TURBIDITY MEASUREMENTS AND MODIFIED IMHOFF CONE METHOD FOR ESTIMATION OF SUSPENDED SEDIMENT CONCENTRATION

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ABSTRACT

The requirement for monitoring of suspended sediment concentrations (SSCs) with good temporal and spatial resolution has led to the development of methods for sediment measurements. In this study, two practical and relatively cheap alternative methods (namely turbidity sensor and Imhoff cone method) were used to estimate SSC. Imhoff cone is a practical and indirect free settleable solid analysis method. Although this method is easy to use and cheap, moving the water samples to the laboratory and allowing them to settle can be time consuming. Therefore polyacrylamide (PAM), which is a soil conditioner and a flocculant, was tested as an accelerant of sediment settling in Imhoff cone method. PAM concentrations of 0.05 and 0.1 ppm were used in water samples. The results showed that it causes turbidity sensor measurement method had high reliability and advantage including continuous monitoring and ability to read and store more data at high expected sediment concentrations (<10.0 g/L). Finalizing the flocculation and settling material stabilization processes in a short time, like 10 min, increased the use of Imhoff cone method in the field conditions without having to move samples to the laboratory. However, this method had disadvantages of causing errors at low sediment concentrations and requiring sensitive measurements due to the graduation of the cone. These problems can be solved by using better graduated cones or digital sensors in the cones. Finally, this study showed that these methods have potential with high reliability and are good alternatives for practical and economical sediment measurements.

KEYWORDS:
Suspended sediment, Imhoff cone, Turbidity, Sensor

INTRODUCTION

Suspended sediment yield is the main parameter for hydrological studies and varies spatially and temporally depending on many factors, such as hydraulic characteristics of the streams, geomorphological conditions of the catchments, climatic regime of the area and presence of vegetation. Laboratory sediment measurements are made by means of water samples taken using special equipment and methods. Sediment measurements in the laboratory involve some difficulties and restrictions due to the required number of samples needed to represent a cross-section of the river conditions and the need to move these samples to the laboratory, filter and dry them [1,2]. Different methods are needed for continuous monitoring of sediment transport, which varies with time and location.

Turbidity measurements are increasingly used to generate continuous records of SSCs in rivers. Turbidity is described as "an expression of the optical property that causes light to be scattered and absorbed rather than transmitted in straight lines through the sample" [3]. Turbidity, an index of light scattering by suspended particles, has been widely used as a simple, cheap, instrumental surrogate for suspended sediment that also relates more directly to optical effects of suspended matter than does mass concentration [4].

The use of turbidity values, NTU (Nephelometric turbidity units), for sediment monitoring generally requires that a statistical relationship be established between turbidity and SSC. This relation is often expressed in a linear regression, non-linear equation or polynomial function [5]. Besides concentration, size, colour, and mineral composition of the sediment affect turbidity. These effects should probably be calibrated with suspended-sediment samples collected over the range of turbidity conditions at the same time that continuous turbidity measurements are made [6]. Gravimetric analysis with water sampling is the most reliable way to estimate SSC and is essential to properly calibrate measurements of the various surrogates in spite of its limitations [4].

Chanson et al. [7] carried out two different experiments using fine silt, mud and slightly coarser (fine sand) material. They measured turbidity in concentrations of particles less than 0.8 g/L. In their study, there was a strong relationship between SSC and NTU (R^2=0.9924 and 0.9922), and the tests yielded different turbidity readings for a given SSC, although the overall trends were similar with both soil samples. Mitchell et al. [8] investigated different relations between SSC and NTU and flow rate in river conditions and developed estimation models. They suggested this method for spring tide conditions under low fresh water flow conditions and indicated that measurement errors increased due to the complexity of sediment concentration in suspension.

Another practical alternative indirect method for sediment measurement is free settleable solids (FSS) analysis using Imhoff cones. Settleable solids are defined as the solids that settle in a sample of liquid after a specific time period. This technique is very common in wastewater analysis, and its units are usually expressed in mL/L [3].

Pavanelli and Bigi [9] reported that Imhoff cones, which are usually used to estimate settleable matter for sewage, can be used for estimating suspended sediment concentrations in stream water and are notable for their characteristics of simplicity, cost competitiveness and reliability. They prepared water samples with 12 different sediment concentrations between 1.5 and 30.0 g/L at laboratory to compare turbidity meter and Imhoff cone measurements. After the sample cone is taken, the material that settles down (free settleable solids, FSS) in 1 h and in 24 h is measured in units of ml. It is especially well established that there is a good relation between the 24 h reading and SSC.

