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Estimation of the concentration of suspended solids in rivers from turbidity measurement: error assessment

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Abstract The concentration of suspended solids in rivers is traditionally determined by means of slow and relatively expensive methods. There is therefore a need for alternative approaches. The development and validation of models which relate the concentration of suspended solids (*SSC*) to the water turbidity (*Turbidity*), represents one potential approach. This paper presents the results of a study of the errors involved in the use of *SSC*/*Turbidity* models to estimate *SSC*. Three types of model were developed: in the first, *SSC* = *f*(*Turbidity*); in the second *SSC* = *f*(*Turbidity*, *Colour*, D_{50}); and in the third *SSC* = *f*(*Turbidity*, *Colour*, D_{50}, *Cu*), where *Colour* is the apparent water colour, and D_{50} and *Cu* are the mean diameter and the coefficient of uniformity of the suspended sediment, respectively. For the model *SSC* = *f*(*Turbidity*), the maximum error was 28%, whereas for the model *SSC* = *f*(*Turbidity*, *Colour*, D_{50}), the maximum error was 23.3%. The simple model *SSC* = *f*(*Turbidity*) was found to have considerable potential, if the model for a given catchment could involve different relationships for different ranges of *SSC*. In this study, when the *SSC* range was split into two ranges i.e. 20–320 mg l^{-1} and 320–640 mg l^{-1}, the maximum errors for the model *SSC* = *f*(*Turbidity*) were equal to 11 and 9%, respectively. The parameters *Colour*, D_{50} and *SSC* were shown to exert a significant effect on the SSC/turbidity relationship.

Key words colour; concentration/turbidity relationships; grain size; suspended sediment concentration; turbidity

INTRODUCTION

Suspended solids (SS) concentrations in water bodies are usually determined in the laboratory using the gravimetric method. This is a time-consuming procedure with considerable operational costs. It is therefore difficult to assemble detailed SS records for monitoring water quality in catchments. An on-line measurement methodology could offer many advantages. The literature indicates the possibility of meeting this demand by developing relationships between the concentration of suspended solids (SSC) and turbidity, such as those reported by Teixeira & Senhorelo (2000), and Pavanelli & Pagliarani (2002), for example. However, the literature also makes it clear that turbidity does not depend solely on *SSC*, but will also be influenced by other parameters such as colour and the characteristics of the suspended material, including its grain size composition and specific weight. As a result, Teixeira & Senhorelo (2000) have suggested that there is a need for more detailed studies of the relationship between turbidity and SSC, taking into account the other influencing factors, in order to increase the representativeness of the resulting relationships and the scope for their application.

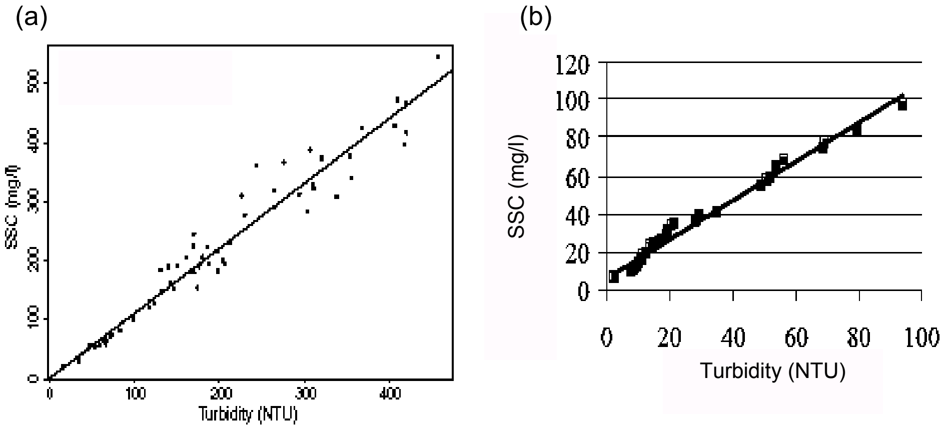

Fig. 1 The relationship between SSC and turbidity as reported by: (a) Lewis & Eads (2001), and (b) Teixeira & Senhorelo (2000).

