A Low Cost Turbidity Sensor Development

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***Abstract*— Water turbidity measurement is important for underwater environmental monitoring. Large changes in this parameter can affect fishes catching the food. This avoids having fishes feed properly and most pellets are wasted and deposited in the seabed. In some cases, it is more important to know the variation of the turbidity in real time than a very accurate value. For this reason, we may not need very high precision in our sensor. In this paper, we show the development of a low cost turbidity sensor. Our sensor is able to take measurements in real-time and presents long useful lifetime. Consequently, it will need low maintenance. To test our system, we are going to create a set of samples with different concentrations in sea water. We will calibrate our system and we will estimate the analytical model that follows the behavior of our low cost turbidity sensor.**

Keywords-Turbidity; turbidity optical sensors; low cost sensor.

I. INTRODUCTION

Nowadays, it is important to have wide knowledge in underwater parameters because large changes can be important in some areas such as aquaculture, pollution monitoring, sewage treatment or oceanography.

The Water Framework Directive [1] proposes to measure some physicochemical parameters like temperature, dissolved oxygen or salinity, among others, to evaluate the quality of all water bodies (including marine water till one nautical mile from the coast).

In last years, the most common methods to analyze the water and to define these variables were sampling in-situ and the subsequent analysis at laboratories. The use of sensors to perform this kind of measurements is becoming increasingly common because these methods can reduce the analysis cost of the physicochemical parameters. The use of sensor nodes can be a way to eliminate the manual process of sampling because the measurements are performed automatically in the environment (river, lake, fish farm, etc.) by the sensor nodes. The use of sensors reduces costs avoiding going to the field for taking samples. When measurements and analysis are performed directly in the medium by using sensors, the sampling process is enhanced and we are sure that the number of samples is representative.

The lifetime of a physical sensor is longer than a chemical sensor. The chemical methods used at laboratories use reagents consumed during the analyses. Physical sensors also let us measure in real time. If we use several sensors forming a network along a river, it is possible to have measures along any type of environment such as a river bed or in the surrounding area of a marine fish farm. For these reasons, the use of sensor networks is growing day by day and now, it is easy to find many examples [2].

The turbidity is defined as the decrease of transparency of a water solution caused by the presence of dissolved or suspended particles. The size of particles is also important although sizes lower than 0.45μm do not affect to this parameter. These particles reflect, scatter and attenuate the light [3]. Turbidity measurements are important for environmental monitoring and management. In some cases, the sampling process is complicated and it may alter the environmental conditions. The alteration of a sample can make it not being a representative sample, so it should not be taken into account. Turbidity is expressed in Nephelometric Turbidity Units (NTU).

Turbidity values can vary by changes in the composition of the solids and some dissolved substances in water. In the seas, oceans and rivers those substances can have different origins and different effects. On one hand, the solids can come from the erosion of the emerged zones which provide nutrients to the water. On the other hand, the solids can come from different industrial effluents and in this case they can be dangerous for the environment. The suspended solids can also have a biological origin. They can be different type of microorganisms like phytoplankton, zooplankton or organic particles matter. Consequently, turbidity can indicate a wide range of situations (pollution, eutrophication or the increase of solids in the water mass). The sediments in suspension can cause several environmental damages such as benthic smothering, irritation of fish gills and the transport of absorbed contaminants. These sediments also produce an attenuation of the light penetration and this affects to the photosynthesis process [4]. The light dispersion can be used to measure the turbidity at specific wavelength and at specific angle, usually 90º [3].

In this paper, we propose the design of a low cost turbidity sensor. In addition, we have performed a set of measurements in sea water for several turbidity levels. Finally, we have performed a verification process to ensure that our system is working correctly.

The rest of this paper is structured as follows. Section 2 shows a review of the main methods which are used to measure the turbidity. Our low cost turbidity sensor is presented in Section 3. Section 4 explains the processes carried out to measure and calibrate our system. Finally, Section 5 shows our conclusion, compares the prize of our proposal with existing proposals and presents our future work.

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II. Related Work

Turbidity can be directly and quantitatively measured using several methods. In this Section, we are going to present the main ones.