Sediment settling velocity depends on specific gravity, density and diameter of the sediment [10]. Xia et al. [11] measured sediment settling velocities between 0.001 – 0.02 cm/s depending on particle size. In the clay class (<0.002 mm particle size), sediment settling velocity was less than 0.005 cm/s. In addition, particles finer than 0.0001 mm in water remain continuously in motion due to an electrostatic charge that causes them to repel each other.

For that reason, measurements of sediment samples that include high clay or fine silt take a long time by Imhoff cone method. Although Imhoff cone method is practical, cheap and simple to use, transporting these samples to laboratory and the process of settling can take a long time. Reducing the settling time can increase the effectiveness of this method. Several chemicals known as flocculants can be used to increase the settling velocity of particles in water. Many flocculants are multivalent cations such as aluminum, iron, calcium or magnesium [12].The anionic form of polyacrylamide (PAM) is frequently used as a soil conditioner on farmland and for erosion control. It also helps to protect the water quality of nearby rivers and streams [13,14]. Furthermore, PAM can be used as a flocculant for wastewater treatment. Given these properties, it can be concluded that the Imhoff cone method can be accelerated using PAM.

Therefore in this study, two alternative methods were used for providing ease and continuity of sediment measurements. Firstly, the possible use of the Seapoint Turbidity Meter sensor to provide accurate, reliable, automated and continuous time series of SSCs was investigated. For this aim, the best calibration equations were developed to estimate SSC using turbidity sensor readings for different sediment materials under laboratory conditions. Additionally, the use of the Imhoff cone method over short time periods was investigated in field conditions. Different amounts of PAM were tested for accelerating the settling of sediment in Imhoff cone method. Soil samples with different textures were collected from catchments as sediment material, and different concentrations were tested.

MATERIALS AND METHODS

The suspended sediment solutions were prepared with three soil types (passed through a 250-μm sieve) in black plastic buckets to prevent the ambient light in the laboratory from disrupting the turbidity measurements. Some physical and chemical properties of soils used in the experiment are presented in Table 1. Twenty-five concentrations between 0.0 and 16.0 g/L were chosen for each of the three soil types (0.2/0.4/..2.0/2.5/..5.0/6.0/../10.0/12.0/14.0 and 16.0 g/L). Homogeneity was maintained with continuous mixing during the measurement process. Available running water was used for preparing samples (0.415 dS/m and pH of 7.6).

The turbidity measurements were made with a Seapoint Turbidity Meter, which measures the scattered light (880nm) at 15–150^0 to the axis of the light beam from a small volume within 5 cm^2 of the sensor window. This sensor is factory adjusted for consistent responses to the Formazin Turbidity Standard measured in Formazin Turbidity Units (FTUs) and has linear output for 0-750 FTU with 2% deviation [15]. It is small, consumes very little

TABLE 1 - Some physical and chemical properties of soils used for suspended sediment solutions

Soil Types	Soil texture, %			$CaCO_3$, %	OM*, %	pH	EC, dS/m	BD g/L
	Clay	Silt	Sand					
Soil-1	12.03	26.18	61.79	24.5	1.033	7.893	1.072	1.42
Soil-2	13.10	24.33	59.67	16.9	1.116	8.093	1.221	1.17
Soil-3	35.83	26.60	37.57	1.7	2.272	7.557	1.450	1.22

*OM: organic matter, EC: electrical conductivity, BD: bulk density power, is highly sensitive and has a wide dynamic range. It is also insensitive to ambient light when it is under water, and it has a very low temperature coefficient. This sensor was connected to Aquascat data logger devices manufactured by Aquatec Group, UK. Sensor readings were stored once per second during a two-minute period, resulting in an average of 120 readings for each of 25 sample concentrations.

Similar concentrations range were prepared by using the same soil types for Imhoff cone measurements, but due to cone graduating restriction, the numbers of low concentration were reduced. Eighteen concentrations between 0.0 and 16.0 g/L were chosen for each of the three soil types (0.5/ 1.0/…..5.0/6.0/…..10.0/12.0/14.0 and 16.0 g/L) and three replicate were applied for each concentration. For this analysis, a 500-ml water sample was used, and 0.05 ppm and 0.1 ppm PAM (charge density of 20%, molecular weight of 14-18 million mg/mol) (Fig. 1) by water volume were added, respectively, to accelerate settling. The sample was then stirred. After this process was complete, the sample was spilled into an Imhoff cone. Sediment settling time has been determined to be 10 and 20 min after deposition into the Imhoff cone. Settled amounts of sediment (free settled solids, FSS) were measured in mL at predetermined time intervals. Measurements were repeated three times for each sediment concentration.

