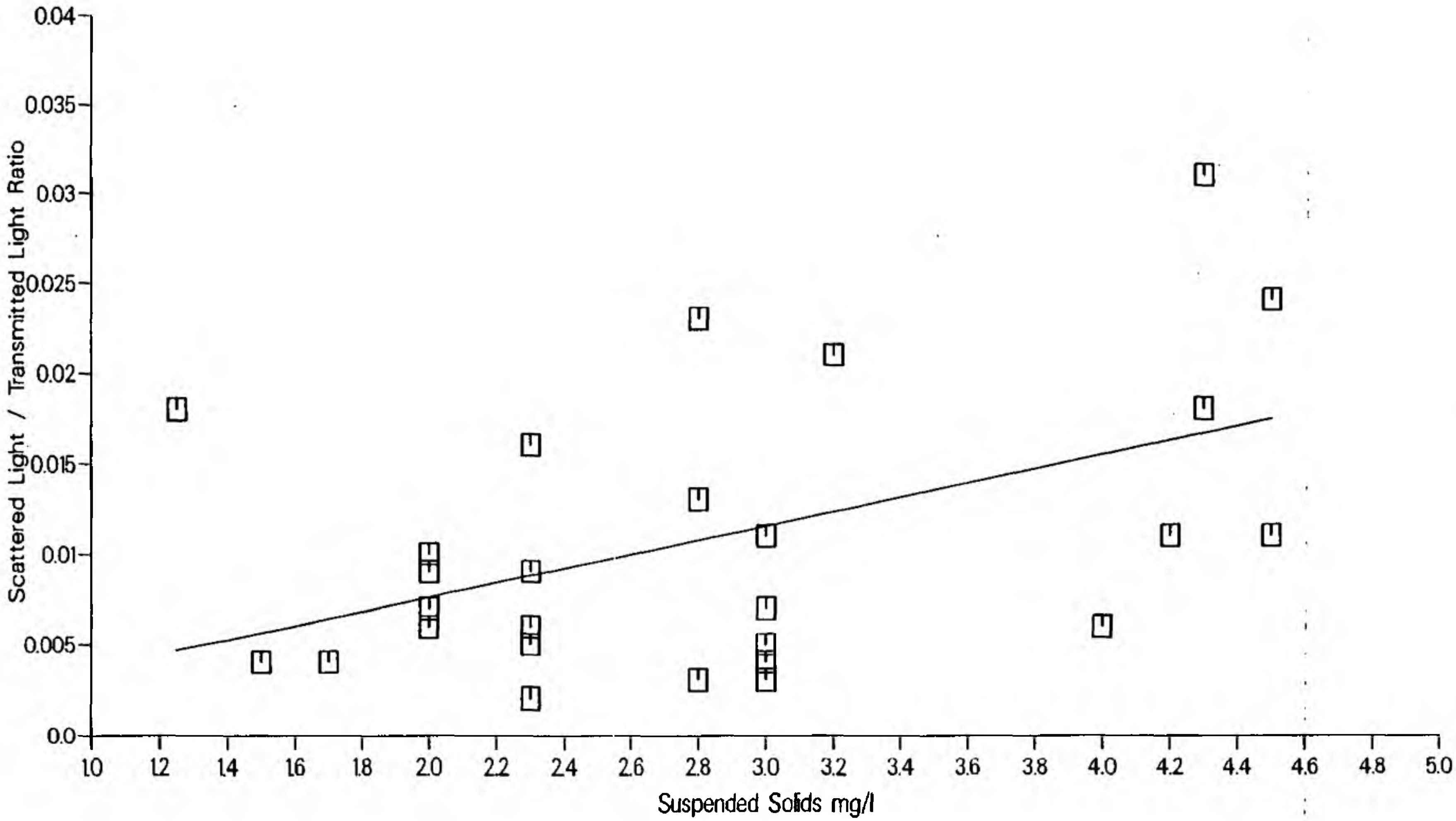


Correlation Coefficient = 0.59

Slope = 0.034 l/mg

Intercept = -0.028

Figure B7 Reed Bed Near Infra Red Light 90 degrees

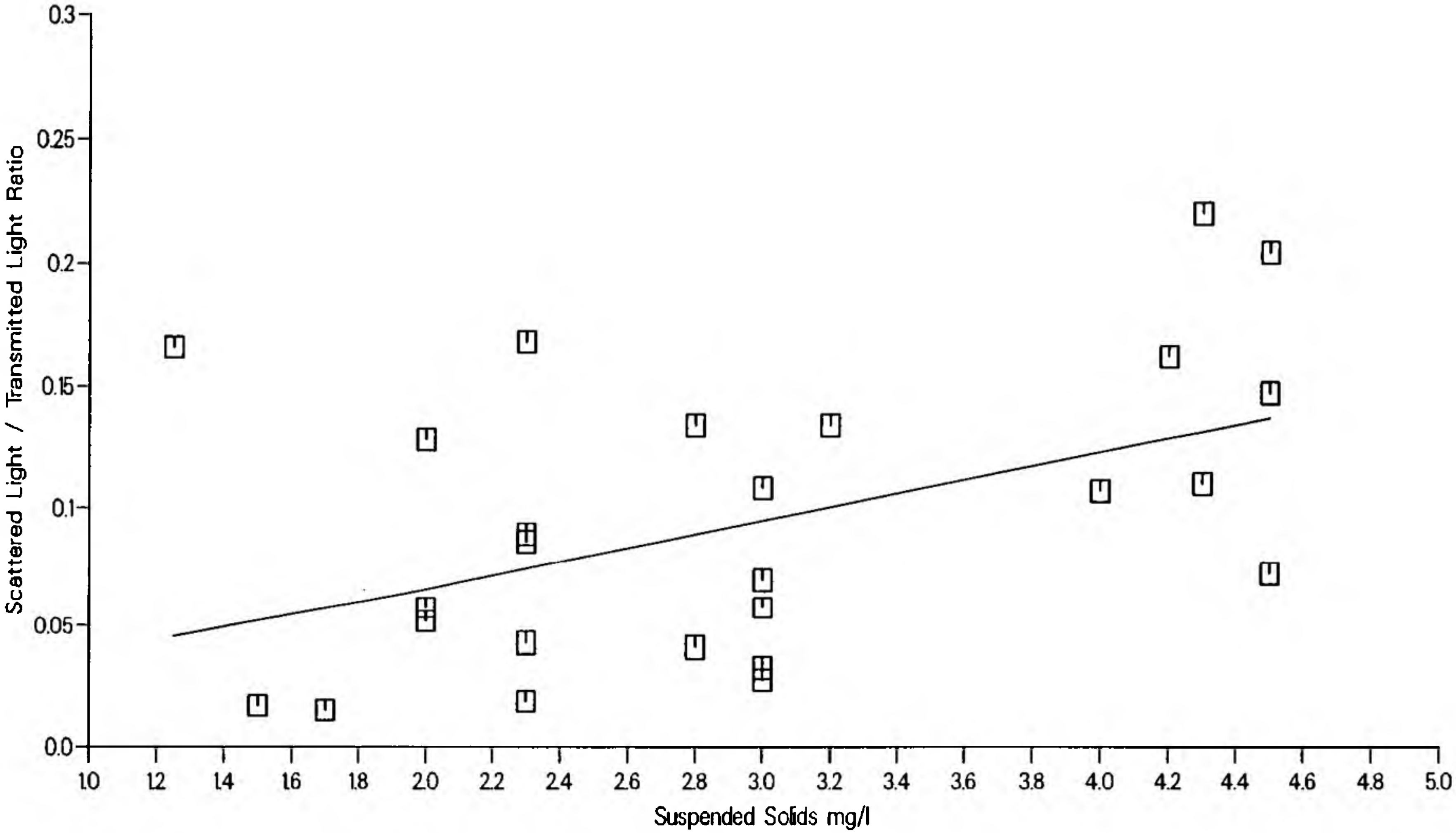


Correlation Coefficient = 0.49

Slope = 0.0039 l/mg

Intercept = -0.00024

Figure B8 Reed Bed Near Infra Red Light 25 degrees

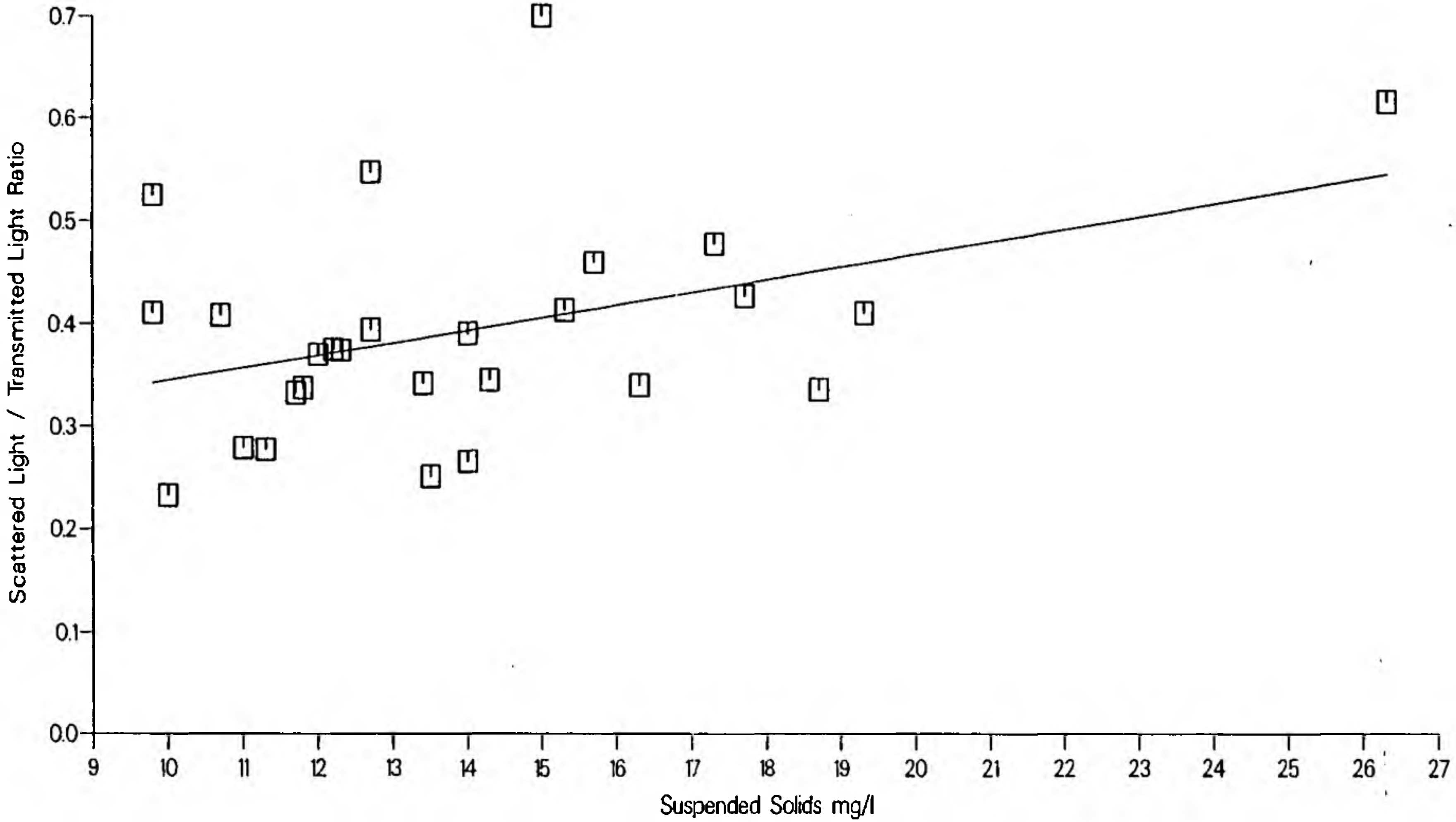


Correlation Coefficient = 0.47

Slope = 0.028 l/mg

Intercept = 0.0100

Figure B9 Reed Bed Near Infra Red Light Low Angle

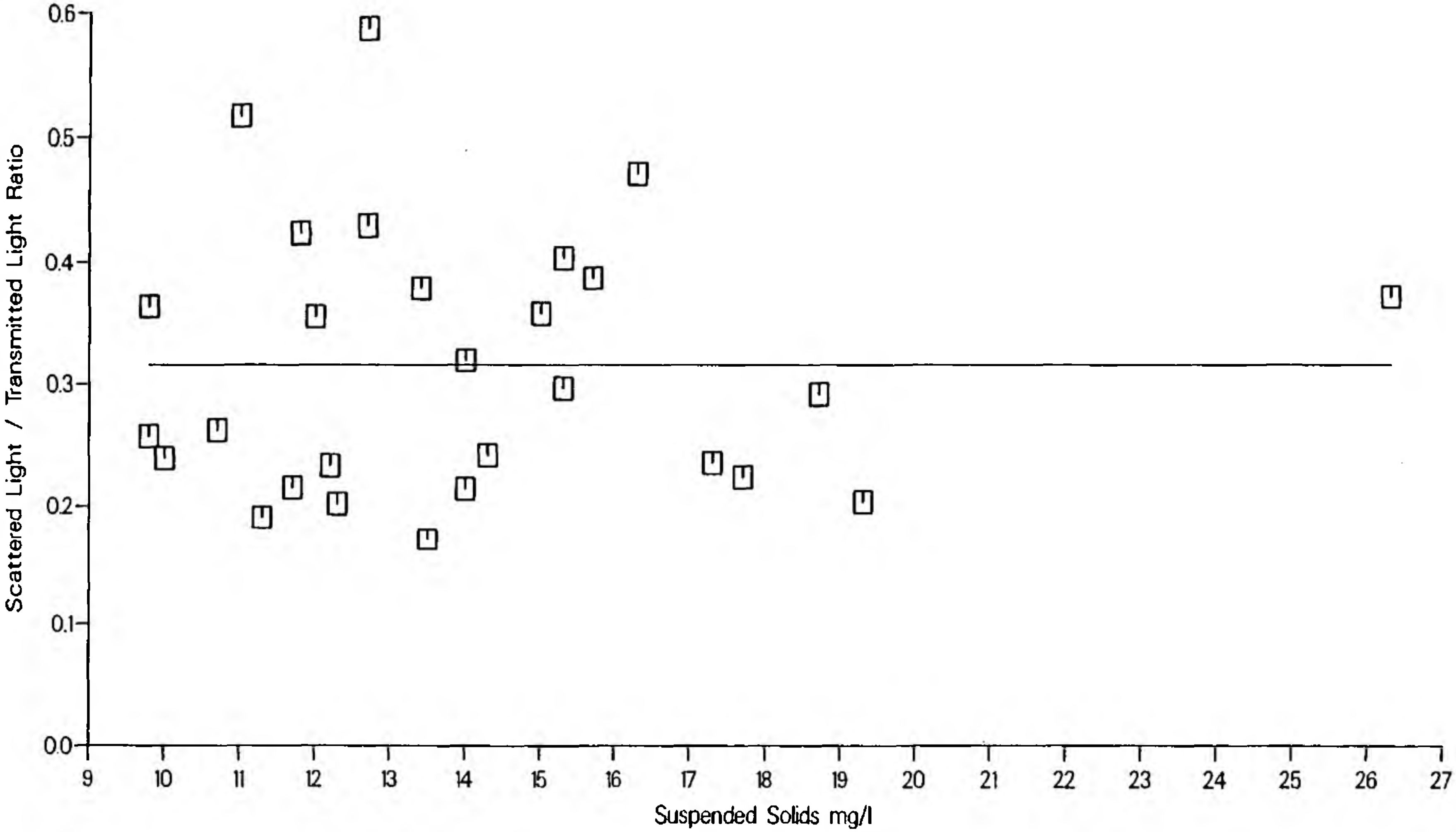


Correlation Coefficient = 0.41