THE RELATIONSHIP BETWEEN SSC AND TURBIDITY

Since the turbidity of water is a function of the presence of suspended particles, its magnitude will increase with an increase in the suspended sediment concentration. This can be observed in Fig. 1.

The influence of D_{50}, *Cu* and water colour on the relationship between SSC and turbidity

Pavanelli & Pagliarani (2002) indicate that solutions of similar SSC, but with different grain size composition, may cause different levels of light scattering, and thus that the level of turbidity will depend on the size, as well as the concentration, of the dispersed particles. Turbidity is therefore very sensitive to variations in the size of suspended particles (as, for example, represented by the coefficient of uniformity (*Cu*) of the sediment). According to Bhargava & Mariam (1994), an increase in the size of particles leads to a reduction in turbidity. Russell *et al.* (2001) state that the smaller the diameter of the suspended particles, the larger the reflective surface per unit mass and, thus, the higher the turbidity.

According to Packman *et al.* (2002), the relationship between SSC and turbidity may be influenced by water colour. APHA (1995) state that turbidity is reduced where particles absorb light.

Errors in the estimation of SSC as a function of turbidity

According to Teixeira & Senhorelo (2000), considerable potential exists for determining SSC from turbidity measurements. However, there is a need for an improved understanding of the effects of other parameters that will influence this relationship (e.g. the size and geometry of particles), in order to increase the statistical rigour of the resulting regression relationships. The study reported in this paper aims to develop an improved understanding of these effects.

MATERIAL AND METHODS

Characterization of suspended sediment

An attempt was made to identify the range of SSC observed in rivers by gathering data from government bodies, sanitation companies, water resources management agencies and the literature. The minimum and maximum *SSC* values found were 20 and 640 mg l^{-1}, respectively. Four intermediate values (40, 80, 160 and 320 mg l^{-1}) were also considered in the development of this study.

According to Walling *et al*. (2000) and other publications, more than 90% of the suspended sediment transported by many rivers has a diameter less than 63 µm. Based on this evidence, the following values were adopted for D_{50}: 32, 38, 45 and 53 µm.

The coefficient of uniformity (*Cu*) affords an effective means of representing the degree of uniformity of the grain size distribution of a sample of solid particles. This parameter represents the ratio between the D_{60} and D_{10} values obtained from a grain size analysis, which represents the particle sizes which are exceeded by 60 and 10% of the sample, respectively.

No detailed studies of the influence of the grain size composition of suspended sediment on the SSC *vs* turbidity relationship could be found in the literature. Thus, the selection of *Cu* values to be used in this investigation was somewhat arbitrary. Four values were adopted for this parameter (1.32, 1.62, 1.93 and 2.29). These were obtained by manipulating the values of D_{10} and D_{60} as indicated in Table 1.

In relation to colour, existing information obtained from ANA (2002), CESAN (2002) and Piccolo *et al.* (1999) provided a maximum verified value for this parameter of 700 mg Pt l^{-1}, while preliminary tests undertaken in this study found a maximum value of 1352 mg Pt l^{-1}. A value of 1500 mg Pt l^{-1} was therefore adopted as the upper limit for colour to be employed in the development of the tests.

For some tests it was necessary to control the colour of the water. This was achieved by using dyes. The intermediate values of colour employed were 200, 400, 600, 800, 1000, 1200, 1400 and 1500 mg Pt l^{-1}.

Table 1 Values for the coefficient of uniformity (*Cu*), and their respective values of D_{50}, D_{10} and D_{60} (µm).