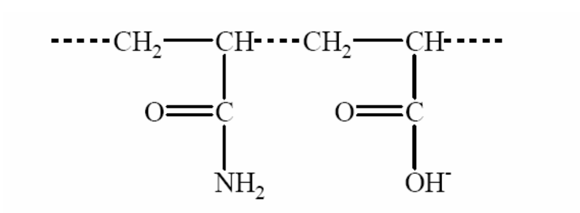

FIGURE 1 - Molecular structure of anionic polyacrylamide [13].

The simple regression analysis was used to get determination coefficient R^2 and predictive equation between known sediment values (SSC) and each method's results (FTU and FSS). Besides Student- t test was used to determine the effect of different soil types and PAM applications.

RESULTS AND DISCUSSION

Turbidity measurements

The turbidity measurement results, known as FTU values, for three soil types are presented in Fig 2. Generally, no clear effect of selected soil textures, passed through a 250-µm sieve, on FTU values was observed, and similar results were obtained for all groups ($P<0.05$).

The measurements yielded a reasonable distribution until a concentration of nearly 10.0 g/L. After this value, unstable FTU measurements were observed. Basically sensor's output deviation increases after greater than 750 FTU [15]. For that reason, measurements taken at concentrations greater than 10.0 g/L were removed from the analysis. The same situation was reported by Mitchell et al. [8]. They found that the turbidity method resulted in errors when sediment concentrations were greater than 13.0 g/L in river conditions. Pavanelli and Bigi [9] found that the SSC within 7.0 g/L can be measured with high reliability, besides they suggested the solution to the problem of excessive turbidity of diluting the sample under laboratory conditions.

There is an especially strong relationship between concentration and turbidity up to 5.0 g/L concentration. In addition to whole values, values grouped into concentrations of ≤ 5.0 g/L and >5.0 g/L were taken into account when considering the determination coefficient between FTU and SSC (Fig.3). The high R^2 and polynomial rela-

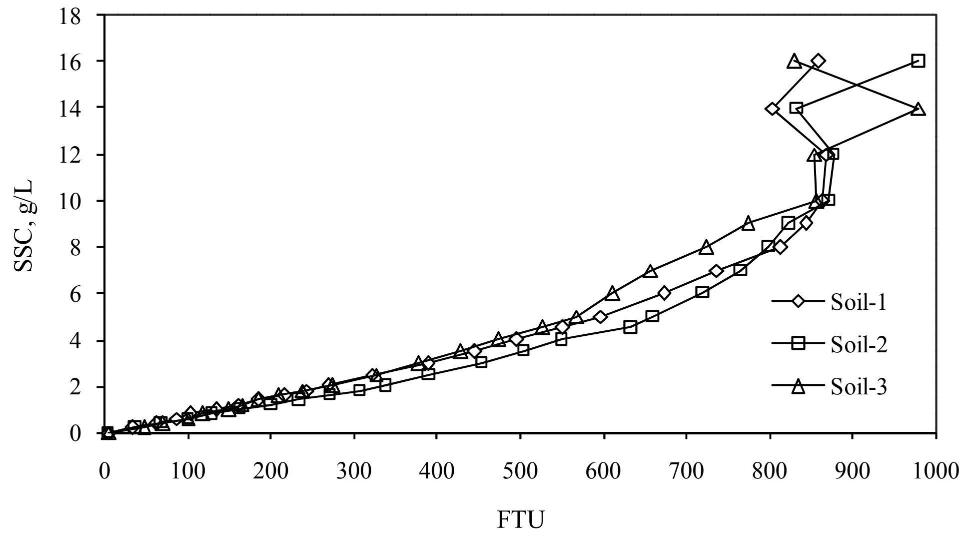

FIGURE 2 - The turbidity (FTU) for all soil types.