A. Secchi disc and variations

Steel and Neuhausser [5] performed a study in Skagit River (Western of Washington State) where the turbidity was measured with 3 discs: horizontal black disc, horizontal Secchi disc and vertical Secchi disc. They also measured the clarity of the river with a nephelometer. Finally, they compared the results obtained by the nephelometer and the distances of the disc. These results are shown in Table I.

Larson et al. [6] addressed the possibility of reducing sources of error in measuring lake water clarity using a Secchi disk by investigating the use of beam transmissometer readings for estimating Secchi disk clarity. To do this, the authors investigated how Secchi disk works and performed the measurements in the Crater Lake in Crater Lake National Park, Oregon, USA. From their results, they extracted a prediction model to determine the water turbidity. The results demonstrated that this prediction model reliably estimated Secchi disk depths and could be used to significantly expand optical observations in an environment where the conditions for standardized Secchi disk deployments are limited.

B. Optical sensors

An optical turbidimeter bases the turbidity measure on the light detection at different angles. The name of the instruments changes according to the angle used to perform the measurements. If the angle is 90º, it is called nephelometer. If the angle is 0º, it is called absorbimeters. Because the turbidity is a value which depends on the quantity of suspended solids in water, the solids intercept the line of light causing scattering and absorption, so not all light arrives to the detector [7].

When the turbidity is low, the light scattered away from its original direction is lower. This is one of the most important problems when we try to measure low turbidity levels with a turbidimeter. To improve these measures, A. F. B. Omar and M. Z. B. MatJafri proposed the use of light detector in different angles, from 90 to 180º. This is called backscattering [7]. Other problems that optical sensors can have are the fouling, the high variability of the size and the reflectivity of particles [8].

Laser sensors are being investigated as an alternative method to the nephelometers. T. S. Melis et al. [9] developed a study of turbidity in Colorado River. They used Laser In-Situ Scattering and Transmissometry to measure the sand and thinner material. They measured the sensor output voltage in mV and the concentration of the sediments in mg/l. Their results showed the correlation in (1):

$$Sensor\ Output(mV) = [sediments]\left(\frac{mg}{l}\right) \cdot 0.971 - 1.942 \quad (1)$$

The interval of sediments concentration measured was from 10mg/l to 160 mg/L, and the recorded voltages were from 10 mV to 150 mV. Their results show that LISST-100-B is suitable for providing data of suspended solids of the Colorado’s River, The measurement results presented a high confidence bound. It was around 95%.

Gray et al. in 2003 [10] took continuous in-situ turbidity measurements with the purpose of estimating the sediment concentrations in the Kansas River. They found a correlation of R=0.93, and the formula that relates the suspended sediment concentration (SSC) with the water turbidity was (2):

$$SSC\left(\frac{mg}{l}\right) = 1.797 * NTU * 0.905 \quad (2)$$

The range of values of their experience was between 10mg/l to 4000mg/l and between 10 NTU to 4000 NTU.

C. Acoustic sensors

Other method to measure the turbidity is the use of an Acoustic Dolpper Velocimeter (ADV) with backscattering. Chanson et al. [11] performed an experiment where the correlation between acoustic backscatter intensity and the sediment concentration showed a monotonic increase instead of the linear relationship. It is similar than the one that we can see between turbidity and suspended sediments [11]. They prepared some experiences in the laboratory and other ones in the estuarine zone of Eprapah Creek with low sediments concentration (Eastern Australia). Their results showed that the quality of water and the composition of sediments affect to the calibration curves. For this reason, each sensor must be calibrated with the water and soil material of the study area.

D. Other methods

There are several papers where authors use satellite images (LANDSAT) to measure the turbidity in water bodies [12]. However, this methodology is not interesting for our purposes because we need a continuous measurement process. In addition, we want to have values in a short period of time. Satellite systems cannot provide us short temporal scale (every hour), enough spatial resolution (few meters) and low economic prices.