	$D_{50} = 32$		$D_{50} = 38$		$D_{50} = 45$		$D_{50} = 53$	
Cu	D_{60}	D_{10}	D_{60}	D_{10}	D_{60}	D_{10}	D_{60}	D_{10}
1.32	33.7	25.5	42.1	32.0	50.8	38.5	55.3	41.9
1.62	38.3	23.6	50.8	31.3	50.8	31.3	55.3	34.1
1.93	45.5	23.6	50.8	26.3	50.8	26.3	55.3	28.7
2.29	54.0	23.6	50.8	22.2	50.8	22.2	55.3	24.2

Preparation of samples with a known D_{50} and *Cu*

Sixteen dissimilar samples of soil were generated, by combining the four values of the mean diameter referred to above and the four values of the coefficient of uniformity selected. The following stage consisted of weighing the material to obtain each of the desired concentrations (20, 40, 80, 160, 320 and 640 mg l^{-1}). Then 96 samples were generated, to be later suspended in distilled water (Turbidity = 0), in order to evaluate the effects of *SSC*, D_{50} and *Cu* on turbidity measurements.

The influence of colour on turbidity measurements was evaluated by using eight samples selected randomly from the 96 samples described above. In each case, the turbidity value was measured before and after the addition of the dye.

Models for estimating *SSC*

The relationship between *SSC* and *Turbidity* is usually expressed using various regression functions, including linear (Teixeira & Senhorelo, 2000; Pavanelli & Pagliarani, 2002), logarithmic or exponential (Piccolo *et al*., 1999; Teixeira & Senhorelo, 2000) and power functions (Piccolo *et al*., 1999). When other parameters are considered together with *Turbidity* for the estimation of *SSC*, a multiple regression analysis must be used. Only one study (Bhargava & Mariam, 1994) that used this approach could be found. In this, the following formulation was used.

$$SSC = \left(A + B_1 \cdot P_1 + B_2 . P_2 + ... + B_n \cdot P_n\right)^C \qquad (1)$$

where A, B_1, B_2, …, B_n, and C are constants, and P_1, P_2, …, P_n are variables (*Turbidity*, D_{50}, etc.).

The form of equation (1) was adopted in this study for the development of models involving *Turbidity* and *SSC* only, as well as models involving *Turbidity*, *SSC*, D_{50} and *Colour*. Evaluation of the goodness of fit of the resulting relationships was based on analysis of their coefficients of determination (R^2), as well as analysis of the absolute residuals (difference between estimated and measured values). The agreement between observed and predicted values was also assessed for specified ranges of *SSC*, instead of the whole range of *SSC*.

RESULTS AND DISCUSSION

The variation of *Turbidity* values for samples with a constant *SSC*

The measurements showed that waters with identical values of *SSC* could produce different values of *Turbidity*, in agreement with Pavanelli & Pagliarani (2002). According to these authors, water samples with a similar *SSC*, but characterized by different grain size compositions, do not generate the same amount of light scattering. Table 2 reports the maximum, minimum and mean values of *Turbidity* (NTU), as well as the percentage variation in relation to the mean value of *Turbidity*, for each level of concentration analysed. The number of water samples analysed for each level of concentration was 16.

The effects of changes in concentration (*SSC*)

The results of this study have shown that an increase in *SSC* leads to an increase in *Turbidity*, when other parameters are kept constant. Figure 2 provides an example of such behaviour, for a typical data set from this study.

Table 2 Maximum, minimum and mean values of *Turbidity* (NTU) and percentage variation in relation to the mean value of *Turbidity*, for each value of *SSC*.

SSC (mg l^{-1})	*Turbidity* (NTU): Maximum	Minimum	Mean	Variation (%)*
20	29.7	24.9	26.7	17.98
40	55.5	48.3	51.3	14.04
80	106.1	90.9	97.6	15.58
160	193.8	167.8	179.4	14.49
320	349.0	311.8	326.8	11.38
640	683.1	601.6	641.6	12.70

*Variation (%) = (| Maximum – Minimum | / Mean) × 100.

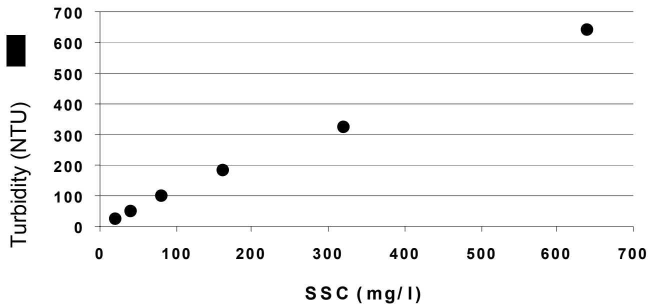

Fig. 2 The variation of *Turbidity* with *SSC*, a typical data set obtained from this study.