Slope = 0.012 l/mg

Intercept = 0.22

Figure B12 Activated Sludge White Light Low Angle

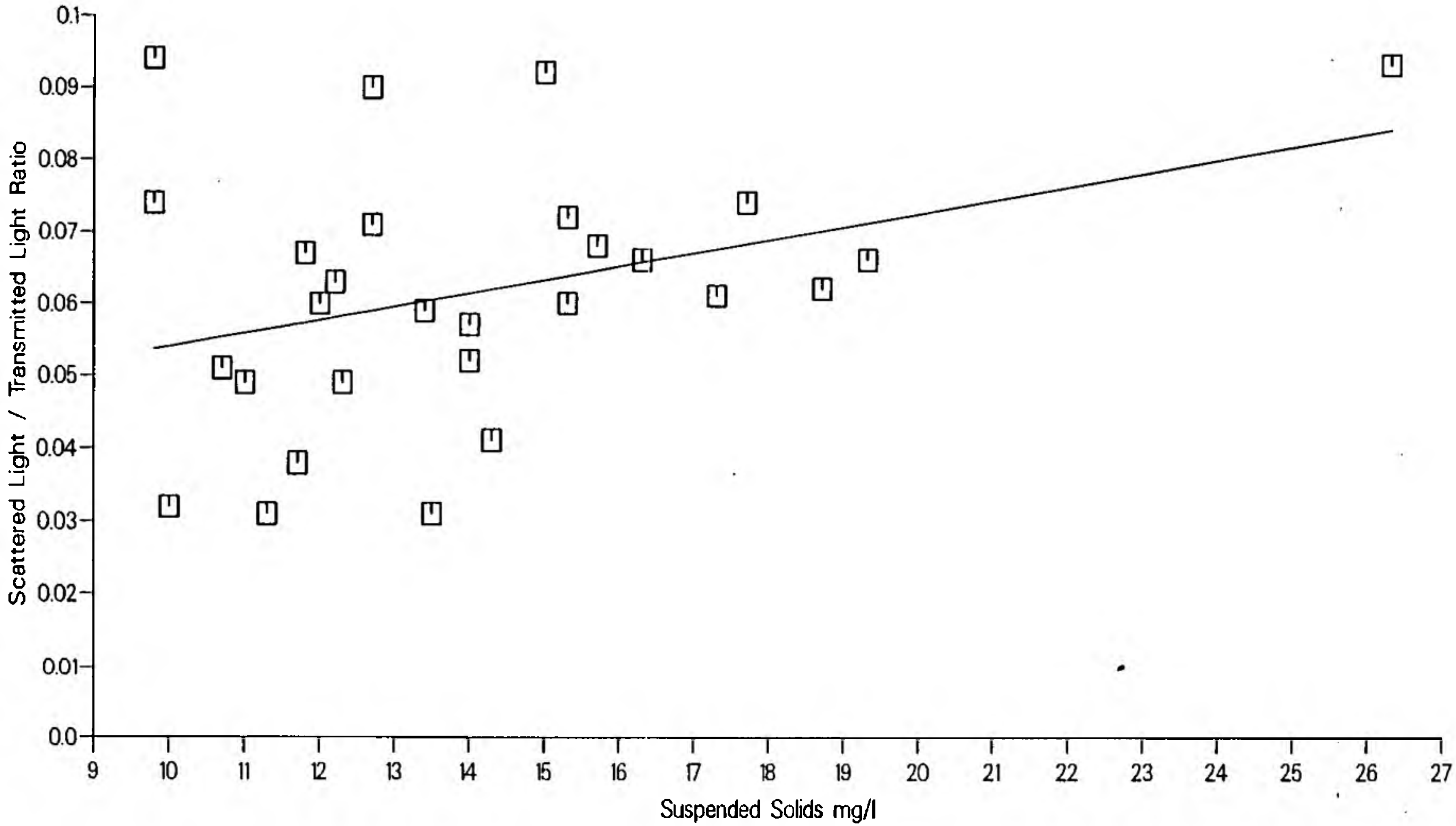


Correlation Coefficient = 0.000082

Slope = 0.0000025 l/mg

Intercept = 0.32

Figure B10 Activated Sludge White Light 90 degrees

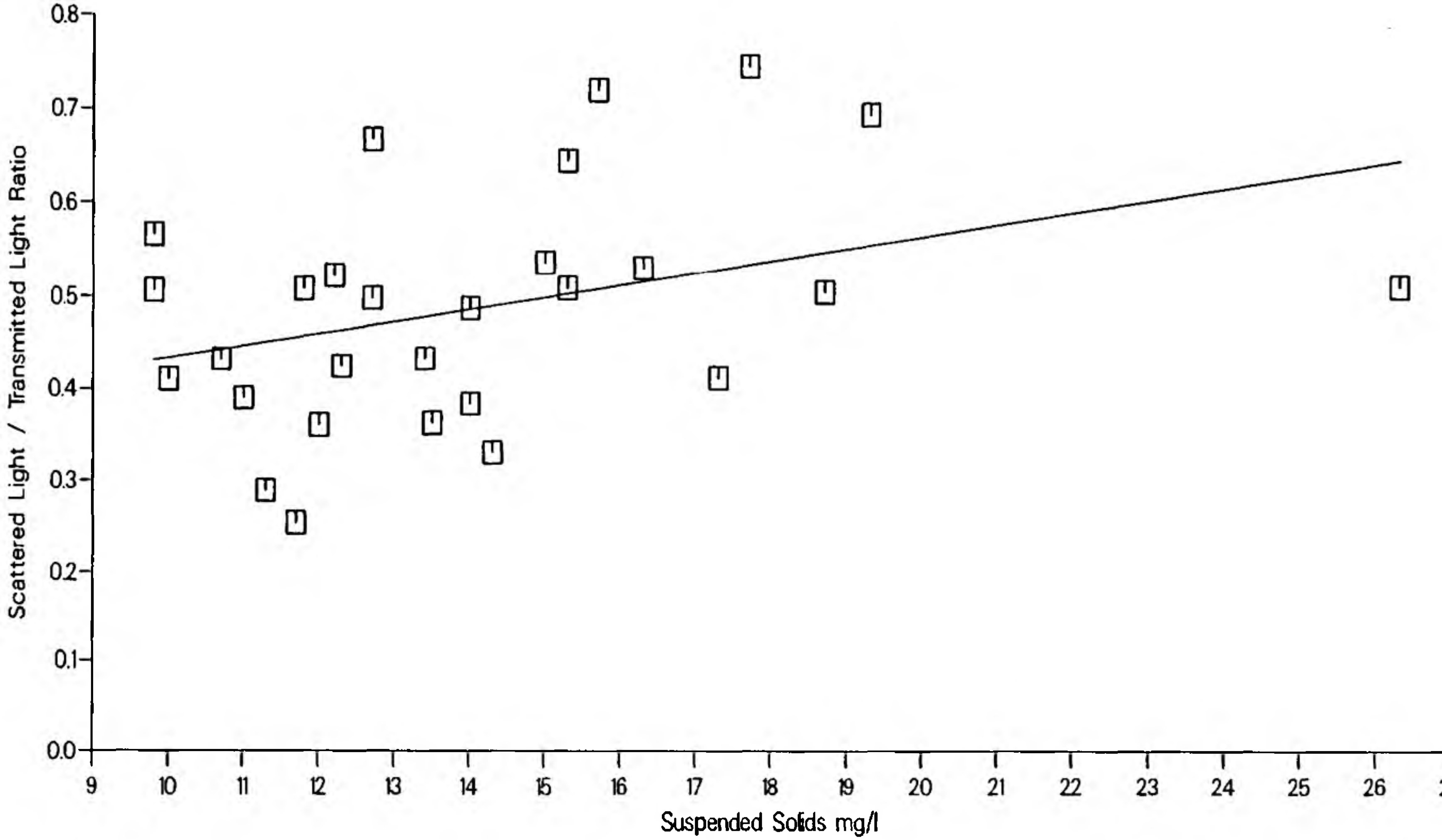


Correlation Coefficient = 0.37

Slope = 0.0018 l/mg

Intercept = 0.036

Figure B11 Activated Sludge White Light 25 degrees

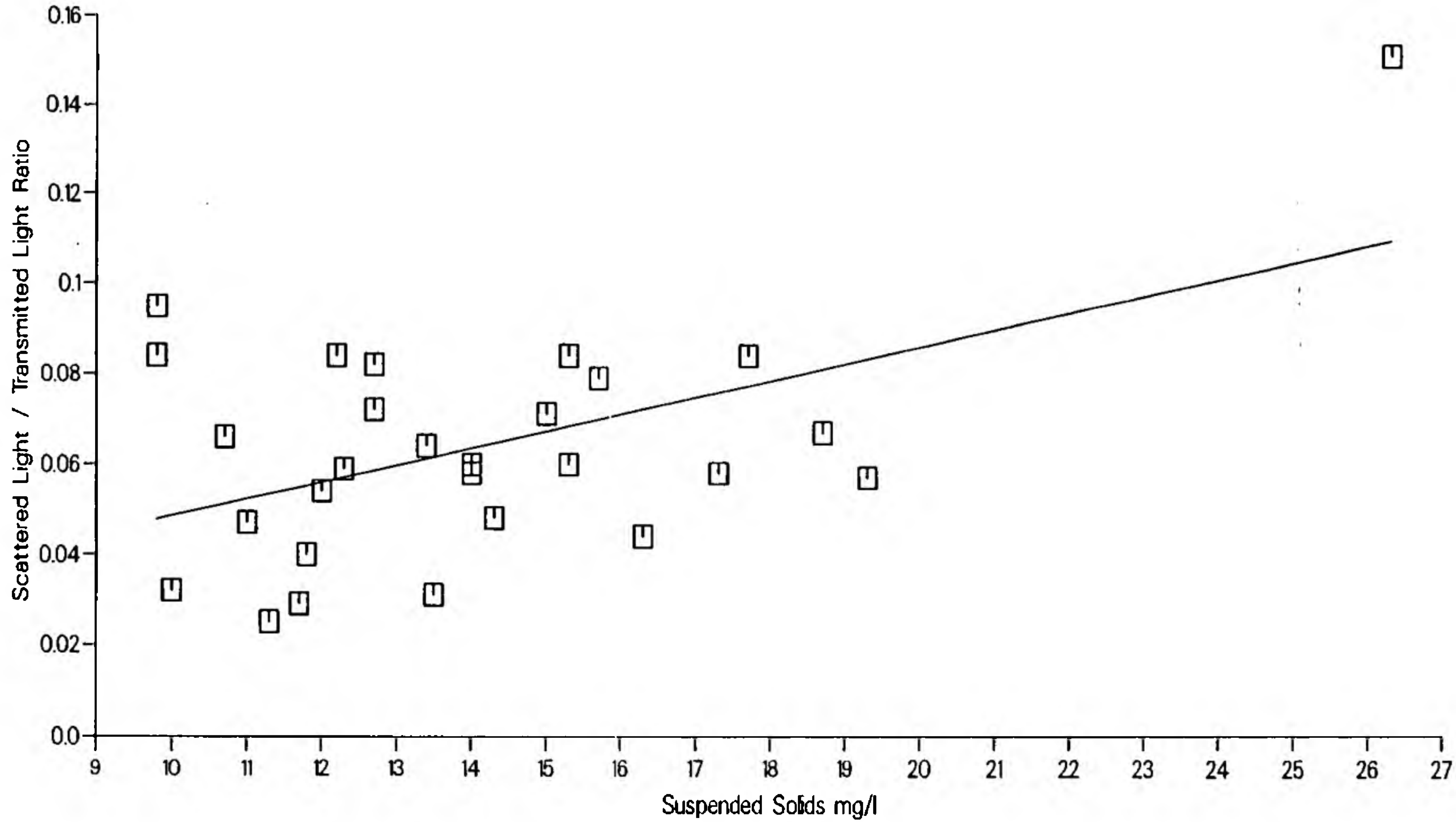


Correlation Coefficient = 0.37

Figure B13 Activated Sludge Visible Light 90 degrees

Slope = 0.013 l/mg

Intercept = 0.30