TABLE I. MEASURES AND CORRELATION BETWEEN DISC AND NEPHELOMETER

Type of disc	**Results**			
	Authors	***Depth***	***NTU***	***Value of r***
Horizontal black disc	E. A. Steel and S. Neuhausser [5]	3.5 – 5 (cm)	1 - 4	r =-0.86
Horizontal Secchi disc	E. A. Steel and S. Neuhausser [5]	4 – 5 (cm)	1 - 4	r = -0.85
Vertical Secchi disc	E. A. Steel and S. Neuhausser [5]	3 – 5.5 (cm)	1 - 4	r =-0.86

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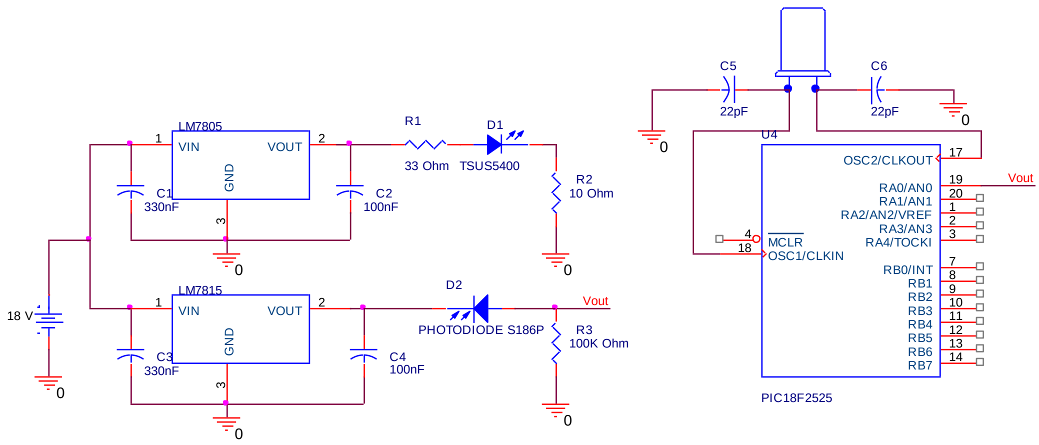

Figure 1. Esquematic of our low cost turbidity sensor.

The pressure-differential principle can also be used to measure the turbidity. This method is promising to be used in highly concentrated stream flows [10]. But, we cannot use this method because our measures are performed in the sea where the concentration of sediments is usually low.

III. Low Cost Turbidity Sensor Proposal

In this section, we are going to present our low cost turbidity sensor. This section also shows its fabrication cost.

A. *Our proposal*

Our system is based on the use of an infrared LED as a source of emission and a photodiode as a receiver. Both elements are disposed at an angle of 180° and they are faced so that the photodiode can capture maximum infrared light from the LED. The infrared LED and the photodiode are placed at a distance of 4 cm.

TSUS5400 is an infrared emitting diode using GaAs technology molded in a blue-gray tinted plastic package. This infrared diode has a peak wavelength of 950 nm and its angle of half intensity is 22°.

S186P is a high speed and high sensitive photodiode in a plastic package. It is an IR filter, spectrally matched to GaAs or GaAs on GaAlAs IR emitters ($\geq$ 900 nm). The large active area combined with a flat case gives a high sensitivity at a wide viewing angle. The angle of half sensitivity is ±65º. S186P is covered by a plastic case with IR filter (950 mm) and it is suitable for near infrared radiation.

The transmitter circuit is powered by a voltage of 5V while the photodiode is supplied with a voltage of 15V. To achieve these values, we use two voltage regulators of LM78XX series, where XX is 05, for the transmitter circuit, and 15 for the receiver circuit. This type of regulatory permits a maximum output current of 1 A.

In our system, the water turbidity is proportional to the potential difference registered in the resistor R3. To process the voltage values recorded in the receiver circuit a microcontroller is used. This element is responsible for taking the data and performs the necessary calculations to estimate the turbidity value of the analyzed solution. The model we have used is the PIC18F2525 which is fed at 5V. We can use the microcontroller to display information via a LCD display or to send the information through the RS232 port to a personal computer.

Fig. 1 shows the schematic of our turbidity sensor.

B. *Cost of our turbidity sensor*

The electronic components used in our turbidity sensor can be easily found. We have asked for their prize in a Spanish electronic distributor. The prizes of the main components are shown in Table II.