The effects of changes in mean diameter (D_{50})

The results demonstrate that waters with the same value of *SSC* but different values of D_{50}, produce different values of *Turbidity*. *Turbidity* was seen to reduce as D_{50} increased (Fig. 3). Similar results were obtained by Bhargava & Mariam (1994).

Variations in turbidity associated with a change in D_{50} were shown to be higher, in percentage terms, for lower values of *SSC*. This tendency was also reported by Lenzi & Marchi (2000), who stated that larger particles tend to generate lower values of turbidity. The increase in turbidity as a result of a reduction of the mean diameter of the suspended particles is due to the fact that fine sediment presents a larger reflective surface area per unit mass (Schoellhamer, 2001).

The effects of changes in the coefficient of uniformity (*Cu*)

The results obtained for this parameter indicate that changes in *Cu* do not produce a consistent effect on *Turbidity*. For some water samples an increase of *Cu* produced an increase in *Turbidity*, while for others it produced a reduction in *Turbidity*, as seen in Fig. 4. Thus, it can be inferred that variations of turbidity cannot be explained directly by the variation of *Cu*. A coefficient that indicates the relative percentage of sediment finer and coarser than the D_{50} might prove more appropriate.

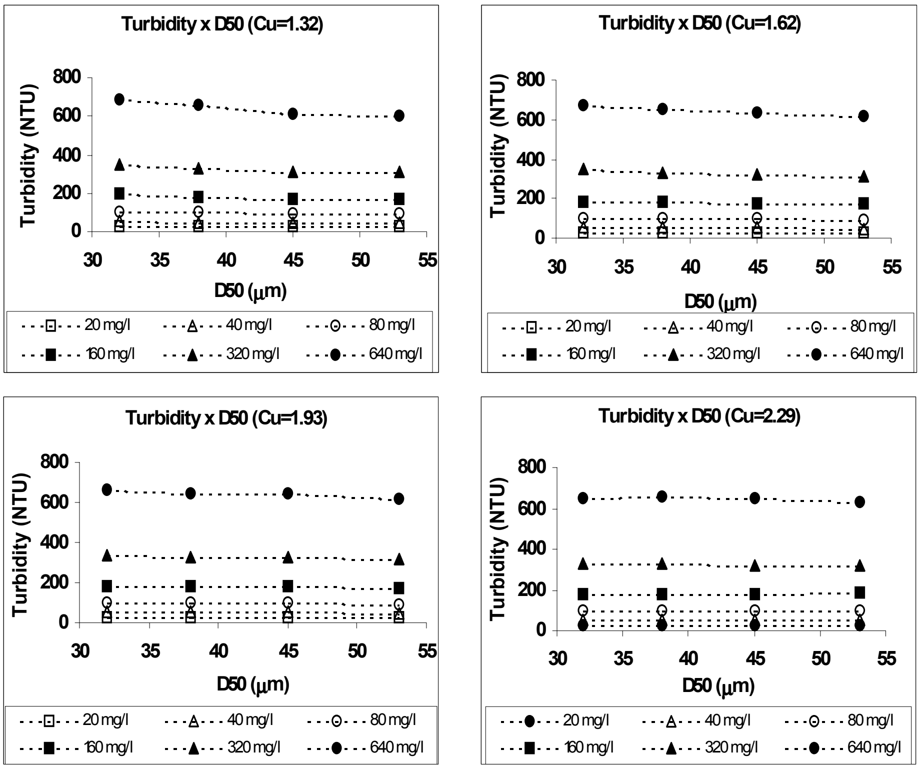

Fig. 3 Turbidity behaviour as a function of the D_{50} for different values of *SSC* and *Cu*.