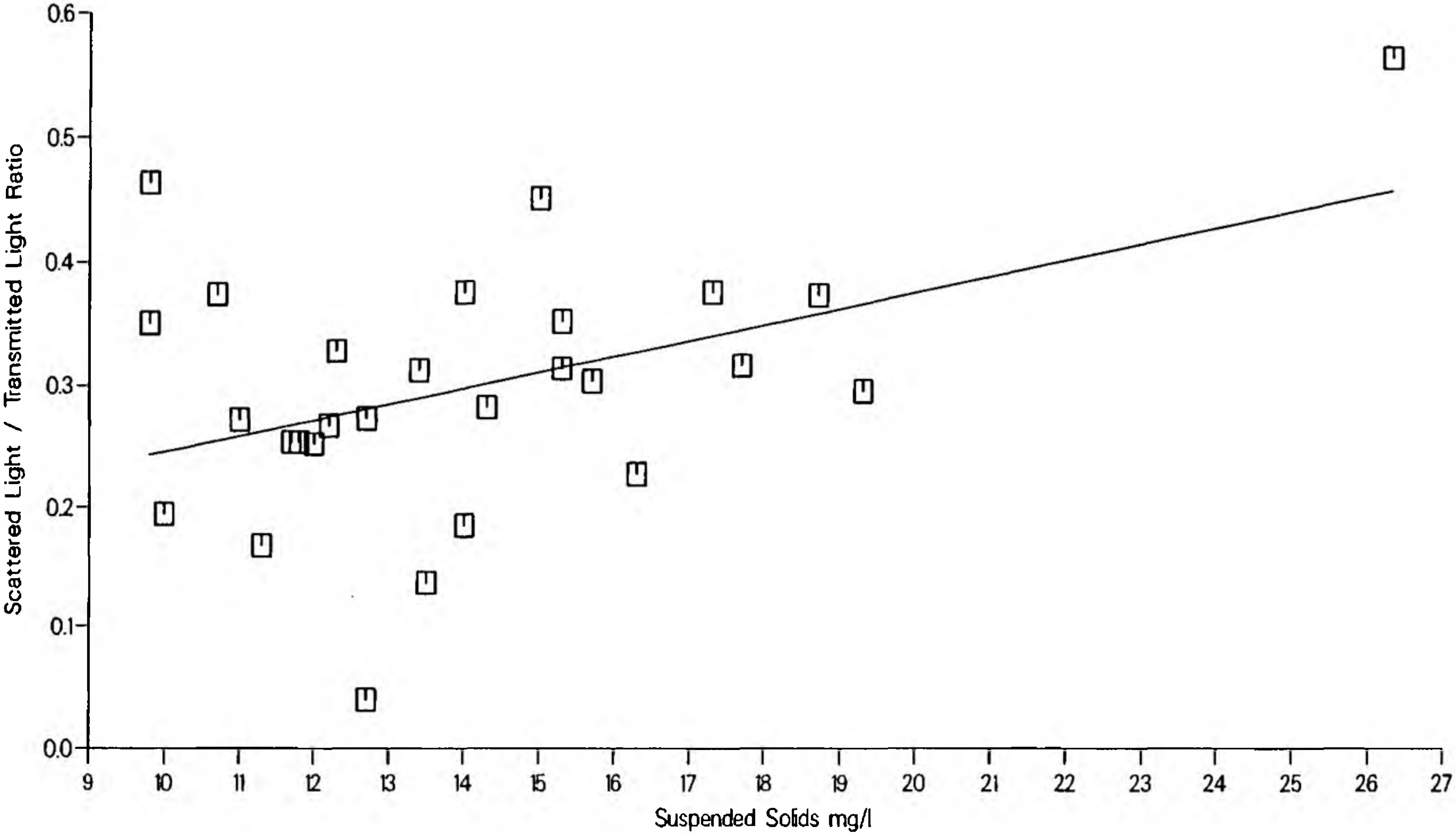


Correlation Coefficient = 0.52

Slope = 0.0037 l/mg

Intercept = 0.011

Figure B14 Activated Sludge Visible Light 25 degrees

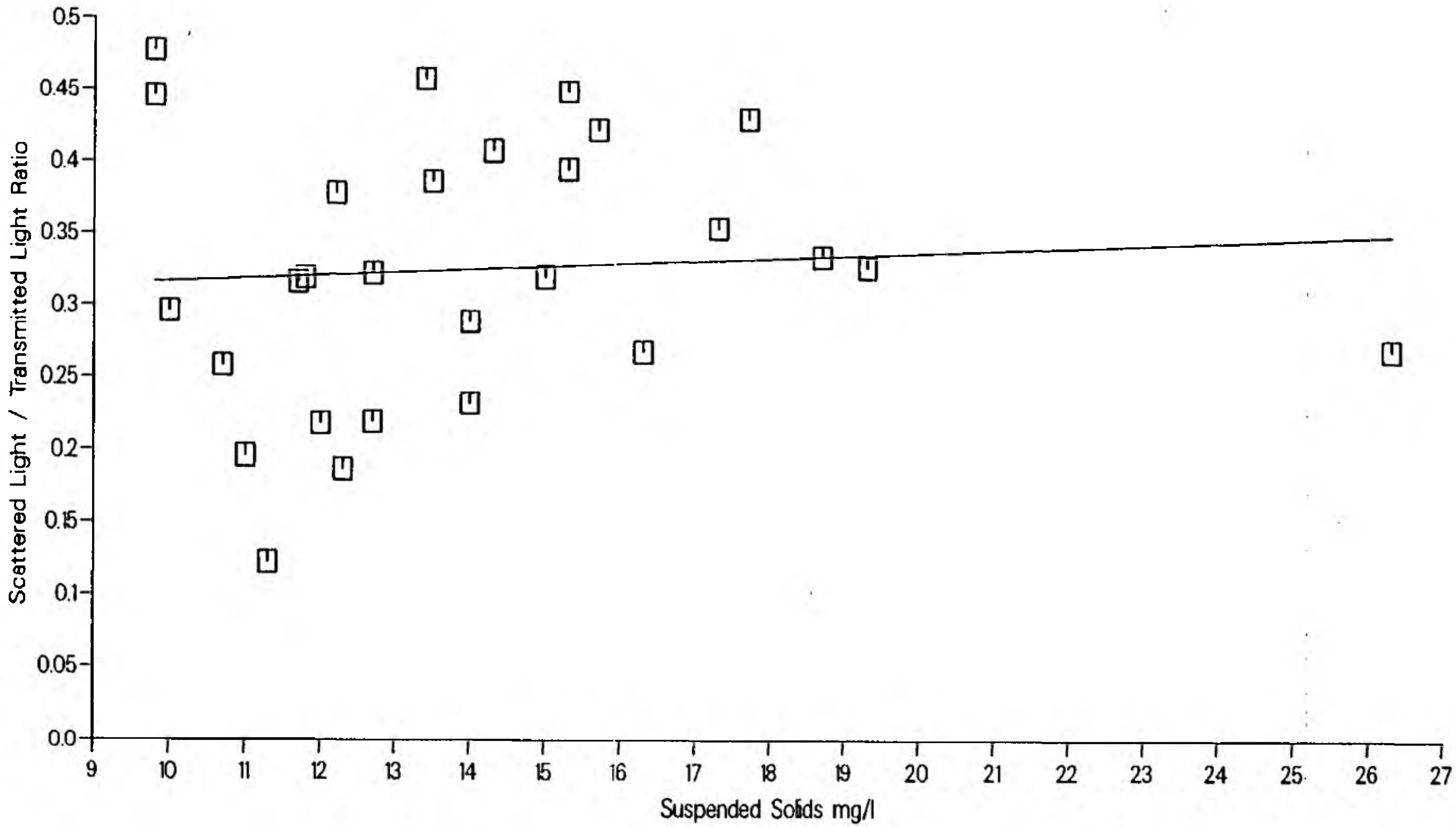


Correlation Coefficient = 0.44

Slope = 0.013 l/mg

Intercept = 0.12

Figure B15 Activated Sludge Visible Light Low Angle

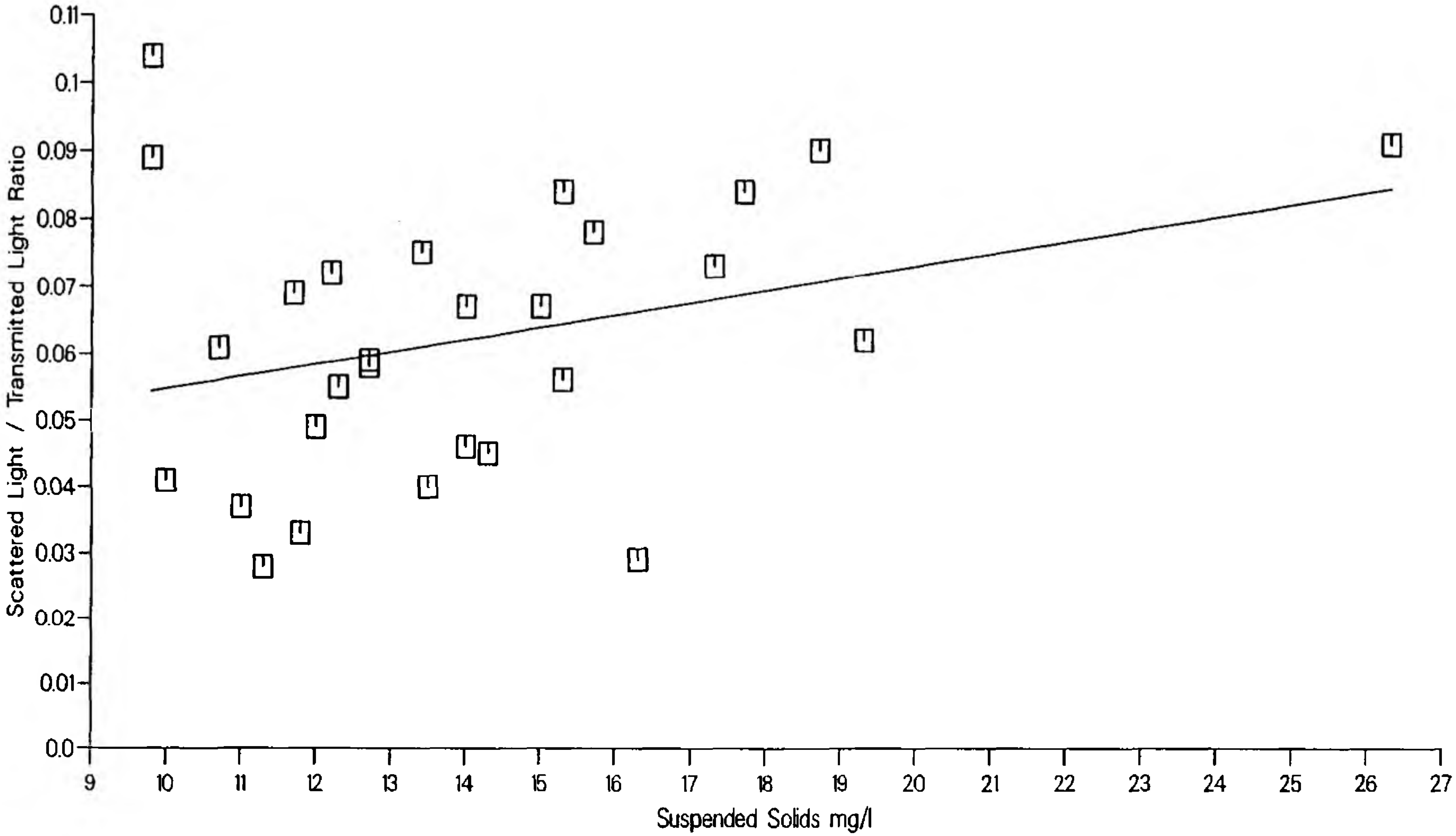


Correlation Coefficient = 0.074

Figure B16 Activated Sludge Near Infra Red Light 90 degrees

Slope = 0.0019 l/mg

Intercept = 0.30

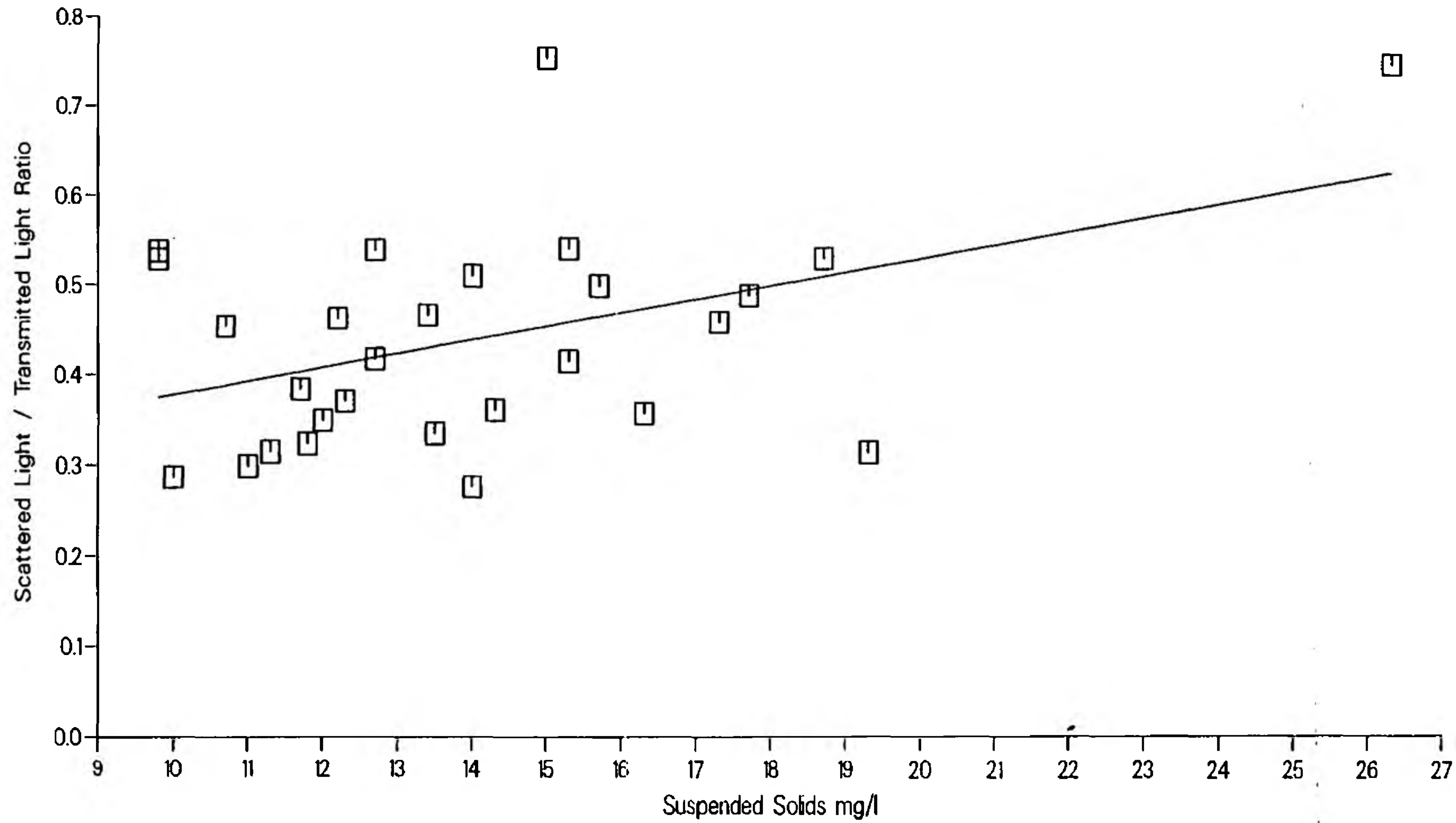


Correlation Coefficient = 0.32