TABLE II. Prize of Main Components

Component	Prize of components (in €)
Voltage regulator LM7805	0.80
Voltage regulator LM7815	0.86
IR LED TSUS5400	0.176
Photodiode S186P	0.94
PIC 18F2525	5.71
All Capacitors	2
oscilator	2.18

As Table II shows, the prize of the needed electronic components is very low

IV. Test Bench and Measurement Results

Our main problem when taking the turbidity measurements was to determine the turbidity level of each solution test probe. These values were necessary in order to estimate the analytical model of our system. This section explains the process carried out to take the measurements and the calibration process of our system.

A. *Used elements*

On the one hand, we employed a calibrated turbidimeter to know the accurate value of turbidity of each test probe to be measured. The used device is Turbidimeter Hach 2100N. This turbidimeter can take measurements in two modes (ratio mode and non-ratio mode). We have used the non-ratio mode, which measures the turbidity by using a detector placed at 90 degrees.

All measures have been performed for seawater. The salinity of the sea water depends on the geographic position. Our samples were taken from the east coast of the Mediterranean Sea (Spain). The average water salinity ranges from 36 to 38 grams per liter. pH is 8.07 and its temperature is 21.1ºC.

Regarding to the elements used to generate the dissolutions with different turbidities, we have used a mixture of clay and silt. The silt is a loose material with a grain size between fine sand and clay. It is an incoherent classic sediment transported in suspension by rivers. The particle size of our sample is between 0.002 mm and 0.06 mm.

The glass containers used in our test had a volume of 30ml. First, took four calibration samples in the turbidimeter Hach 2100N. Then, we took 10 samples with turbidities. Next, we performed more samples at lower concentrations than at higher ones because lower concentrations are most usual. The concentration samples we prepared are shown in Table III. We have selected samples with low turbidity because for devices low turbidities are more difficult to measure these.

Fig. 2 shows the relationship between the amount of solute and the concentration of the test probe.

We can extract the relationship between both values using (3) with a correlation coefficient of 0.9999.

$$C = 33.333 \cdot S + 10^{-13} \quad (3)$$

where C represents the concentration of the dissolution in mg/l and S represents the amount of solute in g. Because the independent term is extremely small value, we can approximate this relationship as (4):

$$C = 33.333 \cdot S \quad (4)$$

Each prepared sample has a turbidity value. Fig. 3 shows the relationship between the concentration of silt-clay in ocean water and the water turbidity value.

Equation (5) shows the relationship between both parameters with a correlation coefficient of 0.9999.

$$T = 0.517 \cdot C + 3.0027 \quad (5)$$

where, T represents the turbidity in NTU and C is the dissolution concentration in mg/l.

Finally, we can express the turbidity as a function of the amount of clay-silt dissolved combining (4) and (5). It is given by (6).

$$T = 17233.161 \cdot S + 3.002 \quad (6)$$

where, T represents the turbidity in NTU and S, the amount of solute in g.

B. *Obtained results*

After measuring the turbidity of each sample, we placed each one in our system in order to measure their voltage values.

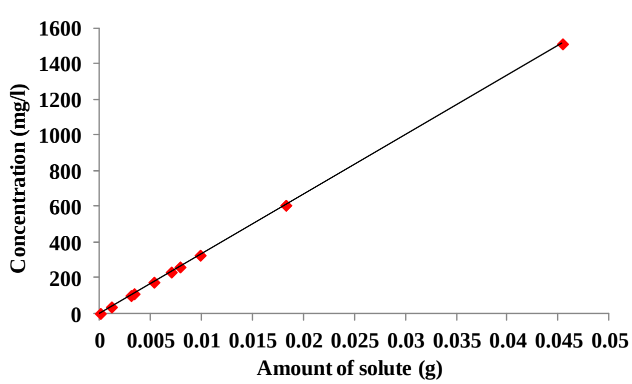

Figure 2. Value of dissolution concentration as a function of the amount of solute.

