DEVELOPMENT OF A DIGITAL OPTICAL SENSOR SYSTEM FOR MEASURING SUSPENDED SEDIMENT CONCENTRATION

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ABSTRACT

Streams draining agricultural watersheds are always characterized by high transport of suspended sediment especially during the raining season, and result to water quality and downstream degradation. It has become imperative to continuously monitor sediment discharge so as to develop effective methods of soil and water conservation. This study aimed at developing at developing an optical sensor system for in-situ measurement of suspended sediment concentration in streams. Water samples were collected from Ebonyi River at Obollo-Etiti, Enugu State, Nigeria and used in testing the optical sensor instrument. Suspended sediment concentration readings were obtained using the developed instrument and compared with values obtained using oven-drying method in other to confirm the validity of the instrument. Linear regression equation was obtained with a coefficient of determination of $R^2 = 0.8$, which shows good comparison between the two methods. The developed optical sensor system can be used in-situ for measuring suspended sediment concentration.

KEYWORDS: Optical backscatter sensor, microcontroller, suspended sediment

1. INTRODUCTION

Streams draining intensively-used agricultural watersheds are frequently characterized by high transport of suspended sediment especially during rainfall event (Eder et al., 2010). Sedimentation is a primary and growing environmental, engineering and agricultural issue around the world (Landers et al., 2010). It is also an important index with respect to the mechanics of soil erosion, environmental impact monitoring and reservoir safety capacity (Shi and Zhang, 2012). Loss of aquatic habitats, changes in photosynthesis and visibility, and impacts from contaminants attached to transported sediments are some of the environmental impacts caused by high sedimentation (Wood and Armitage, 1997). The transport of sediment particles in rivers also, has important implications for the management of watersheds, the evaluation of land surface erosion, reservoir sedimentation, ecological habitat quality and coastal sediment budget (IAEA, 2005). Knowledge of sedimentation is also important for the development and management of water resources. High suspended sediment concentration in aquatic ecosystem decreases light penetration into the water column and poses serious threat to aquatic organisms. Therefore, clarity of a natural water body is an indicator of the condition and productivity of that aquatic system. Edwards and Glysson (1999) highlighted some of the practical needs for collecting sediment data which include: (a) For the evaluation of sediment yield with respect to different natural environmental conditions – geology, soils, climate, runoff, topography, ground cover, and watershed size; (b) For the evaluation of sediment yield with respect to different types of landuse; (c) The time distribution of sediment concentration and transport rate in streams; (d) The evaluation of erosion and deposition in channel systems; (d)The amount and particle size characteristics delivered to a water body.

The distribution of suspended sediment in water bodies can be quantified by measuring suspended sediment concentration (Guillen et al., 2000). Manual sediment sampling method by oven-drying is now obsolete, highly time-consuming and cumbersome but however provides a standard for calibrating improved sediment sampling methods. In-situ sensors for measuring suspended sediment concentration have become a suitable practical alternative as it can give high frequency measurements over a long period of time (Vousdoukas et al., 2011). The use of optical sensor systems to monitor suspended sediments in surface water bodies have been widely adopted (Sutherland, 2000). Its advantage includes simple technology, relative low cost of components, ease of deployment and potential high frequency response (Clifford, 1995). Optical backscatter sensors also offer a convenient means of estimating suspended sediment in natural waters (Hatcher et al., 2000).

The objectives of this study are to: develop an optical sensor system for in-situ measurement of suspended sediment concentration in streams and calibrate the new instrument using oven-drying method of estimating suspended sediment concentration.

2. MATERIALS AND METHODS

2.1 Methods of Measuring Suspended Sediment Concentration

Many methods exist for the determination of suspended sediment concentration in streams. Shi and Zhang (2012) however noted that due to different principles, the applicability and precision of each of the method differs considerably. These authors classified the different methods as direct and indirect methods as shown in Table 1.