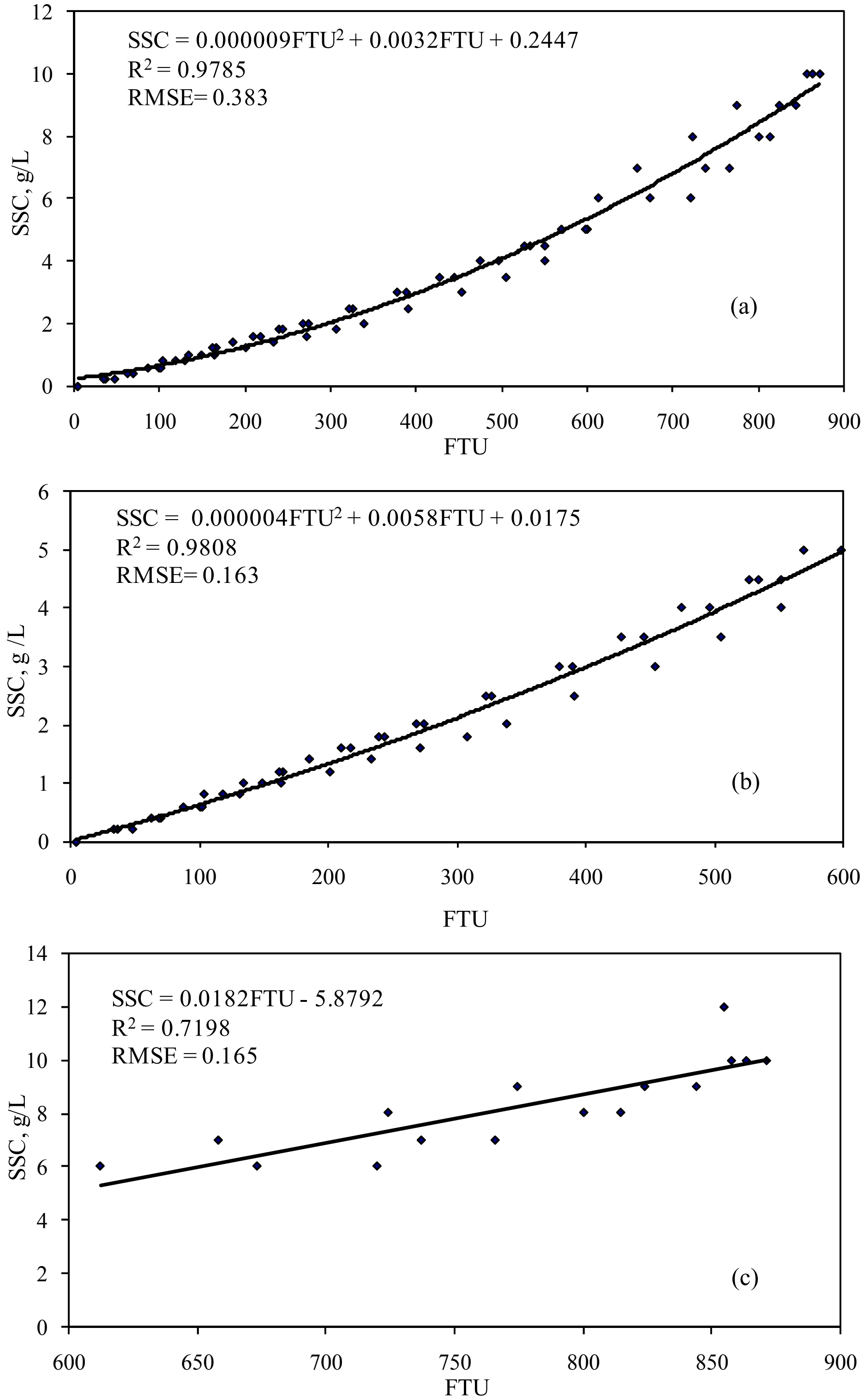

FIGURE 3 - Regression analysis between turbidity (FTU) and suspended sediment concentration (SSC) at SSC a) 0–10 g/L, b) ≤ 5.0 g/L, c) > 5.0 g/L.

tionship were obtained when considering whole values. When root mean squared error (RMSE) was taken into consideration, it was determined that it might be better to obtain a separate determination coefficient for lower concentrations. Similarly, Clifford and Lane [16] preferred to obtain a separate calibration curve for lower concentration measurement with turbidity meter. Generally, the suspended sediment concentration in Turkey's rivers is below 5.0 g/L [17].