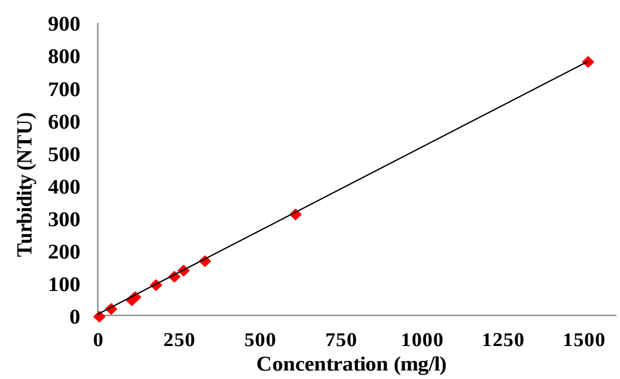

Figure 3. Value of dissolution turbidity as a function of the dissolution concentration.

TABLE III. SAMPLES, THEIR CONCENTRATION AND TURBIDITY

Sample	Samples and Their Concentration									
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Amount of clay and silt added (g)	0	0.00109	0.00301	0.00331	0.00526	0.00696	0.00782	0.0098	0.01821	0.0453
Concentration (mg/l)	0	36.33	100.33	110.44	175.33	232.1	260.66	326.66	607	1512.59
Turbidity (NTU)	0.072	23.7	50.8	60.1	97.2	123	142	171	385	785

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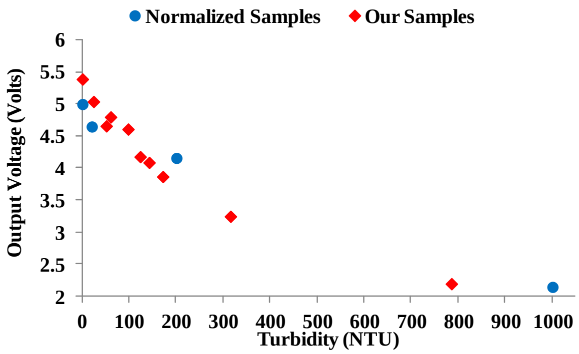

Figure 4. Output voltage as a function of the turbidity value.

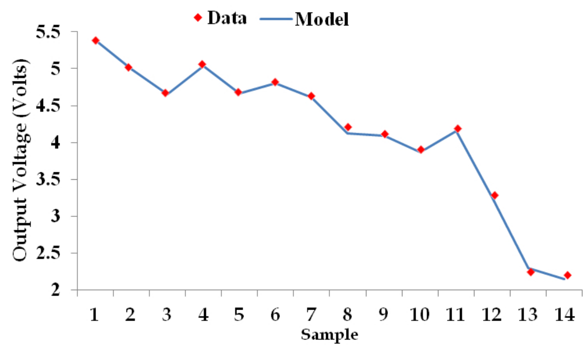

Figure 5. Gathered Data vs. Model response

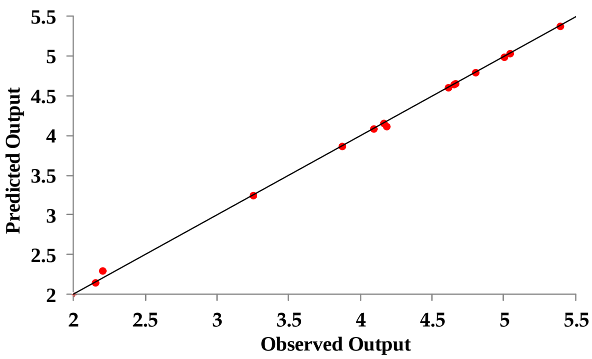

Figure 6. Observed output vs. Predicted output

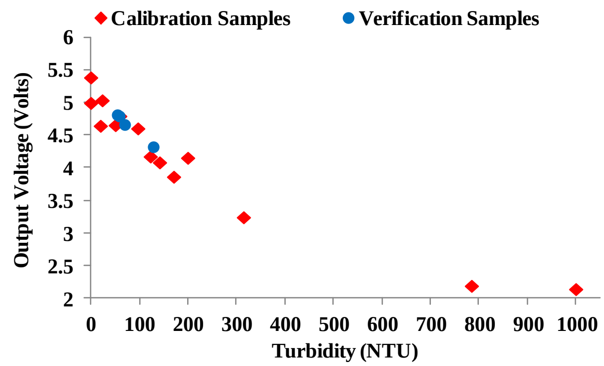

Figure 7. Output voltage value for the verification samples

$$y = a + \frac{b}{(c + x + d \cdot \sin(e + f \cdot x) + g * \cos(h + i \cdot \sin(j + k \cdot x)))} \quad (7)$$