Slope = 0.0018 l/mg

Intercept = 0.037

Figure B17 Activated Sludge Near Infra Red Light 25 degrees

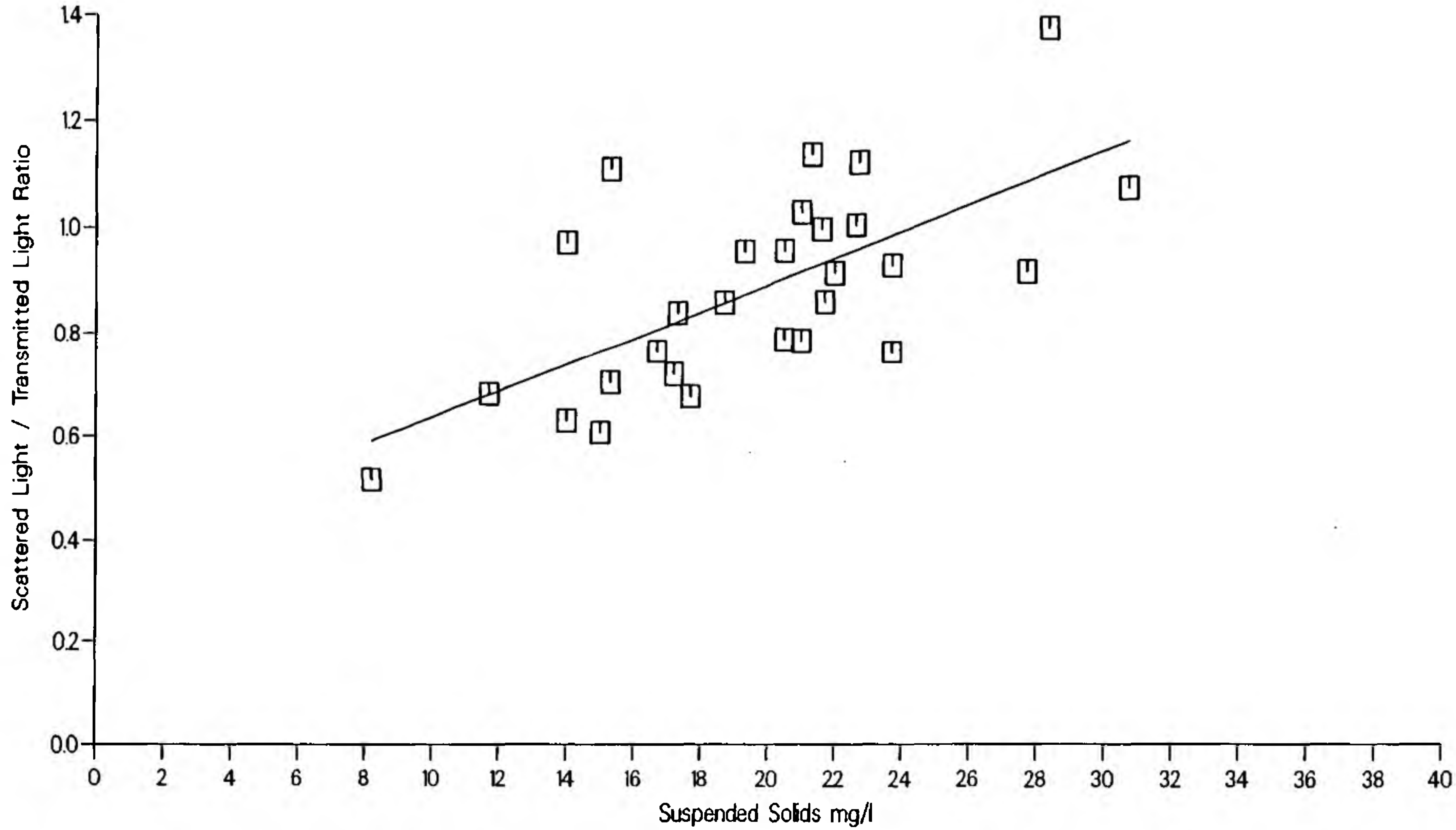


Correlation Coefficient = 0.44

Slope = 0.015 l/mg

Intercept = 0.23

Figure B18 Activated Sludge Near Infra Red Light Low Angle

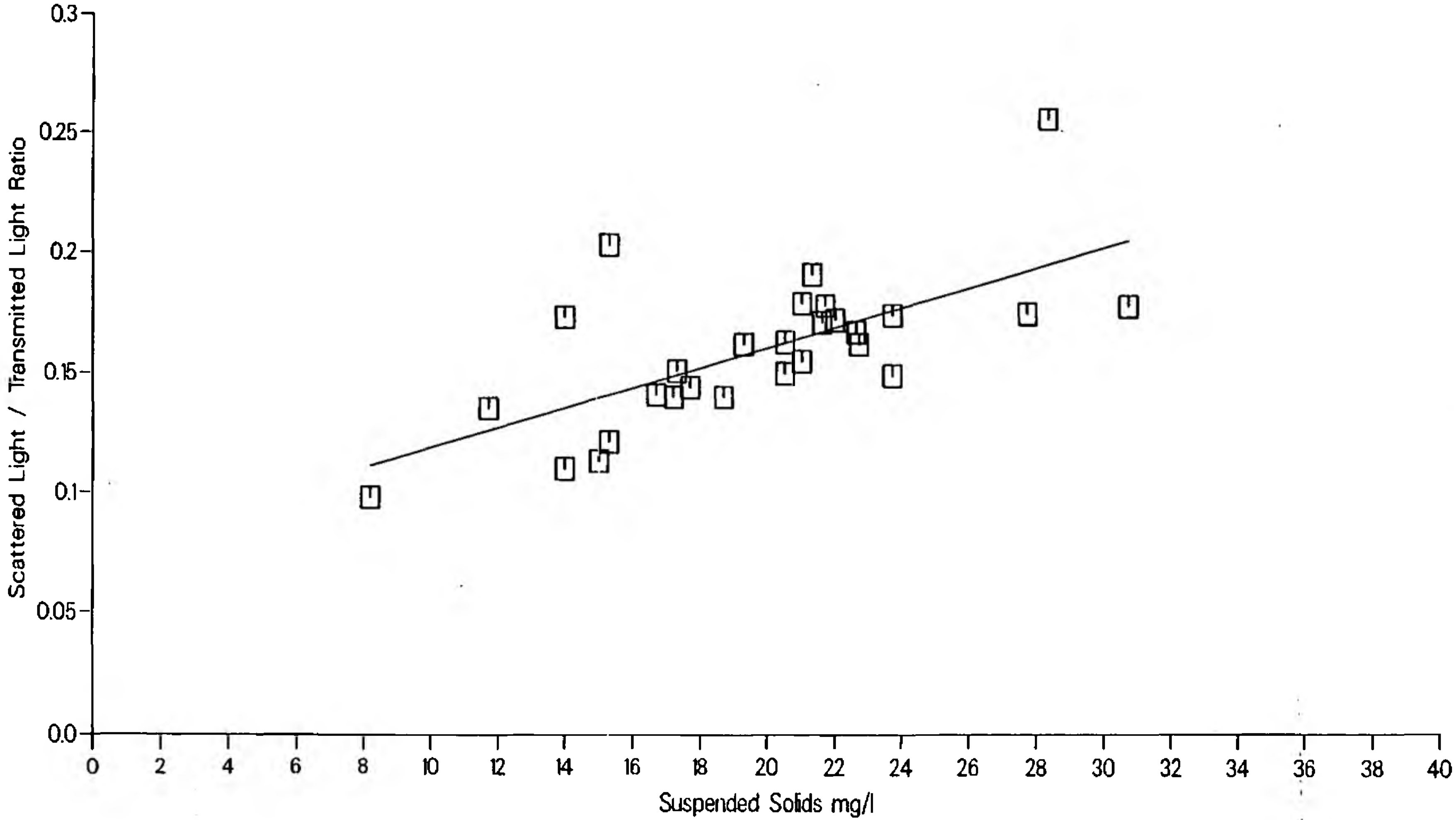


Correlation Coefficient = 0.66

Figure B19 Biological Filter White Light 90 degrees

Slope = 0.025 l/mg

Intercept = 0.38

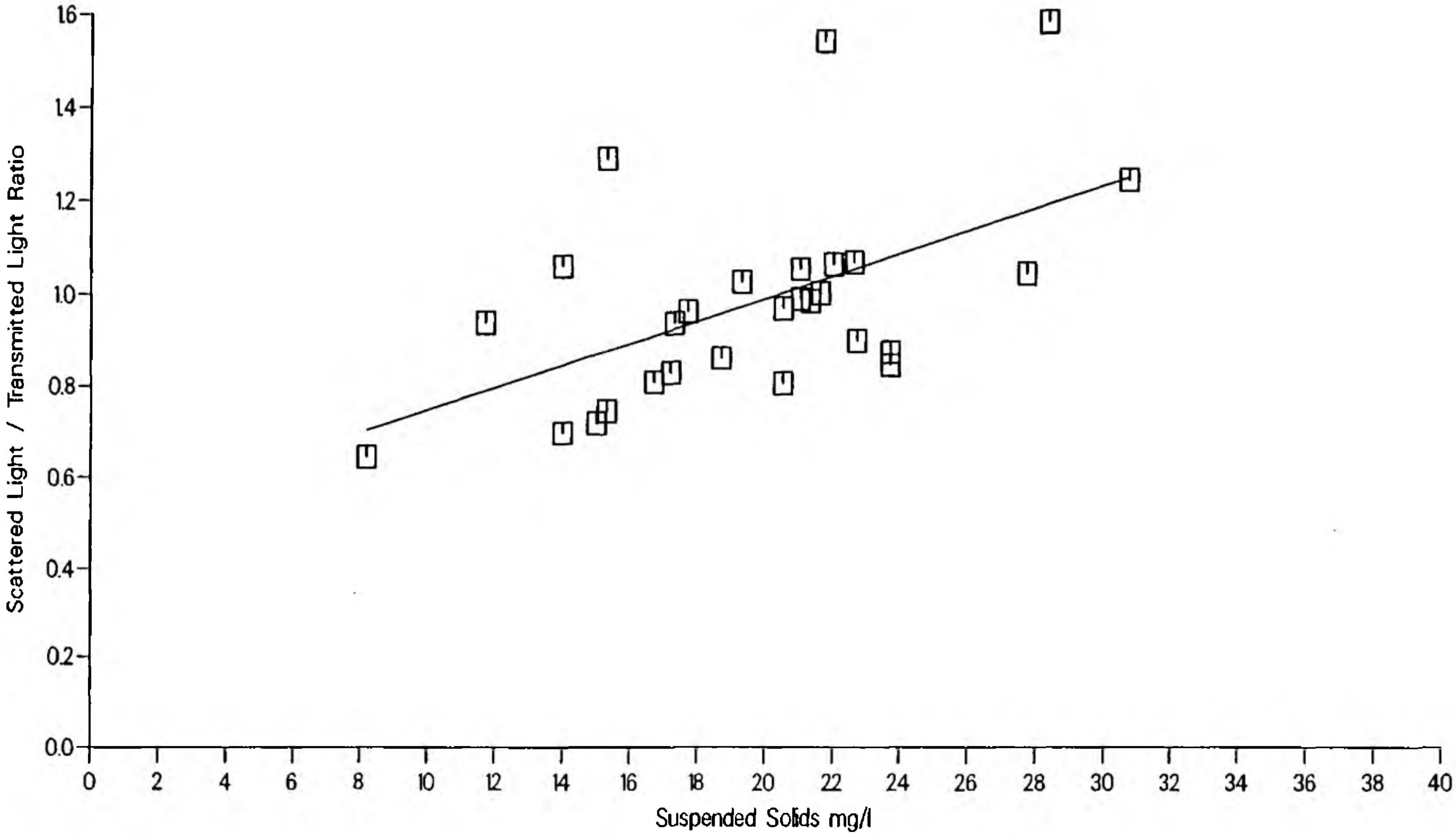


Correlation Coefficient = 0.67

Slope = 0.0042 l/mg

Intercept = 0.077