Table 1: Commonly-Used Measurement Methods for Sediment Concentration

Type	Methods	Limitations	References
Direct methods	Oven-Drying Pycnometer	Sensitive to temperature and salinity content	Abrahams and Atkinson (1993), Zobisch et al. (1996)
Indirect Methods	Capacitance-based	Labour and time consuming	Li et al. (2005), Schlaberg et al. (2006)
	Acoustics	Disturb water flow state; limited scale	Hay and Sheng (1992), Thorne et al.(1993), Huang et al. (1995), Thorne and Hanes (2002)
	Optics	Sensitive to sizes, shapes and distribution of sediment	Vos et al. (2000), Campbell et al. (2005), Orwin and Smart (2005)
	Laser	Expensive, in large sizes, harmful radiation	Lei et al. (2002)
	γ-ray		

Source: Shi and Zhang (2012)

Abrahams et al. (1993) and Zobisch et al. (1996) reported that the traditional oven-drying and pycnometer methods (direct method) for estimating sediment concentration are still widely used even though they are time consuming and labour intensive. The oven-dry method of measuring suspended sediments remains the most direct and accurate but remains inadequate for measuring rapid temporal variations of suspended matter in water bodies (Guillen et al., 2000). These authors also noted that despite its inability to capture temporal variations in the field, this method is considered the best for calibration of other recent methods for determining suspended sediments. Total suspended solids can be determined using:

$$SSC\left(\frac{mg}{L}\right) = \frac{(Residue+Filter)(mg)-Filter\ (mg)}{Sample\ filterd\ (mL)} \times 1000\left(\frac{ML}{L}\right) \qquad \ldots 1$$

Indirect methods for measuring sediment concentration are based on the principles capacitance, acoustics, optics, laser and γ-rays (Shi and Zhang, 2012). The capacitance-based method is sensitive to changes in temperature and salinity in natural water bodies (Li et al., 2005; Schlaberg et al., 2006). Sediment concentration measuring instruments that are based on acoustic principles disturbs the state of streamflow, which results to changes in the stream hydrodynamic properties (Thorne and Hanes, 2002). An optical instrument emits light rays into a sample of water through light emitting diodes (LED) and then measures the reflected light with a photodiode. This reflected light is proportional to the sediment concentration in that water sample (Shi and Zhang, 2012). However, Campbell et al. (2005) stated that such optical

devices need to be calibrated against any direct method before use. Laser and γ-ray based devices have the capability to reduce noises and disturbances from outside, but are usually expensive and large in size (Lei et al., 2002).
Optical instruments have been widely used in the past to monitor suspended sediment and predict the transport of sediment in natural water bodies (Sutherland et al., 2000). Schoellhamer and Wright (2003) reported that the optical backscatter system has been used successfully as a surrogate for suspended sediment concentration in low gradient rivers. Calibrations of optical sensors are important as their measurement depends on sediment particle size, composition, shape and environmental characteristics (Sutherland et al., 2000). Sutherland et al. (2000) also noted that in-situ calibrations of optical sensors are important as it incorporates the effects of sediment quality on the instrument measurement data. Basic designs of optical meters (Omar and Matjafri, 2009) and as shown in Fig. 1 are:

(a) Nephelometer: this is used to directly measure the intensity of light scattered at an angle of 90º from the incident bean on a water sample. The amount of backscattered light is directly proportional to the amount of sediment in the light path. This type of turbidity meter produces higher precision and sensitivity and is normally used for water samples of low turbidity (EPA, 1999). Backscattering technique refers to the measurement if scattered light between 90º – 180º.

(b) Absorptiometer: This is used to measure light intensity after it has passed through the water sample. The transmitted light is measured in relation to initial beam intensity (EPA, 1999).