Imhoff cone measurements

Measurements of settled solids in Imhoff cones were taken after allowing the samples to settle for 10 and 20 min. The aim of this procedure was to determine the minimum time required for the best settling. Obtained average values in mL units for each waiting time are given in Fig.4. The results obtained show that there was no difference between the readings at 10 min and 20 min ($P<0.05$). The applied PAM immediately adsorbed to soil particles and aggregate surfaces and became irreversibly bound to the soil [17]. Thus, PAM not only flocculates suspended sediment particles for settling, but also provides stable conditions in the settled portion. The completion of this process in as little as 10 min increases the usability of this method.

The other variable to be investigated regarding using PAM in the Imhoff cone method is its concentration. The aim in this study was to use the minimum concentration that caused settling. In this study, 0.05 and 0.1 ppm applications were chosen. Increasing the PAM concentration did not affect observed FSS values in Soil-1, which had a low concentration (<9.0 g/L), but it increased the FSS value about 5.6% in soils with high concentration. The observed increase was about 7.4% in Soil-2 and about 6.0% in Soil-3. The data gathered after 10 min of settling for each PAM concentration were used for evaluating results. The relationship between SSC and FSS values was analyzed. Both the determination coefficient (R^2) and root mean squared error (RMSE) values are given in Table 2.

There was a high relationship between FSS and SSC for all treatments. Furthermore, all observations (10 and 20 min) used for determining the effectiveness of FSS analysis of all chosen soil types are given in Fig. 5.

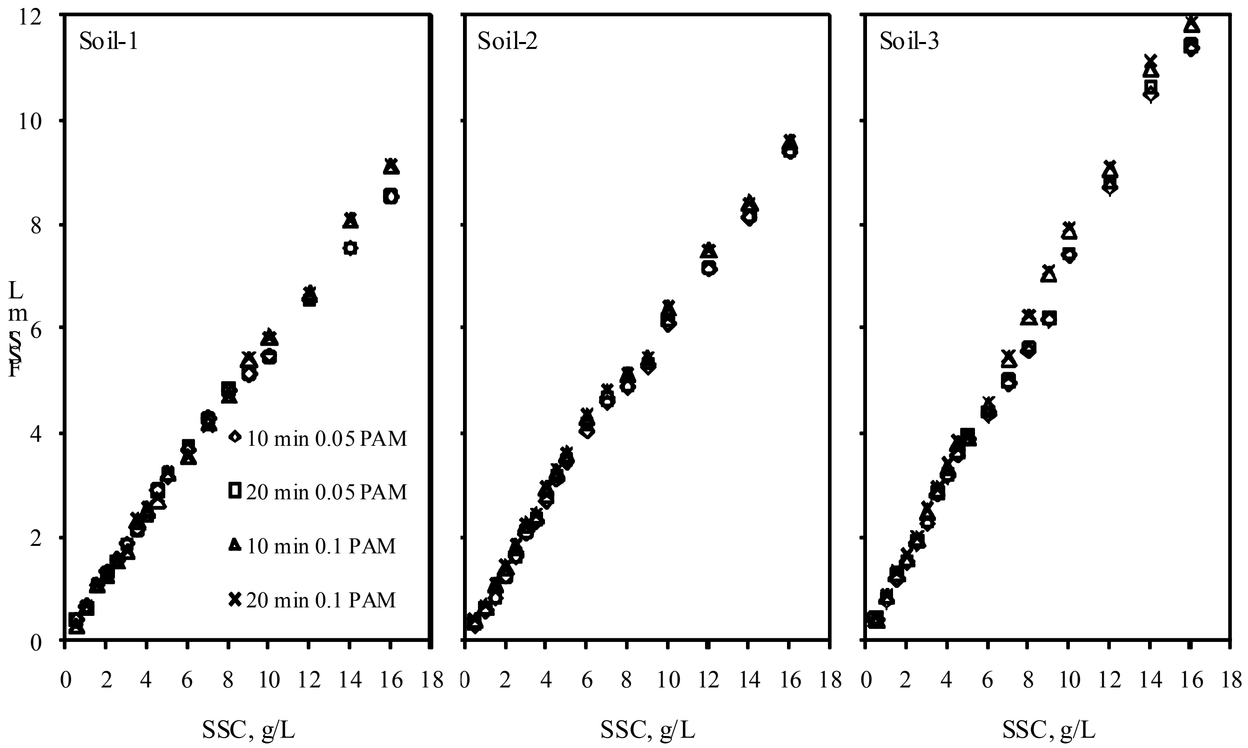

FIGURE 4 - Suspended sediment concentration (SSC) versus free settled solids (FSS) for all soil types at two different PAM concentrations.