Figure B20 Biological Filter White Light 25 degrees

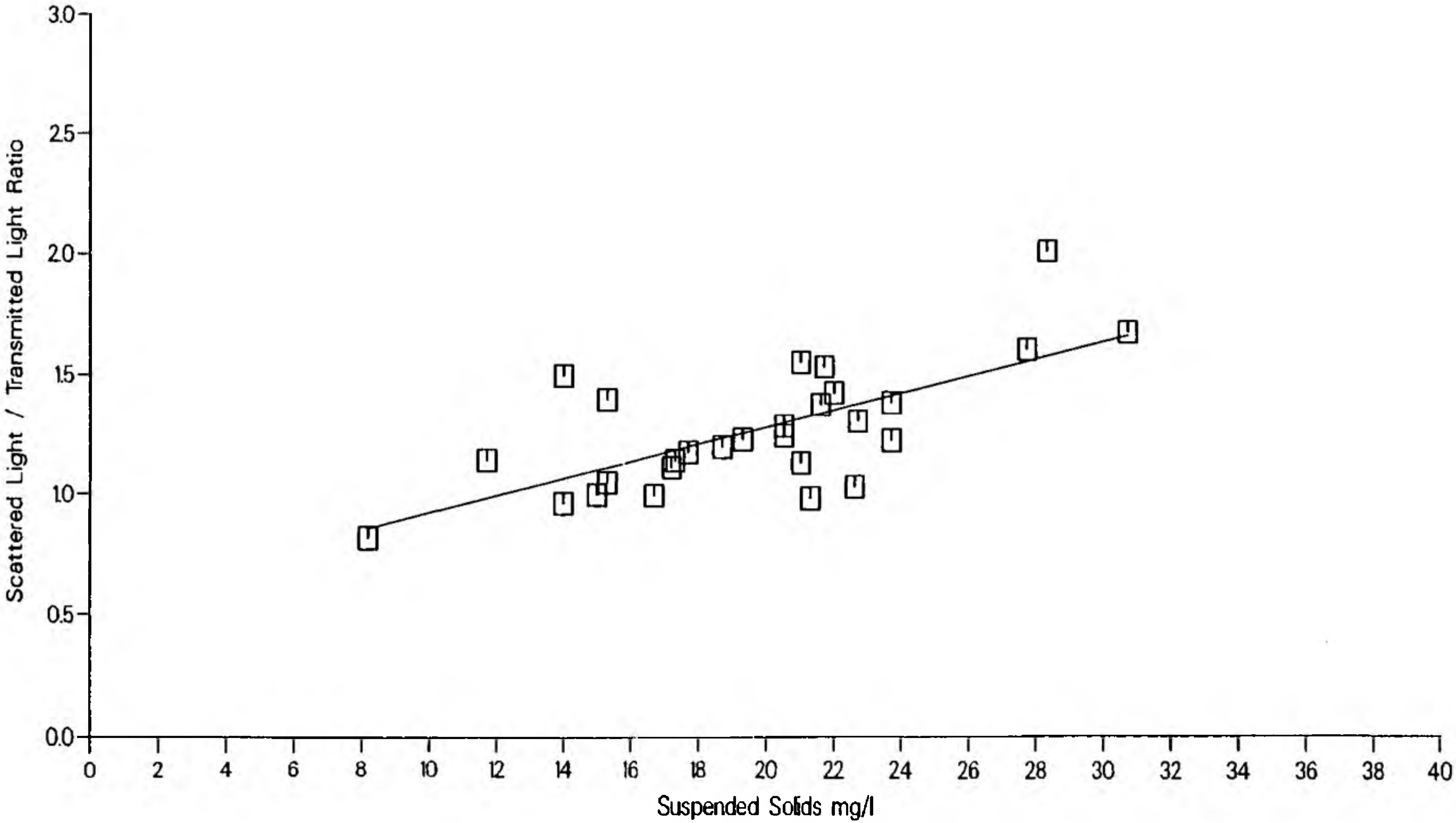


Correlation Coefficient = 0.55

Slope = 0.024 l/mg

Intercept = 0.51

Figure B21 Biological Filter White Light Low Angle

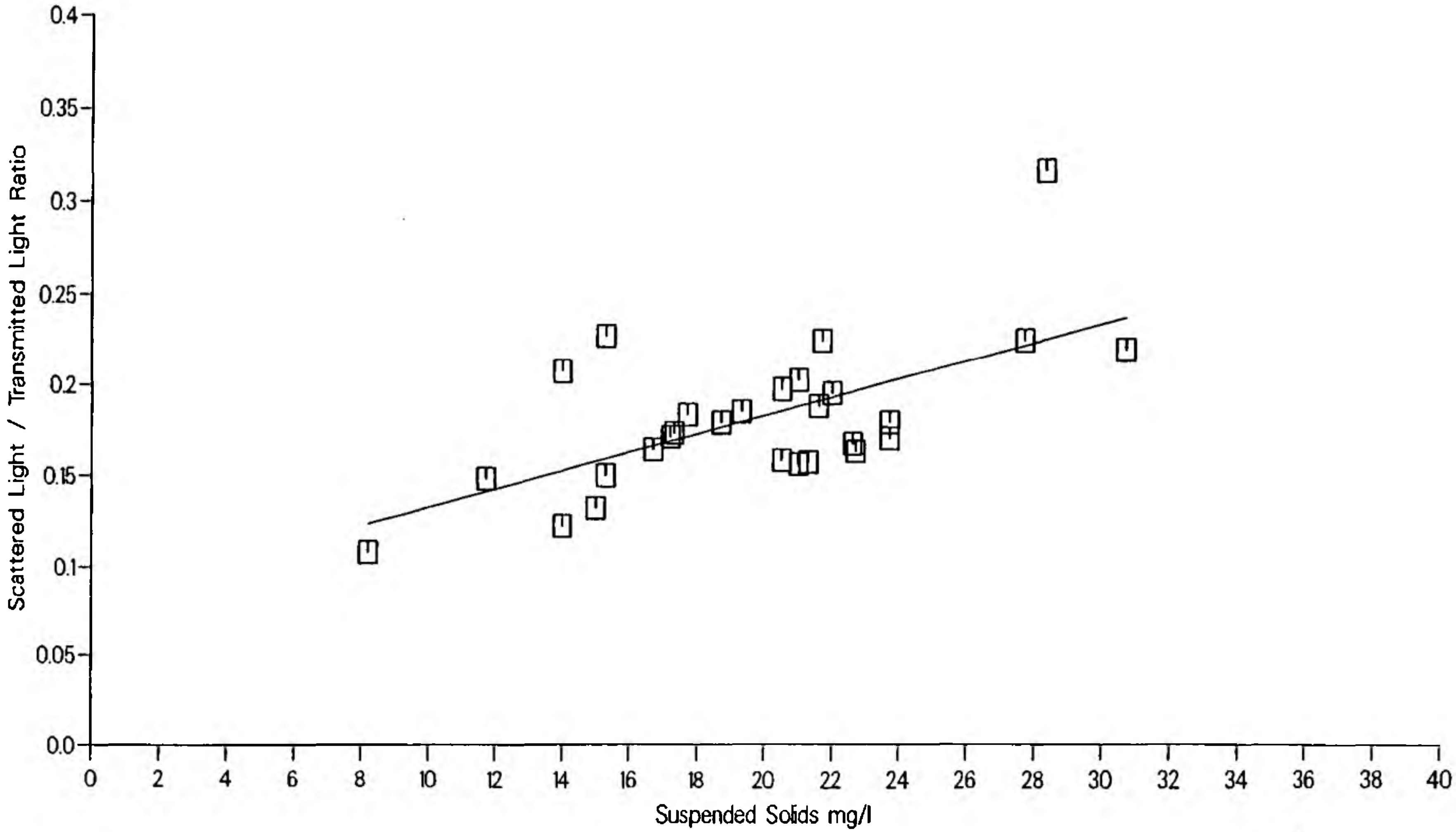


Correlation Coefficient = 0.69

Slope = 0.036 l/mg

Intercept = 0.56

Figure B22 Biological Filter Visible Light 90 degrees

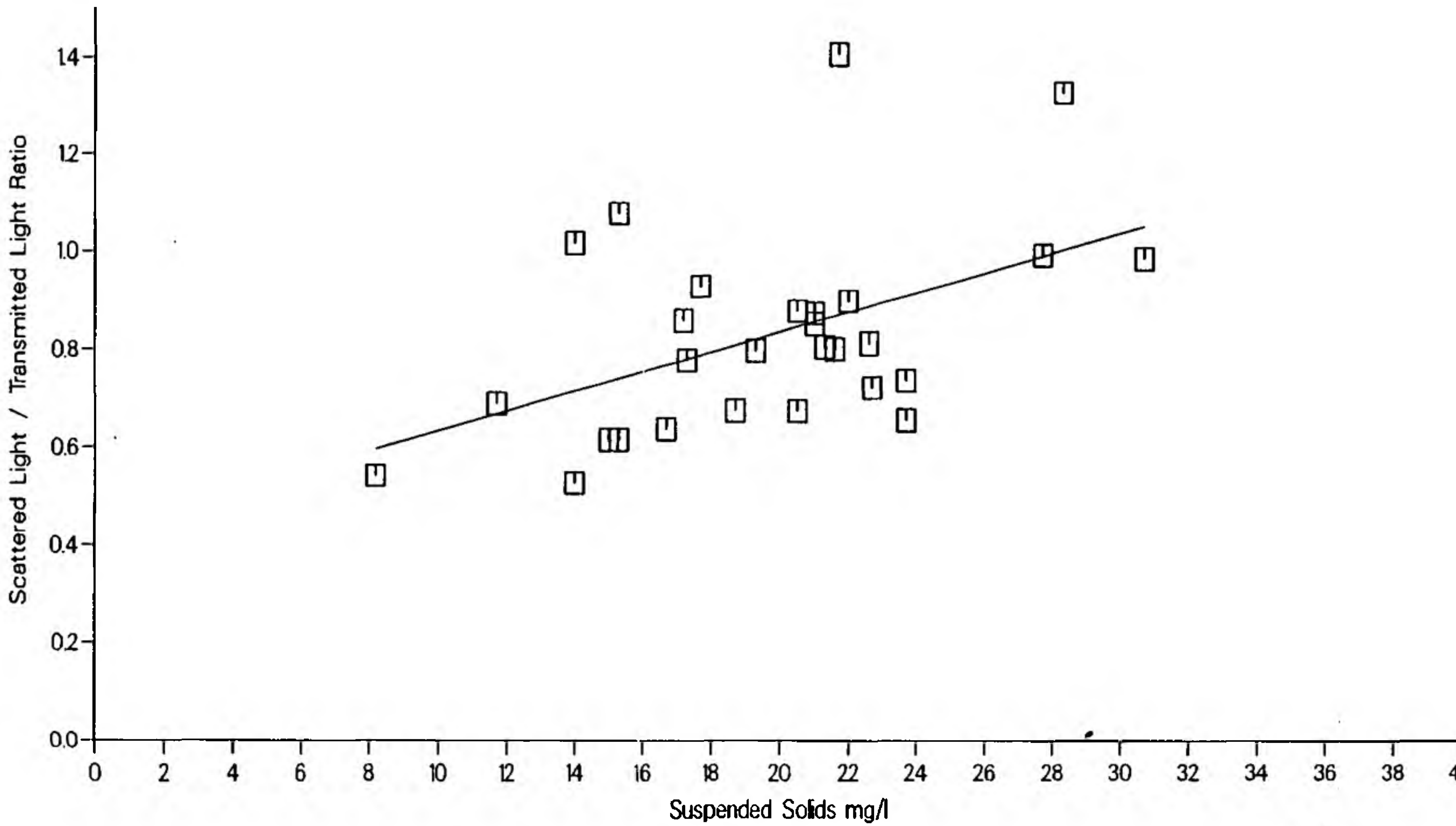


Correlation Coefficient = 0.63

Figure B23 Biological Filter Visible Light 25 degrees

Slope = 0.0050 l/mg

Intercept = 0.082

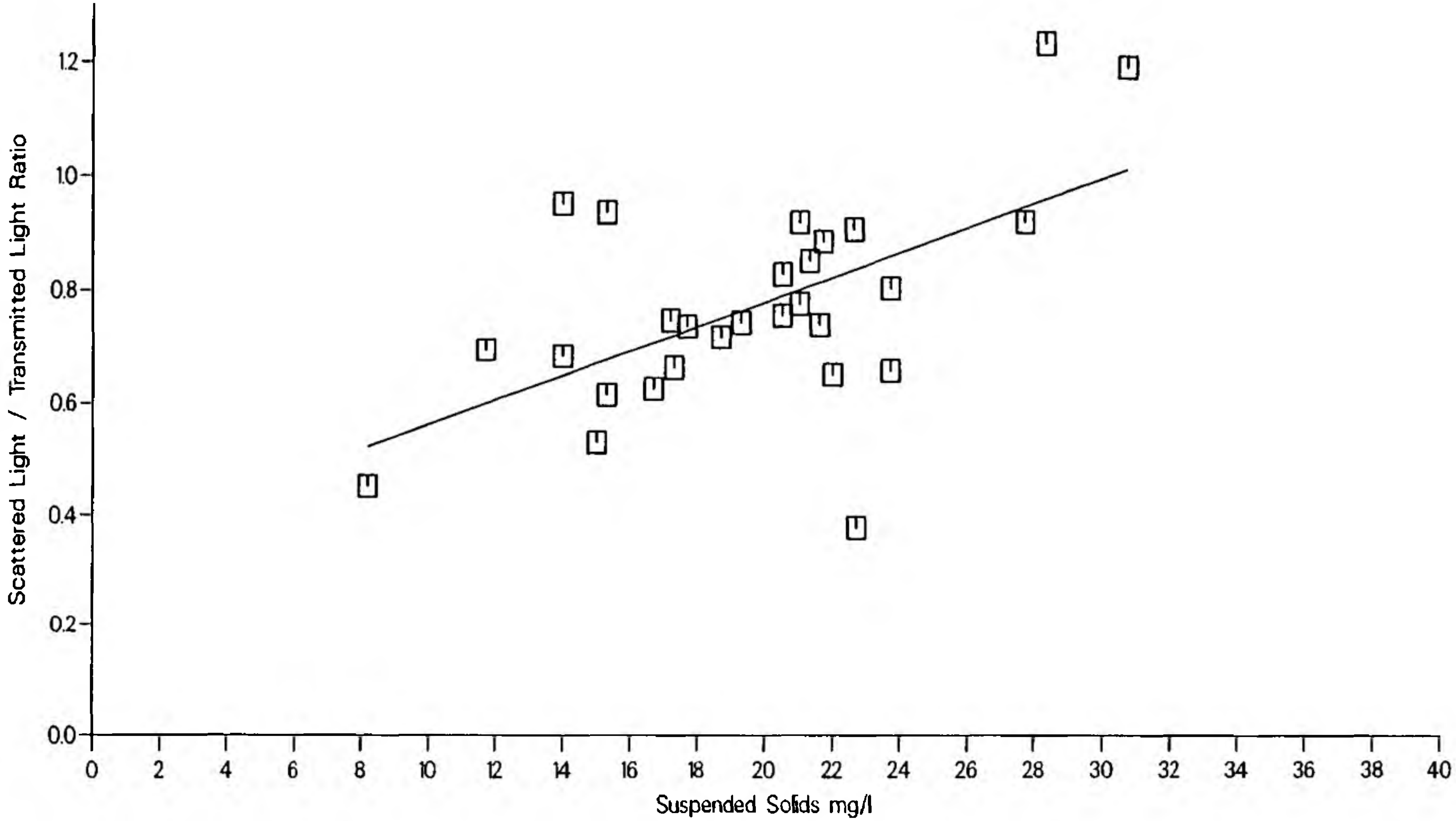