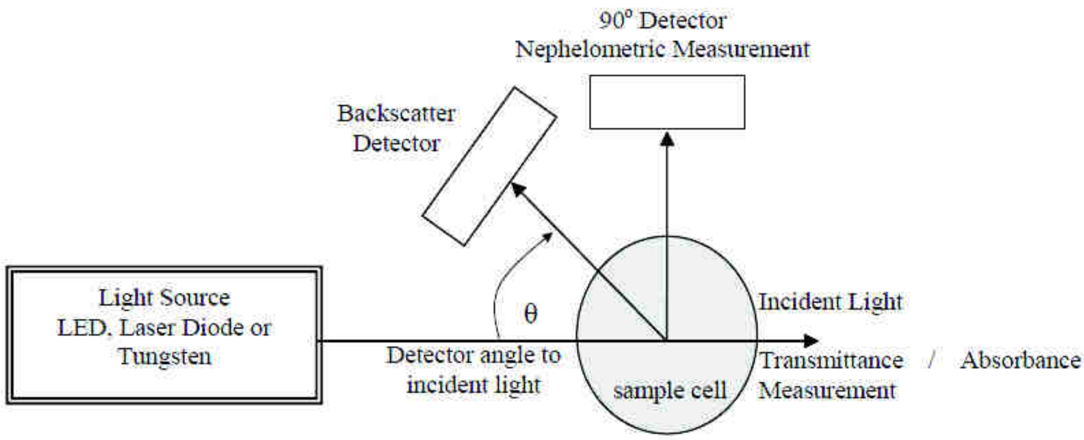

Fig. 1: Turbidity Measuring Techniques

The optical backscatter sensor measures suspended sediment concentration as a result of backscattered light from suspended sediment in water sample. The optical backscatter sensor (OBS) system works on the principle that when it emits infrared light into a water sample, a series of photodiode positioned around the emitter will detect the reelected (backscattered) light (Curtis, 2007). The amount of photocurrent detected by the sensors depends on the illuminated area of the sediment particles and provides an indirect estimate of suspended sediment concentration (Downing, 2006). An important feature of the optical backscatter system sensor is that its signal has a linear relationship with sediment concentration.

2.2 The Measurement System

The materials used for the work are microcontroller, operational amplifier (Op – amp) infrared transmitter, infra-red receiver (light dependent resistor), 7-segment display, transistor amplifier, control switch, connecting wire, resistors, diodes, variable resistors, advance current summer transistors, I.C sockets, capacitors, crystal, LED indicators, 7805 voltage regulator and 9VDC battery cap. The system block diagram and circuit diagram are shown in figure 2 and 3 respectively.