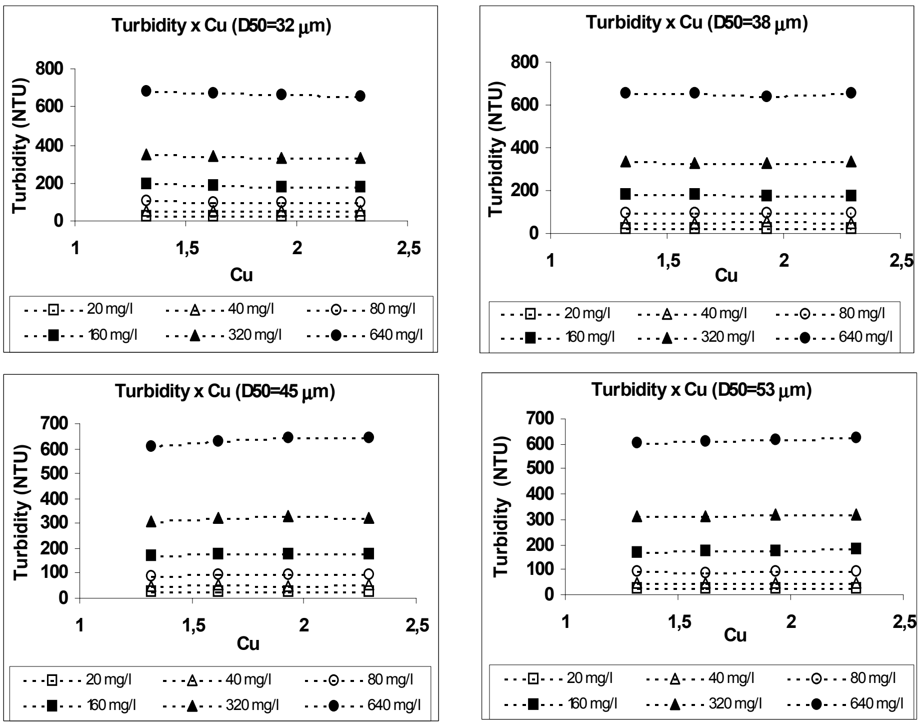

Fig. 4 The relationship between *Turbidity* and *Cu* for different values of *SSC* and D_{50}.

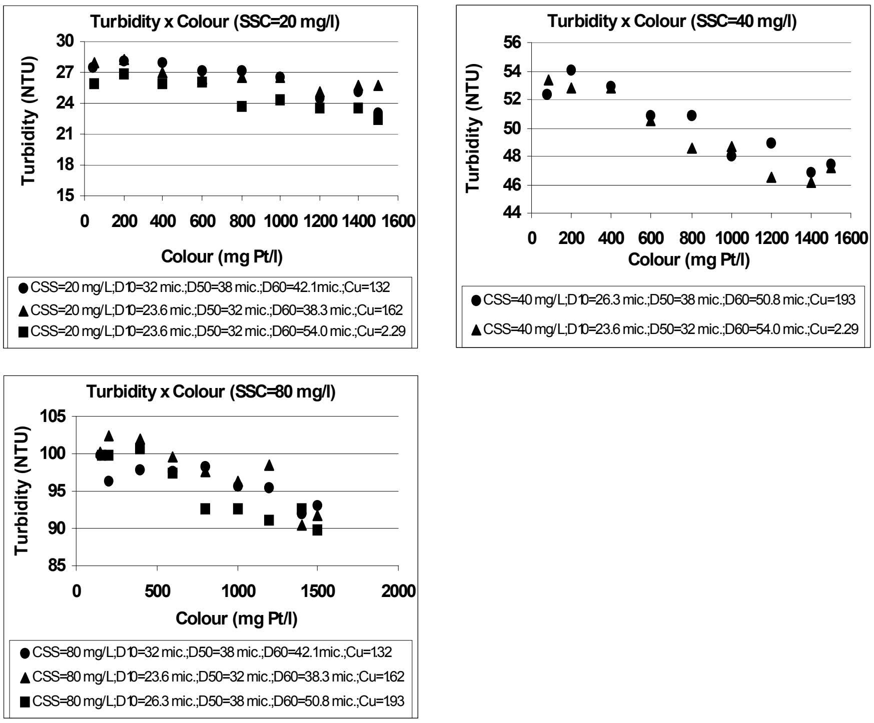

Fig. 5 The relationship between *Turbidity* and *Colour* for different values of *SSC*, D_{50} and *Cu*.