Correlation Coefficient = 0.48

Slope = 0.020 l/mg

Intercept = 0.43

Figure B24 Biological Filter Visible Light Low Angle

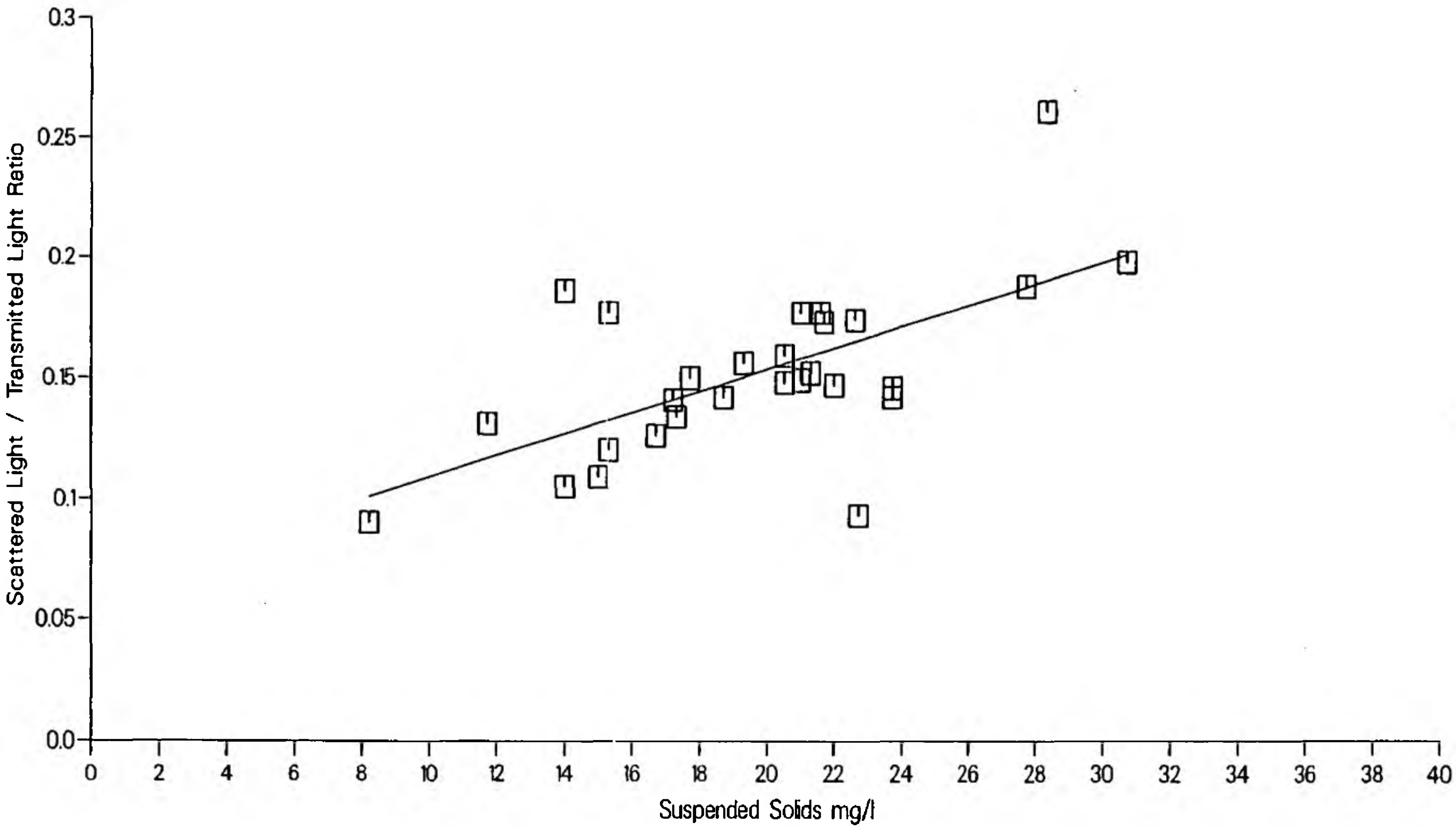


Correlation Coefficient = 0.58

Figure B25 Biological Filter Near Infra Red Light 90 degrees

Slope = 0.022 l/mg

Intercept = 0.34

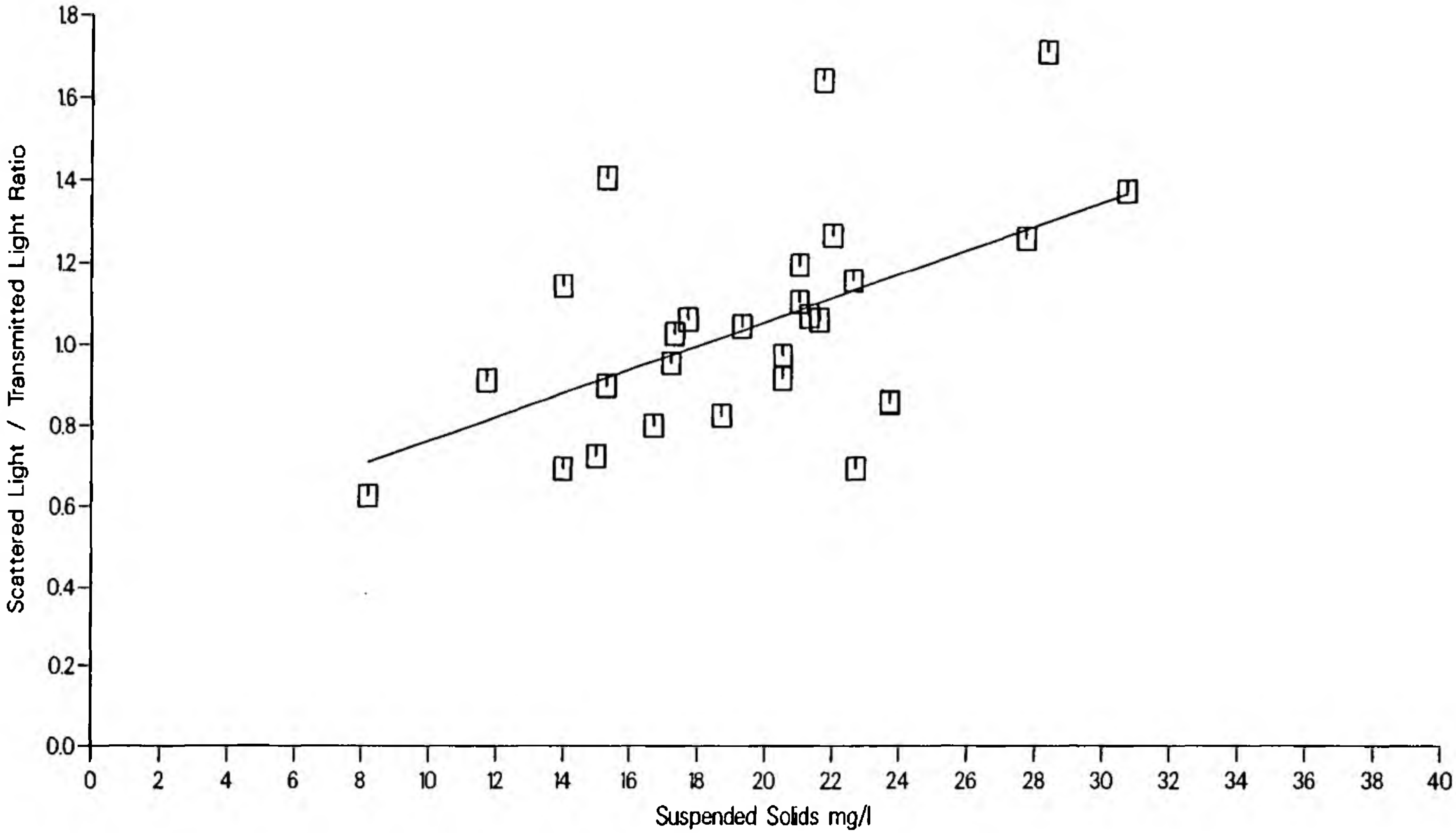


Correlation Coefficient 0.63

Slope = 0.0045 l/mg

Intercept = 0.064

Figure B26 Biological Filter Near Infra Red Light 25 degrees



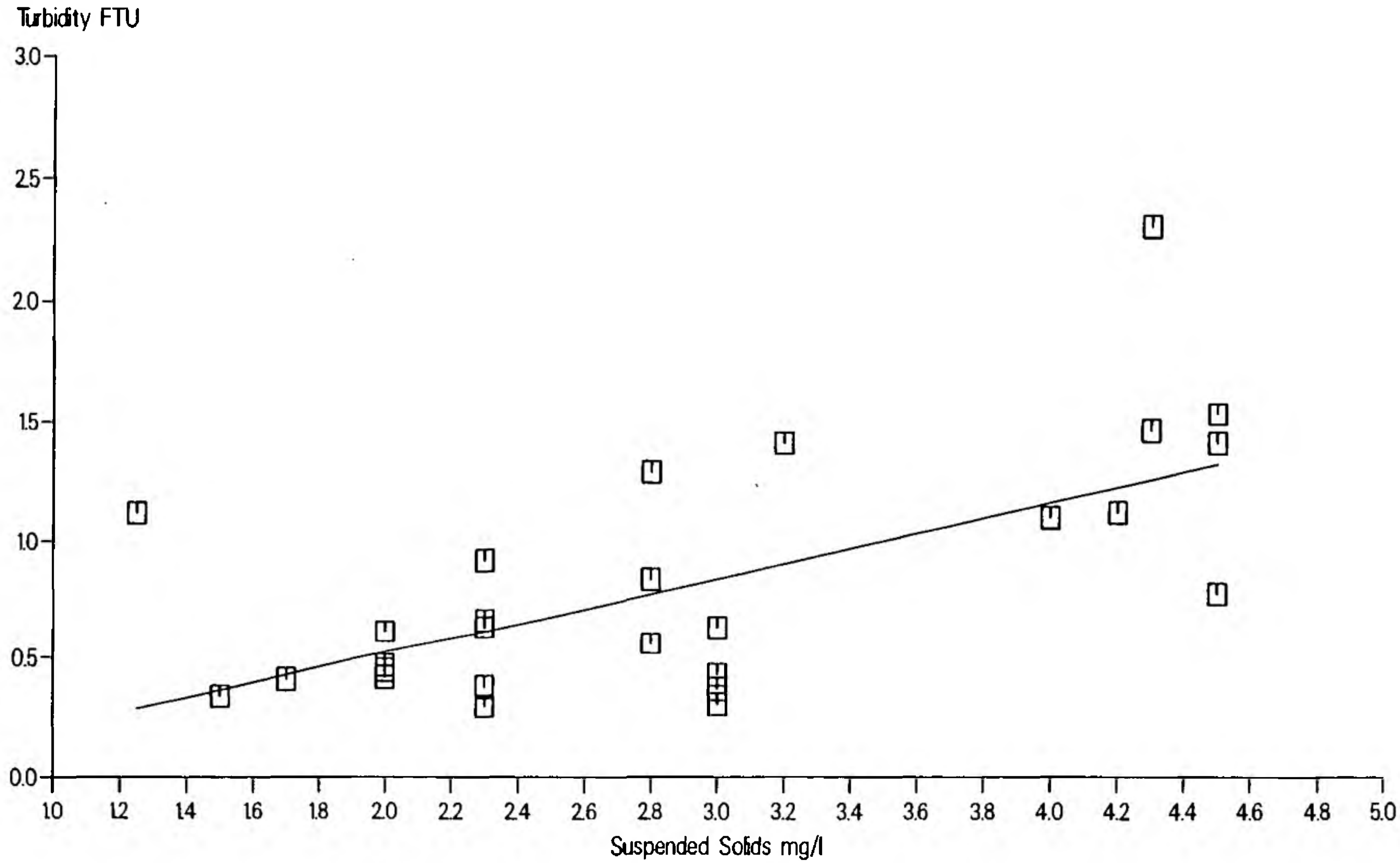
Correlation Coefficient = 0.54

Slope = 0.029 l/mg

Intercept = 0.47