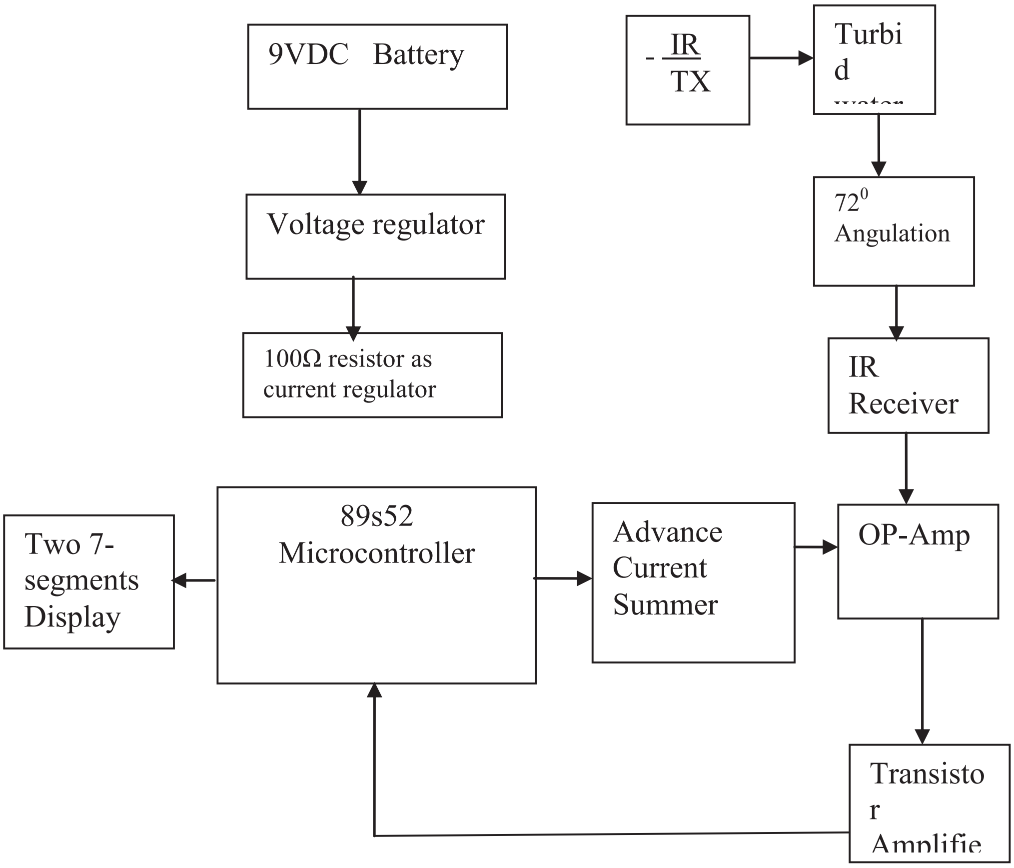

Fig. 2: The System Block Diagram

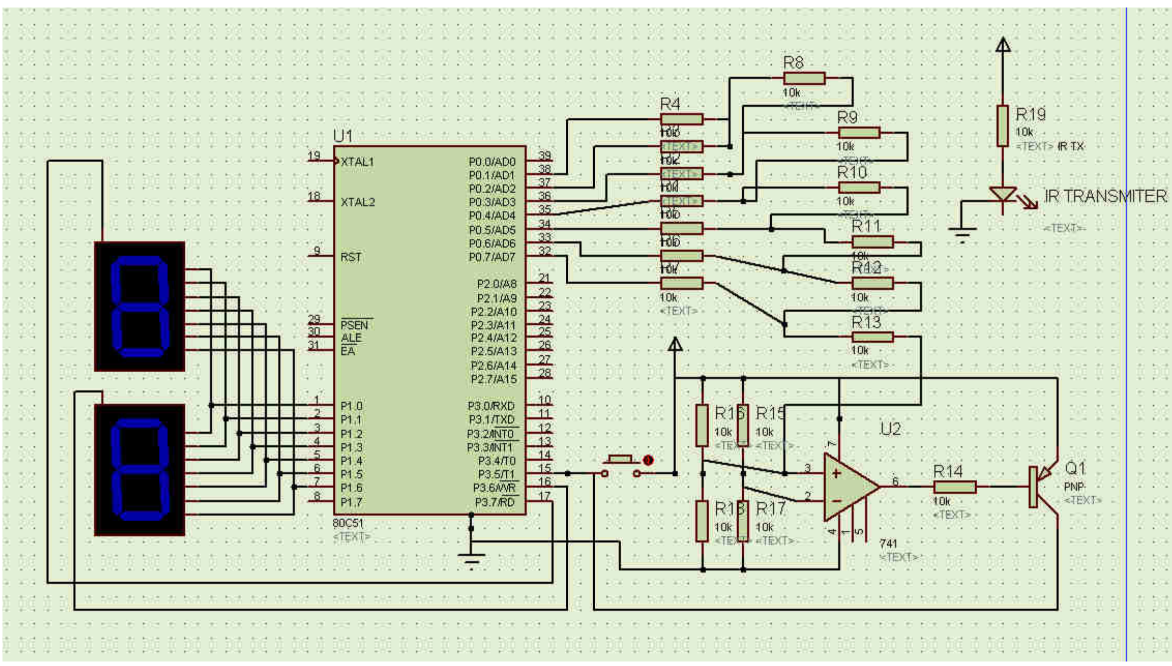

Fig. 3: Circuit Diagram

Microcontroller (MC): This is 89s52 which is an integrated circuit (I.C) of the 8051 family of microcontrollers with 40 pins dual in package (DIP) architecture. It is actually a stand-alone integrated circuit which works like a small computer as indicated by its name. It has a total of four ports for its binary data communication with the external sub-circuits like the infrared receiver, op-amp, 7-segments displays, etc. It has 128 internal general purpose registers address as 00H to 128H or OOH to 7FH (i.e. 00000000B to 01000000B). It has internal microprocessor, Timer 0 and Timer 1, RAMS, ROMs, EEPROM and ALU (Arithmetic and logic unit). The binary/digital input and output to and from the microcontroller ports and its processing of these data, its operations and preferences are controlled by the use of the hex files (i.e. hexa-decimal files) from computer software like ASM, VB.Net, C# (C sharp), JAVA, C, etc. It is not these raw codes/software that we store/burn into the microcontroller using the computer aided programmer but rather, it is a hex (equivalent) file generated from any of raw code/software by our compiler running on our computer system. No matter the programming language used, all of them will give rise to similar hex file for programming our microcontroller (MC). The MC uses an external crystal for stabilizing its clock speed together with two 30μf paper capacitors.