The effect of colour

An increase in water colour was shown to result in decreased *Turbidity*, regardless of the values of *SSC*, *Cu* and D_{50} (see Fig. 5). This is consistent with the findings of APHA (1995), which indicate that the presence of light absorbing dissolved substances generates a reduction in the turbidity of water.

Regression analyses

Based on the findings presented above, which demonstrated that variations in *Turbidity* cannot be explained directly by the value of *Cu*. The model represented by equation (2) was developed, involving the parameters *SSC*, D_{50} and *Colour*.

$$SSC = \left(0.346Turbidity - 0.055D_{50} + 0.270Colour + 1.000\right)^{1.031} \quad (R^2 = 0.9983) \qquad (2)$$

where *Turbidity* is in NTU, D_{50} is in μm; and *Colour* is in mg Pt l^{-1}.

This equation produced a good fit, showing that there is a good correlation between *Turbidity* and *SSC* when the parameters D_{50} and *Colour* are taken into account (Fig. 6(a)). Figure 6(b) presents the errors between the measured value of *SSC* and the value of *SSC* estimated with the regression curve. It can be seen that all errors were below 25%.

A further model involving only *SSC* and *Turbidity* (equation (3)) was developed, in order to provide a simplified method for the determination of *SSC*:

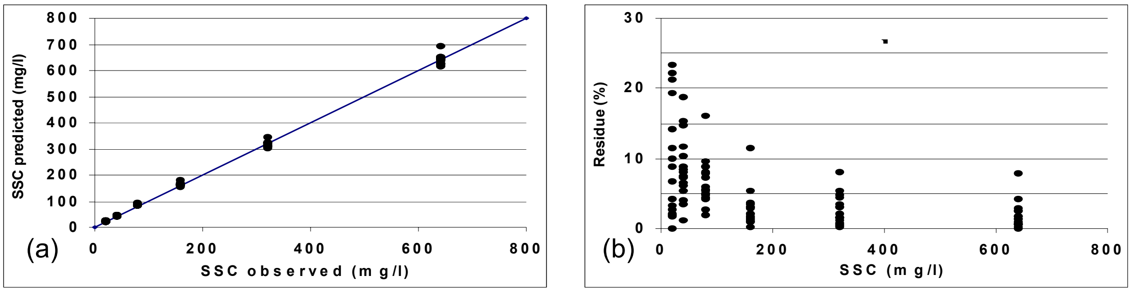

Fig. 6 A comparison of observed and predicted values of sediment concentration based on equation (2) (a), and the associated errors (b).

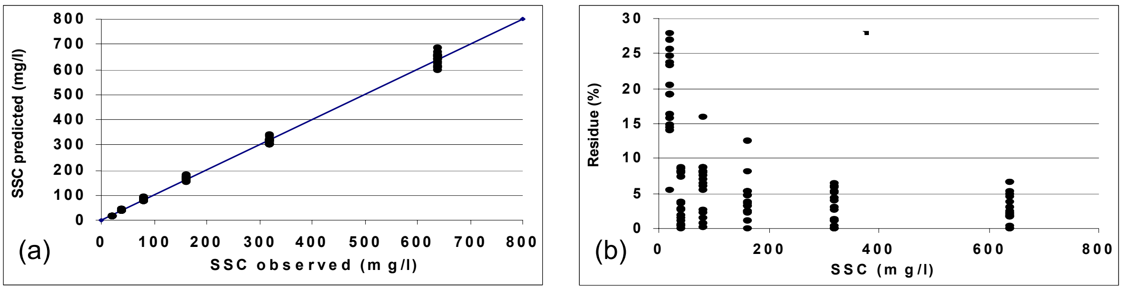

Fig. 7 The relationship between the measured and estimated values of *SSC* for equation (3) (a), and the associated errors (b).

$$SSC = (0.837 Turbidity - 7.513)^{1.030} \qquad (R^2 = 0.9971) \qquad (3)$$

The results provided by this model were also used to verify the goodness of fit between the observed and the estimated values of sediment concentration. This showed that exclusion of the additional variables still resulted in predicted values of *SSC* similar to those estimated by the model involving all parameters (equation (2)). Figure 7(a) presents the measured and estimated values of *SSC* when using equation (3). Figure 7(b) presents the corresponding percentage errors between the measured and estimated values, which can be seen to be lower than 30%.