Figure B27 Biological Filter Near Infra Red Light Low Angle

APPENDIX C CORRELATIONS BETWEEN BENCH TURBIDITY AND SUSPENDED SOLIDS

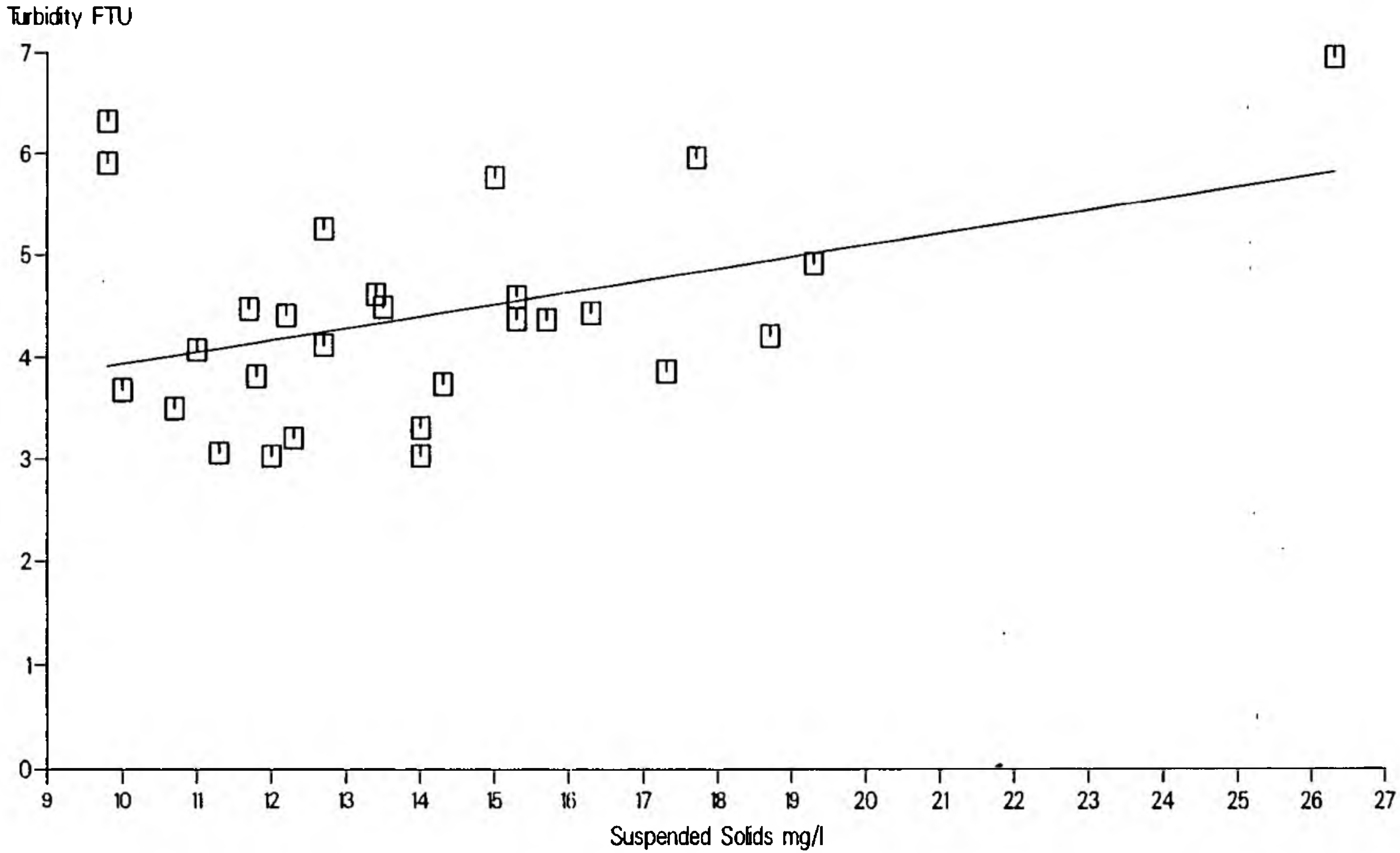


Correlation Coefficient = 0.63

Slope = 0.32 FTU l/mg

Intercept = -0.11

Figure C1 Reed Bed Turbidity vs. Suspended Solids

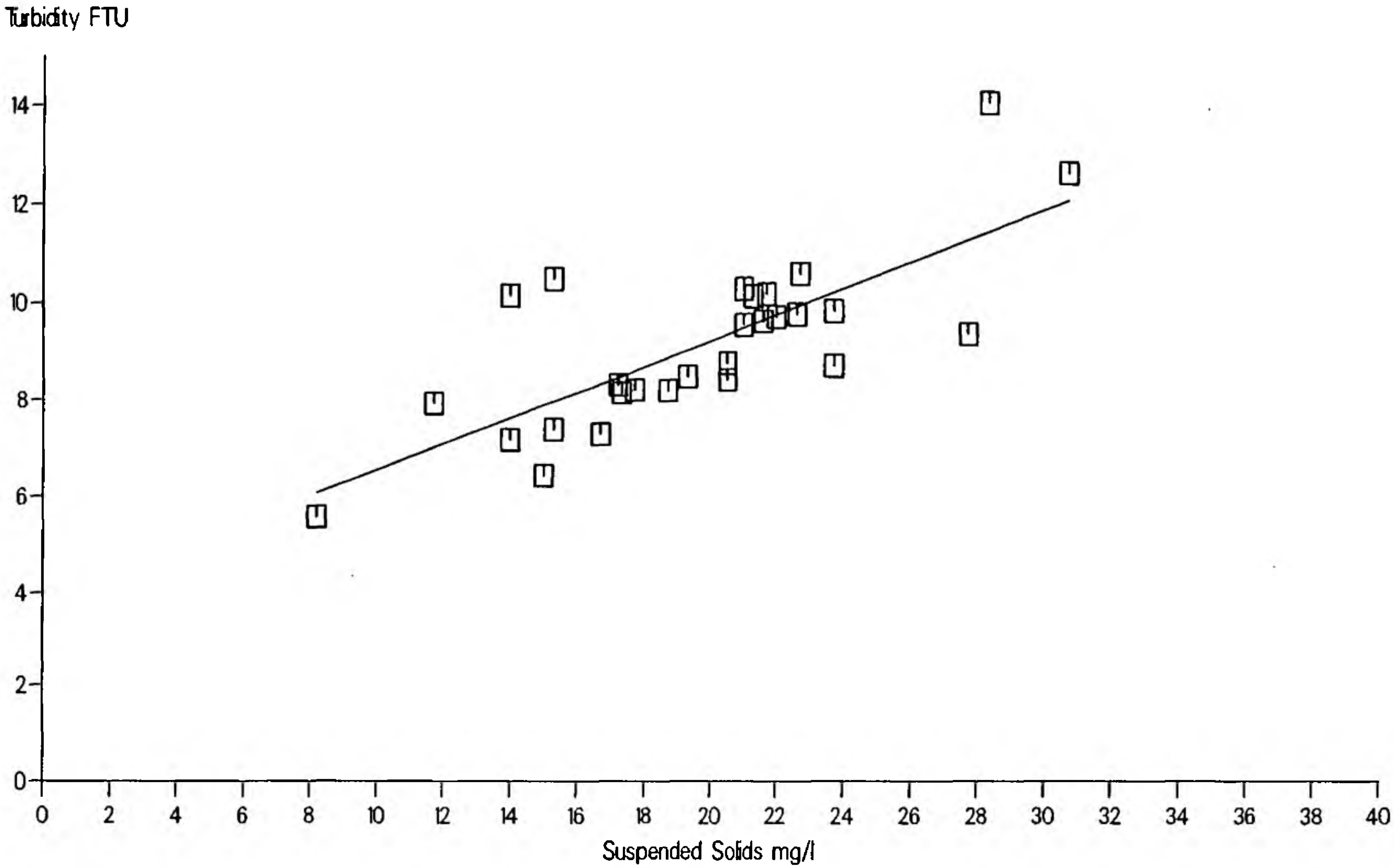


Correlation Coefficient = 0.40

Slope = 0.12 FTU l/mg

Intercept = 2.8

Figure C2 Activated Sludge Turbidity vs. Suspended Solids



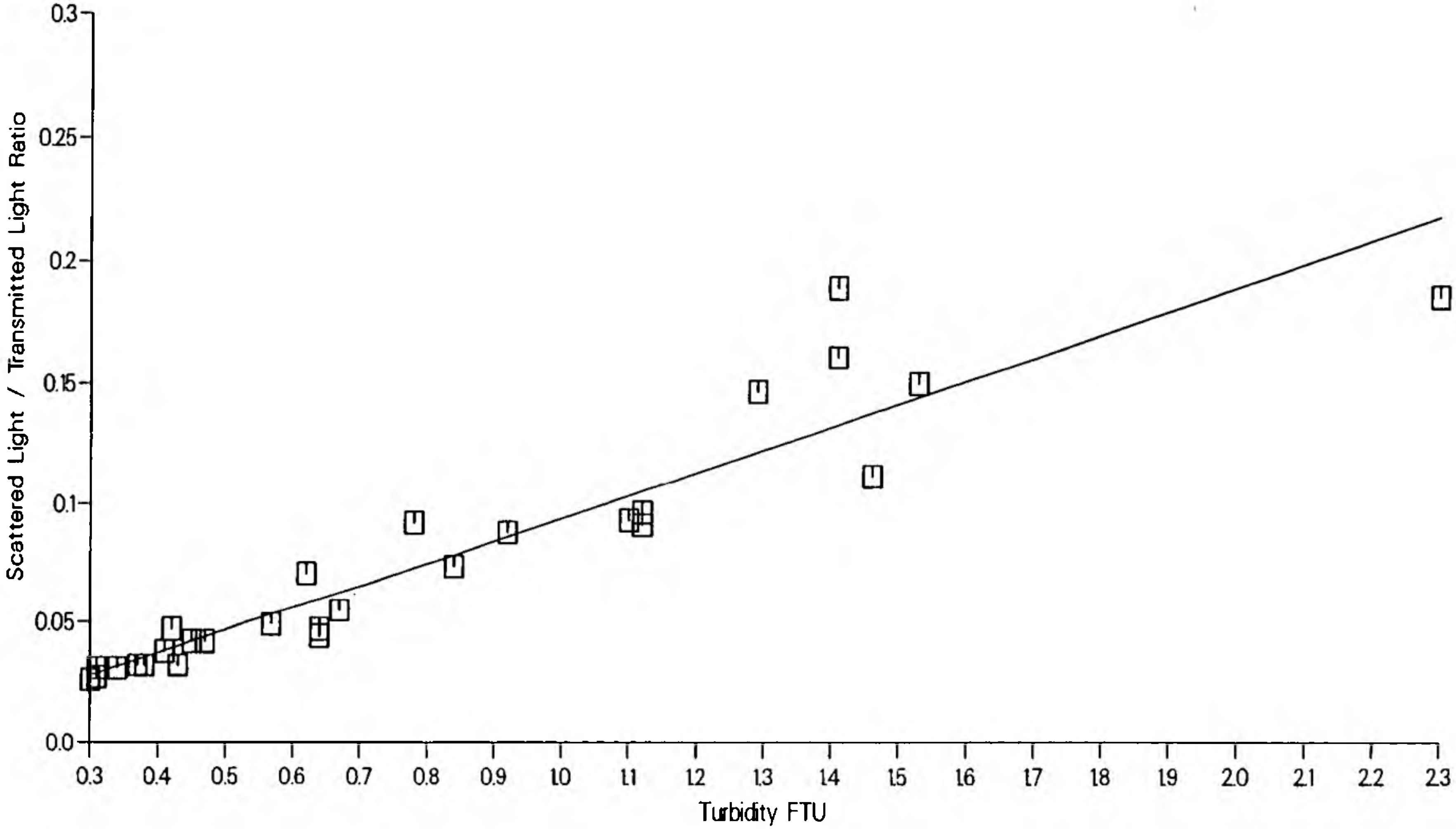
Correlation Coefficient = 0.76

Slope = 0.27 FTU l/mg

Intercept = 3.9