Operational Amplifier (Op-Amp): This is an 8-pin DIP operational amplifier sub-circuit called the 741 Op-Amp. Its major role is to compare the positive and negative voltages and currents at its input pins like pin 2 and 3 as the infra red receiver component (light dependent resistor) is placed between pin 2 and 7 while pin 7 is its V_{cc}/the terminal pin while pin 4 is its GND /ground/negative terminal pin. It can as well amplify the signal input to its pins or amplify the difference between the two signal inputs to its pins. This 741 Integrated Circuit (I.C) is also called a voltage or current comparator since it can compare the degree of positive or negative voltages/currents at its two input pins. Our LDR (serving as our infrared receiver) is connected between pin 2 and 7 of this 741 Op-Amp such that the Op-Amp will be bringing out a negative/low voltage and current output only when the infra red receiver component (light dependent resistor) stop receiving an infrared light (from our infrared transmitter). The light dependent resistor (LDR) serving as our infrared receiver will only stop receiving the infrared light if the water is clear. Our 741 Op-Amp can also stop bringing the needed voltage and current output when the LDR still receives an IR-light (from our IR reflective turbid water) but our microcontroller has counted its binary output (into our advance current summer) balancing/matching our LDR input. It is this high binary count that is being process into outputs being displayed on our two 7-segment display.

Infrared Transmitter: The system has an infrared transmitter sub-circuit. A particular value of resistor was obtained and used to keep our infrared transmitter constantly transmitting infrared light without getting burnt. This stream of infrared light is kept at angle of 78^0 from the infrared receiver (LDR) so that backscattered light (due to presence of sediment in the water) will be detected by the LDR.

Infra-red Receiver and LDR: This optical sensor instrument has an infrared receiver sub-circuit which comprises of the 741 Op-Amp sub-circuitry and it's LDR, resistors, transmitters, diodes, etc. The LDR is used as our infrared receiver as its resistance slightly decreases when it detects the slightly backscattered infrared light by suspended particles in turbid water. The slightest detection of the back scattered infrared light by our LDR will send an appreciable current to our 741 Op-Amp to make it not to give out its usual negative current until our microcontroller counts fast to a level into our advance current summer to meet the LDR matching point in our 741 Op-Amp. At the matching point of the LDR current to our 741 Op-Amp, the Op-Amp will start giving out the expected negative output current which has to be amplified and send to pin 3.5 of our 89s52 microcontroller as a detection of the matching point to enable our microcontroller to quickly process the readings with respect to time before displaying the values on the 7-segment display unit.

Connecting Wire: These are single plastic coated wires of 0.1cm diameter used in connecting our circuit according to its standard block diagram. The connecting wires are also used in connecting the external LDR and infrared transmitter component of our optical sensor system to the Op-Amp circuit which sends its feedback into pin 3.5 of our microcontroller.

Control Switch: This is the 3 by 3 pins soft switch (i.e. 6 pins Dip) that controls the 9V DC battery supply to our circuit via only its two pins out of the six pins. This switch has to be pressed inside to send the current that power on our entire circuit via the 7805 voltage regulator. For the entire system to be switched off, the switch has to be pressed again to bounce out thereby disconnecting its two pins used. An approved standard is for the entire system to be consecutively kept ON via this switch for less than 30 second and rest off for at least one minute for each turbidity reading.