$$v = 0.9767 + \frac{1550}{(353.4 + t + 31.69 \cdot \sin(5.435 + 2.004 \cdot t) + 19.34 * \cos(6.141 + 18.85 \cdot \sin(5.443 + 2.004 \cdot t)))} \quad (8)$$

Fig. 4 shows the gathered output voltage value for each the turbidity. The prepared samples are shown in red while the standard samples are shown in blue. We can see that the behavior of our system is not linear. Its behavior can be approximated to a linear function up turbidity values of 300 NTU. But, for higher turbidity values, the behavior is closer to a curve function with an error lower than ±1%.

We used Eureqa Formulize [13] to estimate the analytical model. Using these 14 samples, we have estimated the analytical expression that models the behavior of our turbidity sensor. The program provided us several models but the one which provided best results is the model show in (7). Equation (8) relates the turbidity with the output voltage of our system, where, *t* represents the turbidity in NTU and *v* the output voltage.

Fig. 5 shows the obtained values for each sample in blue (estimated, using (8)). The obtained output voltage values for the same samples are shown in red. As Fig.5 shows both values are close.

Finally, in order to check the accuracy of our system, we represent the output voltage value predicted by our model versus the value of output voltage obtained by our system. Fig. 6 shows this relation. As Fig.6 shows, most of the points remain in the black line, which indicates a perfect match.

From Eq. 8, Fig. 5 and Fig. 6, we observe that our equation has a correlation coefficient of 0.99897 and its maximum error is 0.1 Volts.

C. Verification

In order to test the accuracy of our system, we have compared the values obtained by the turbidimeter Hach 2100N and the values obtained by our turbidity sensor.

In the verification test, we have chosen low concentration samples, which means low turbidity. In these situations, it is more difficult to measure accurately the turbidity. Commercial Turbidimeters have also problems in low turbidities. In order to perform this step, we have prepared four samples with unknown concentrations. The output voltages obtained for each sample are shown in table IV. Estimating the turbidity values by using (8), we have introduced our samples (in blue) in (7). It shows the behavior of our system. In order to compare the estimated turbidity values with the measured values and the error for the four samples, we provide Table V.

TABLE IV. UNKNOWN SAMPLES

Samples	**Samples to verify**			
	1	***2***	***3***	***4***
Output Votlage	4.67 V	4.82 V	4.80 V	4.33 V

TABLE V. VERIFICATION RESULTS

Results	Samples to verify			
	1	*2*	*3*	*4*
Turbidity obtained	73.66	55.36	57.80	115.2
Turbidity (Hach 2100N)	70	54.8	59	129
Error in Turbidity (%)	5.22	1.03	2.03	10.75

The biggest error in turbidity is registered for the fourth sample (10.75 %) meanwhile the samples with lower turbidity present an error of 1.03 %.

V. CONCLUSION

In this paper, we have presented the circuit of a low cost turbidity sensor. In addition, we have performed several tests in sea water to model and to calibrate the operation of our turbidity sensor.

Although sea water usually presents low turbidity levels and we have focused our system in lower values; we have also added some values of higher turbidity level. For low turbidity values, we have obtained a maximum error of 5.22%. We have also compared the prize of our device with commercial ones in Table VI.

TABLE VI. COMMERCIAL TURBIDIMETERS

Model	Commercial turbidimeters		
	Manufacturer	*NTU range*	*Prize*
PCE TUM 20	PCE Holding GmbH	0 - 1000	285 €
HI 88713-02	Hanna Instruments Deutschland GmbH	0 - 4000	1,287 €
HI 98713-02	Hanna Instruments Deutschland GmbH	0 - 1000	924.75 €
Turbiquant® 1100 IR	Merck Millipore	0 - 1000	1,570 €
Turbiquant® 3000 IR	Merck Millipore	0 - 10000	4.240 €

Seeing these prizes, we think we are able to develop a low cost turbidity sensor.