Figure C3 Biological Filter Turbidity vs. Suspended Solids

APPENDIX D CORRELATIONS BETWEEN BENCH TURBIDITY AND WHITE LIGHT AT 90 DEGREES

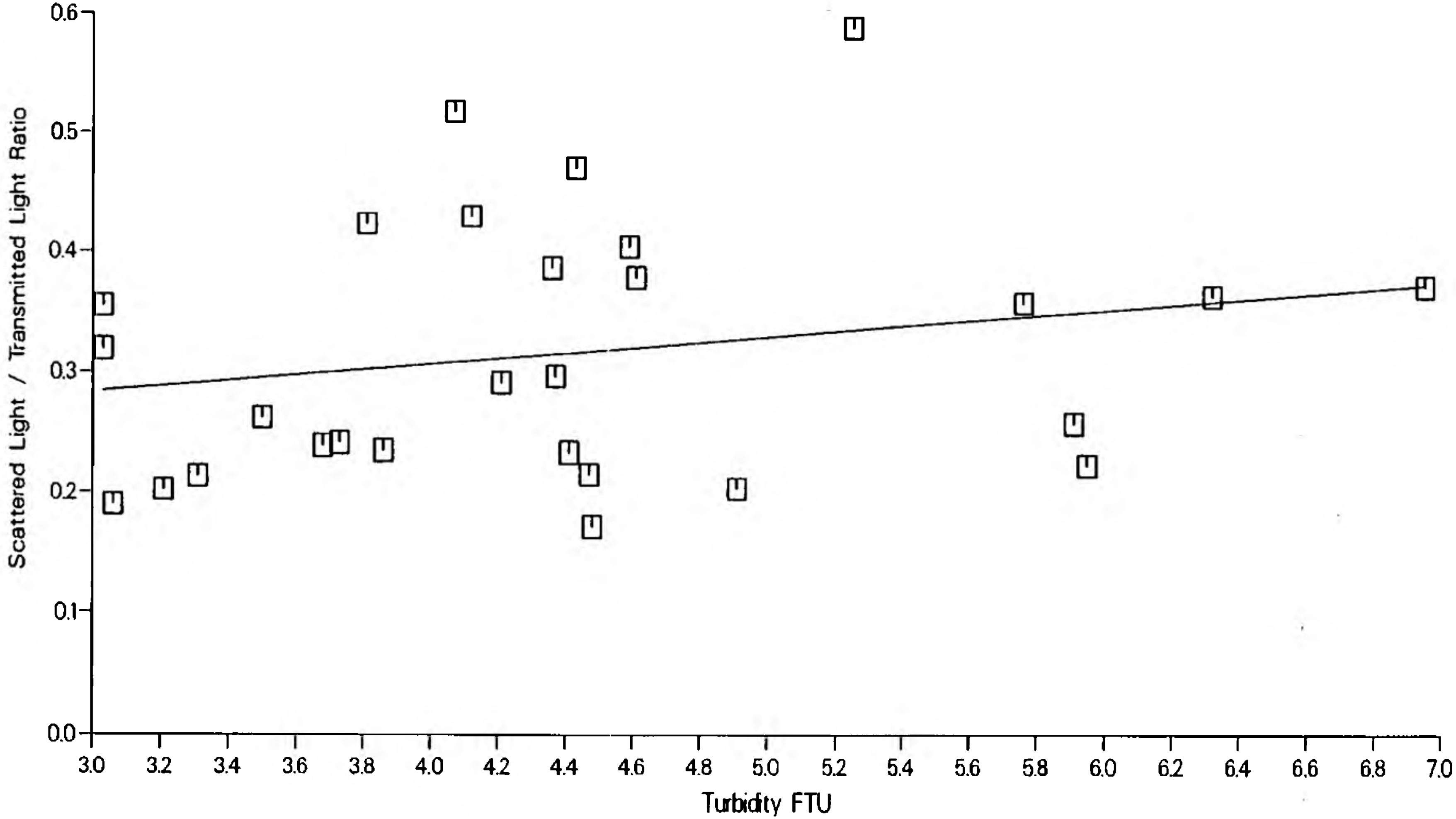


Correlation Coefficient = 0.94

Slope = 0.094

Intercept = -0.00025

Figure D1 Reed Bed White Light 90 degrees

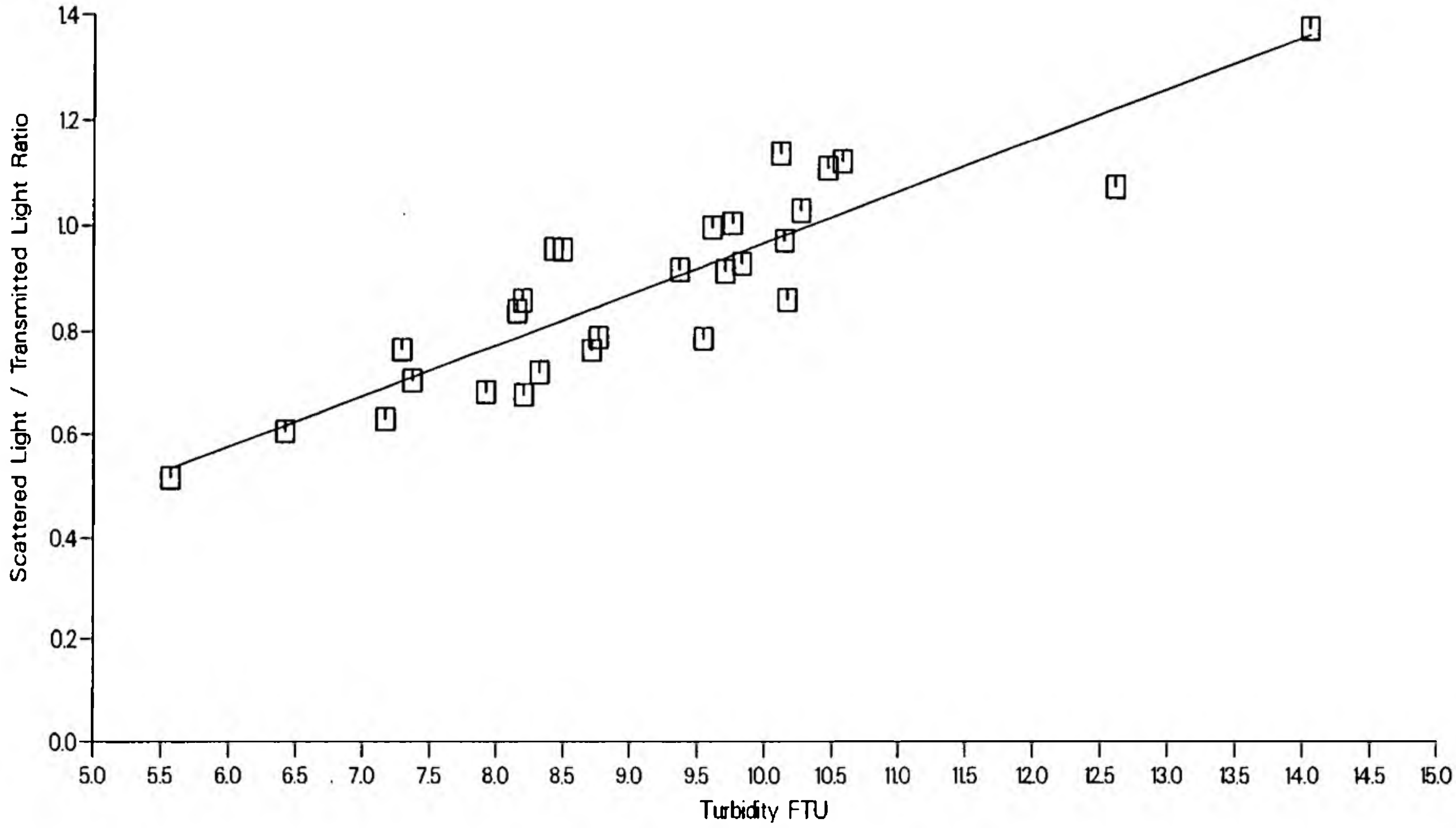


Correlation Coefficient 0.21

Slope = 0.022 FTU-1

Intercept = 0.22

Figure D2 Activated Sludge White Light 90 degrees



Correlation Coefficient = 0.89

Slope = 0.097 FTU-1

Intercept = -0.0085

Figure D3 Biological Filter White Light 90 degrees