7 – Segment Displays: These are electronic components that are each made from a segmented arrangement of seven light emitting diodes (LED) which are arranged to have common positive terminals of the LED. Each of these two 7-segment displays has the ability to display numbers from 0 to 9 making the two 7-segment combination capable of displaying 00 to 99 as the corresponding decimal equivalent of the digital/binary input received from port 1 of the 89s52 microcontroller. Thus, these corresponding decimal/digital/binary equivalents are also corresponding to the various matching resistances and current between the LDR (that receives our backscattered IR-light) and our advance current summer which both feeds their current output into our 741 Op-Amp integrated circuit.

Transistor Amplifiers: These are small three pins bipolar junction transistors (BJT) which are used to amplify the weak current from the 741 Op-Amp of our infrared Receiver circuit before sending their amplified current to port 3.5 of our 89s52 microcontroller. The two transistors are respectively an NPN and a PNP transistor.

2.3 Testing and Evaluation of the Instrument

The optical sensor instrument was calibrated and tested using water samples collected from Ebonyi River at Obollo-Etiti in Enugu State, Nigeria. Seven water samples were collected separately from the river for analysis. Each of the samples was analyzed for suspended sediment concentration using the optical sensor instrument and also in the laboratory by oven-drying method.

3. EVALUATION RESULTS

The readings obtained for each water sample collected using the two methods are shown in Table 2.

Table 2: Suspended Sediment Concentration Measurements

Sample No.	Instrument Readings(mg/l)	Oven-dry Readings(mg/l)
1	21	20.83
2	0	0.16
3	0	0.22
4	11	11.26
5	7	6.59
6	10	9.91
7	10	10.29

Measurements performed with the optical sensor instrument performed well with that obtained using oven-drying method and are plotted as shown in Figure 4.

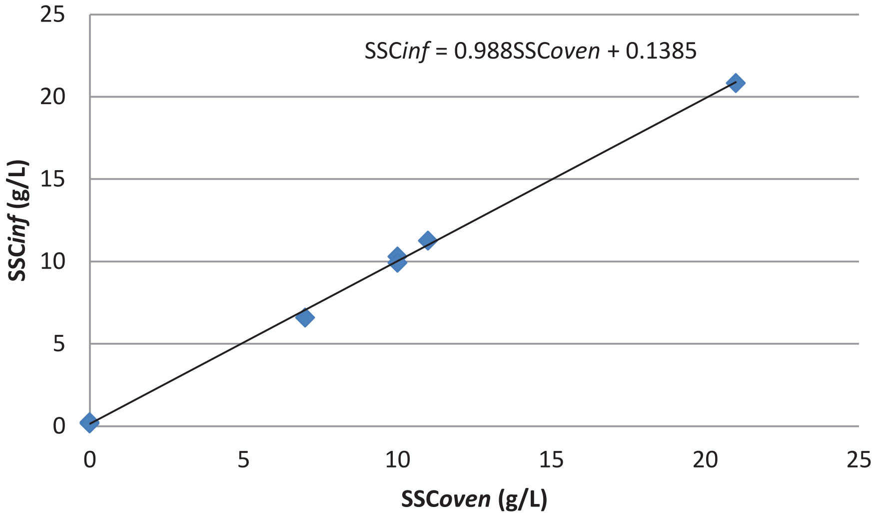

Fig. 4: Comparisons of SSC Obtained Using the Optical Sensor Instrument (SSC_{inf}) and Oven-Dry (SSC_{oven}) Methods

The linear regression equation obtained is given as:
$SSCinf = 0.988SSCoven + 0.1385$ ……………………………………………………………………………….2

Where, SSCinf = suspended sediment concentration measurement obtained using the optical sensor system; SSCoven = suspended sediment concentration measurement obtained using oven-drying method.

4. CONCLUSION

In-situ measurement of suspended sediment provides an alternative and convenient means of estimating suspended sediment concentration in streams rather than the conventional oven-drying method. The optical sensor instrument developed, offers simple technology, relative low cost of components and ease of deployment. Light dependent resistor was adopted in this design instead of photodiode because of its high sensitivity to backscattered light.

However, regular maintenance is needed to keep this digital optical sensor instrument in good working shape. Regular cleaning of the infrared component after each use to avoid biofouling should be strictly adhered to. Also, the instrument should not be left on when not in use and battery should be replaceD as at when needed.

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