TABLE 2 - Regression analysis between suspended sediment concentration (SSC, g/L) and free settled solids (FSS, mL).

Soil types	PAM, ppm	Regression Equation	R^2	RMSE
Soil-1	0.05	SSC = 1.9035FSS-0.6238	0.9956	0.295
	0.1	SSC = 1.7756FSS-0.3198	0.9977	0.214
Soil-2	0.05	SSC = 1.7191FSS-0.3799	0.9972	0.337
	0.1	SSC = 1.6901FSS-0.5990	0.9935	0.495
Soil-3	0.05	SSC = 1.3994FSS-0.1923	0.9966	0.260
	0.1	SSC = 1.3322FSS-0.2529	0.9978	0.207

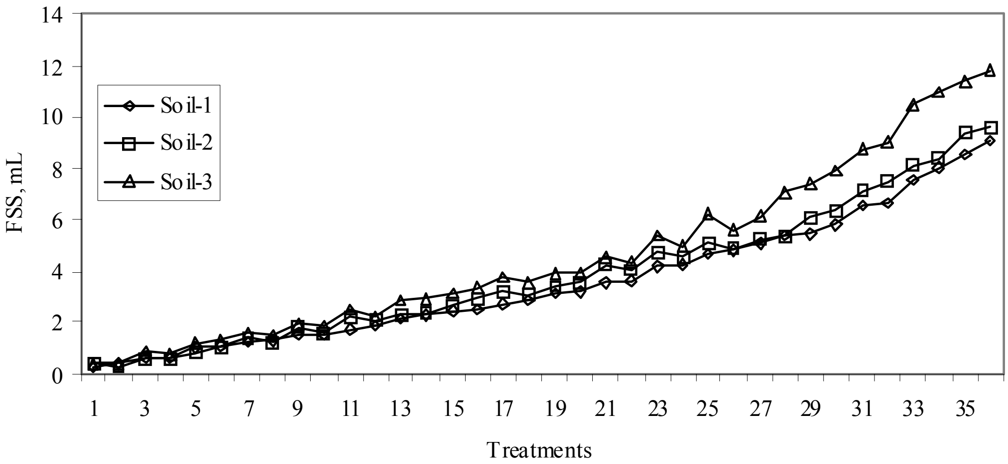

FIGURE 5 - The free settled solids (FSS) results (10 and 20 min) for different soil types

It can be seen from Fig. 5 that higher FSS values depend on the clay content, because PAM flocculates clay particles and produces aggregates. Soil-1 values are lower than the others at the range of 10.7% and 27.7%, respectively. But these differences were not found significantly ($P<0.05$). However this situation necessitates calibration of the Imhoff cone method to obtain sensitive measurements for different sediment materials in river conditions [18].

CONCLUSION

Several methods, such as acoustic, laser in situ scattering and transmissometry (LISST), are available for providing continuous sediment measurements. However, these methods are very expensive, require special training and experience and are still undergoing development [19, 20]. Turbidity sensors, which are easily readable and able to store large amounts of data, are a possible alternative.

The results of this study showed high reliability of the turbidity sensor to estimate SSC for continuous monitoring. The most important disadvantage of this method is its inability to give accurate readings at high concentrations. However, as it is accurate up to 10 g/L, this method can be used easily except in extreme flood conditions. In this study, the selected particle size distributions did not clearly affect the turbidity measurements. On the other hand, colour properties, which are caused by the effects of organic materials and waste products, have to be considered.

Comparison of the Imhoff cone method with the turbidity method showed good performance for highly concentrated sediment measurements, possibly because this method was unaffected by water quality properties. Pavanelli and Bigi [21] reported that Imhoff cone measurements are not significantly influenced by variations in particle size distribution among different samples [21]. This laboratory study shows that Imhoff cone method can be used in the measurements of SSCs. However, it is better to calibrate the method for each river cases in order to get more accurate measurements. The use of this practical and cheap method with PAM accelerated the process and increased its usability. With this modification, the measurements can be made at the sampling site without having to transport samples to the laboratory. Errors at low concentrations and measurement sensitivity can be thought of as the disadvantages of this method. The measurement precision of the graduated cone is 0.5 mL for volumes less than 10 mL; 1 mL for volumes of 10-40 mL and 2 mL for volumes ranging between 40 and 100 mL. This problem may be solved by developing digital sensors for use with Imhoff cones.

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