In our future work, we will improve our system. First, we believe that there are some external factors such as the measurement system disposal and the electronic elements placement, significantly affect the sampling process. So, we will improve our measurement system.

On the other hand, we will improve the way to find the analytical relationship between the measured parameters by adding more mathematical operations. Additionally, we would like to perform other calibrations with others waters.

After these improvements, we would like to test our sensor in marine fish farms [14].

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REFERENCES

[1] Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. Official Journal of the European Communities. Available at: http://faolex.fao.org/cgi-bin/faolex.exe?rec_id=017501&database=FAOLEX&search_type=link&table=result&lang=eng&format_name=@ERALL (Last access: April 22, 2013).

[2] M Garcia, D Bri, S Sendra, and J Lloret, Practical deployments of wireless sensor networks: A survey, International Journal on Advances in Networks and Services vol. 3, no 1 & 2, 2010, pp. 170-185.

[3] Directive 2001/42/EC of the European Parliament and of the Council of 27 June 2001 on the assessment of the effects of certain plans and programmes on the environment. Official Journal of the European Communities. Available at: http://faolex.fao.org/docs/pdf/eur34996.pdf (Last access: June 10, 2013).

[4] A. C. Ziegler, "Issues related to use of turbidity measurements as a surrogate for suspended sediment". Turbidity and Other Sediment Surrogates Workshop, Reno, Nevada, USA, April 30 – May 2, 2002.

[5] E. A. Steel and S. Neuhausser, "A comparison of methods for measuring visual water clarity", Journal of the North American Benthological Society; vol. 21, no. 2, 2002, pp. 326-335

[6] G. L. Larson, R. L. Hoffman, B.R. Hargreaves, and R. W.Collier, "Predicting Secchi disk depth from average beam attenuation in a deep, ultra-clear lake". Hydrobiologia, vol. 574, no. 1, 2007, pp. 141-148.

[7] A. F. Bin Omar and M. Z. Bin MatJafri, "Turbidimeter design and analysis: a review on optical fiber sensors for the measurement of water turbidity", Sensors; vol. 9, no 10, 2009, pp. 8311-8335.

[8] D. H. Schoellhamer and S. A. Wright "Continuous measurement of suspended-sediment discharge in rivers by use of optical backscatterance sensors" Workshop on Erosion and Sediment Transport Measurement in Rivers: Technological and Methodological Advances, Oslo, Norway, June 19-21, 2002, pp. 28-36

[9] T. S. Melis, D. J. Topping, and D. M. Rubin, "Testing laser-based sensors for continuous in situ monitoring of suspended sediment in the Colorado River, Arizona", Workshop on Erosion and Sediment Transport Measurement in Rivers: Technological and Methodological Advances, Oslo, Norway, 19-21 June 2002. Pp.21-27.

[10] J. R. Gray, "US Geological Survey research on surrogate measurements for suspended sediment" 1st Interagency Conference on Research in Watersheds Benson, Arizona, USA, Oct. 27-30, 2003, pp. 95-100.

[11] H. Chanson, M. Takeuchi, and M. Trevethan "Using turbidity and acoustic backscatter intensity as surrogate measures of suspended sediment concentration in a small subtropical estuary" Journal of Environmental Management, vol. 88, no 4, 2008, pp. 1406-1416.

[12] R. Li and J. Li,"Satellite remote sensing technology for lake water clarity monitoring: an overview". Environmental Informatics Archives, Vol.2, 2004, pp. 893-901.

[13] Eureqa Formulize web site. Available at: http://formulize.nutonian.com (Last access: April 22, 2013).

[14] M. Garcia, S. Sendra, G. Lloret, and J. Lloret, "Monitoring and control sensor system for fish feeding in marine fish farms". IET Communications; vol. 5, no. 12, 2011, pp. 1682-1690.