The small difference between the maximum residual values obtained for each of the situations described above (<25% equation (2), and <30% equation (3)) indicates that there is potential to develop models for predicting *SSC* as a function of *Turbidity* only. Thus, following the recommendations of Piccolo *et al.* (1999), an attempt was made to develop models based solely on *SSC* and Turbidity, for selected ranges of concentration, which covered the widest possible range of *SSC* and that generated the smallest possible errors.

Regression analyses for selected ranges of *SSC*

The smallest errors obtained in the regression analyses for selected ranges of *SSC* were associated with the ranges 20–320 mg l^{-1} (equation (4)) and 320–640 mg l^{-1} (equation (5)).

$$SSC = (0.442 \times Turbidity + 1.410)^{1.157} \qquad SSC\ 20\text{–}320\ \text{mg l}^{-1} \quad (R^2 = 0.9967) \qquad (4)$$

$$SSC = (156.2 \times Turbidity - 29369.5)^{0.578} \qquad SSC\ 320\text{–}640\ \text{mg l}^{-1} \quad (R^2 = 0.9896) \qquad (5)$$

Figure 8(a) and (b) shows the percentage errors and the corresponding frequencies associated with equations (4) and (5). It can be seen that the maximum error was, in both cases, of the order of 10%, which compares favourably with the error of approximately 30% presented before. It can also be seen that the highest frequencies correspond to error values less than 10%.

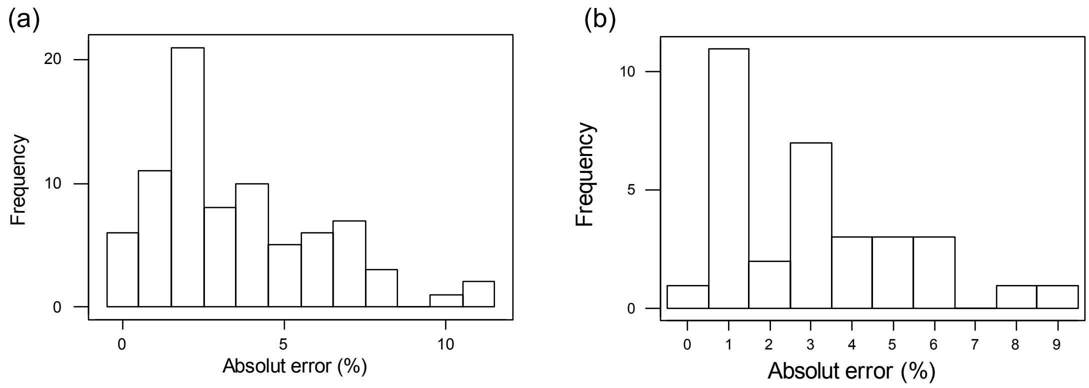

Fig. 8 Frequency distributions for the errors between measured and estimated values associated with (a) equation (4), and (b) equation (5).

CONCLUSIONS

The relationship between SSC and turbidity has been shown to provide a promising approach for determining SSC in rivers, since errors in estimating SSC were found to be comparable to those associated with models which also include other parameters in the relationship (such as water colour and the mean diameter of the suspended particles). Models developed for smaller ranges of SSC tend to generate smaller errors than those obtained for wider ranges of concentration. The parameters *SSC*, D_{50} and *Colour* significantly affected the *SSC*/*Turbidity* relationship. The use of *Cu* as a further parameter affecting the relationship proved unsuccessful.

The equation used in the study to express *SSC* as a function of the other parameters (equation (1)) has shown to provide a good fit to the experimental data.

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