

Estimation of suspended sediment concentration based on water samples' turbidity in aquatic environments

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ABSTRACT

The primary method for measuring suspended sediment concentration (SSC) is the gravimetric analysis of water–sediment samples collected using grab or bottle samplers from the sea or rivers at regular or irregular intervals. Although this method is reliable, it requires substantial effort and cost for sampling, transportation to the laboratory, and long processing times for sample analysis. This study aims to introduce an alternative method for estimating SSC based on measuring the water turbidity (WT) of water–sediment samples. A case study was conducted in the coastal waters of the Caspian Sea to determine the Pearson correlation coefficients between these two parameters.

In-lab calibration between SSC and WT data using site-specific sampling is essential, as the mean particle size and particle size distribution (PSD) can vary considerably in space and time. Therefore, several water–sediment samples were collected from inside and outside the basins of Amirabad and Anzali ports, and grain-size analyses were performed. Subsequently, sediment–seawater mixtures (50 L) were prepared stepwise at eleven concentrations: 125, 250, 500 mg/L and 1, 2, 3, 4, 5, 6, 7, and 8 g/L. For each concentration, WT was measured using a HATCH 2100N turbidimeter and an auxiliary TSW-20 turbidity sensor.

Sieve and hydrometer analyses were conducted, and particle size distribution curves for two water–sediment samples from inside the basins of Amirabad and Anzali ports were plotted. The D_{10} , D_{30} , D_{50} , D_{60} , and D_{90} statistics were extracted and compared. WT values for the eleven sediment mixtures were measured using the HATCH 2100N turbidimeter. Pearson correlation coefficients between SSC and WT were calculated for linear, second-order polynomial, third-order polynomial, and power regression fittings, and SSC–WT correlation curves were drawn.

A step-by-step alternative method for estimating SSC based on WT measurements using a laboratory turbidimeter was designed. Applying this method to the case study yielded Pearson correlation coefficients between SSC and WT for water–sediment samples from Amirabad Port. The proposed approach is suitable for use in a real-time and continuous sediment monitoring network, enabling the integration of WT as a surrogate parameter for SSC in the national sediment monitoring database.

1. Introduction

Understanding the sedimentation regime in an aquatic basin is essential not only for comprehending the gradual transformation of the shoreline and for the optimal design of ports and coastal structures, but also for effective operational management, improving efficiency and performance, and reducing maintenance costs throughout the service life of the port.

The suspended sediment concentration (SSC), expressed in grams per litre (g/L), is an essential physical indicator for better understanding the sedimentation regime, including bed erosion, deposition, accumulation, and sediment transport in lakes, river deltas, estuaries, and the coastal waters of seas and oceans. The mechanism of formation and transport of sediments and suspended sediment load includes cohesive particles (clay minerals and organic matter) and non-cohesive particles (silt, sand, and gravel), as shown in Figure 1. In Figure 1(A), the seabed is dense (rocky or coral), while in Figure 1(B) the seabed is non-dense (muddy), each having a different effect on the amount of SSC [1–3].

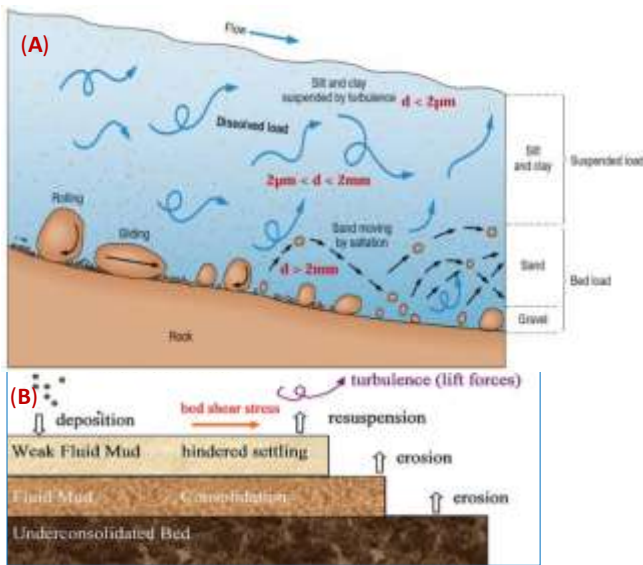


Figure 1. (A) Cohesive and non-cohesive sediments and mechanism of sediment transport in water; (B) The transport of mud model and the interaction between mud and the bed [1, 2, 3]

If the flow velocity is sufficiently strong, some of the smaller and lighter particles deposited at the bottom of a river can be lifted into the water column and remain suspended. The size of particles that can be carried as suspended load depends on the flow velocity: the higher the velocity, the greater the suspension force acting on sediment particles. Larger and heavier particles are more likely to settle out during upward-downward current motion unless the velocity increases to generate greater turbulence along the bed.

Conversely, a reduction in flow velocity can cause suspended sediment to settle.

Suspended sediment can also behave differently at various depths within the water column. In river mouths and coastal areas, sediment dynamics are influenced not only by downstream flow velocity but also by marine currents, tides, waves, diverse geological settings of the watershed, seasonal and climatic effects, storms, pollution, and other environmental processes. For these reasons, understanding sedimentary processes and developing predictive models are challenging tasks [4–6].

The first step toward overcoming this challenge is to establish a sufficiently dense sediment database covering the study area. Due to the diversity and complexity of sedimentary processes, spatial variation in hydrodynamic conditions, and the lack of consistent time-series observations, continuous SSC monitoring within a measurement network with adequate spatial and temporal resolution is necessary.

Traditionally, SSC has been measured gravimetrically by collecting samples from specific locations in waterways or port basins, transporting them to a laboratory, and determining the water volume and sediment mass using oceanographic and river engineering laboratory equipment. In recent years, some portable particle size analysers (PSA) have been developed for in situ sediment analysis, as shown in Figure 2 [7].

However, SSC data obtained through either traditional sampling and laboratory analysis or portable advanced equipment cannot be collected easily, continuously, and in sufficient quantity over the entire study area.

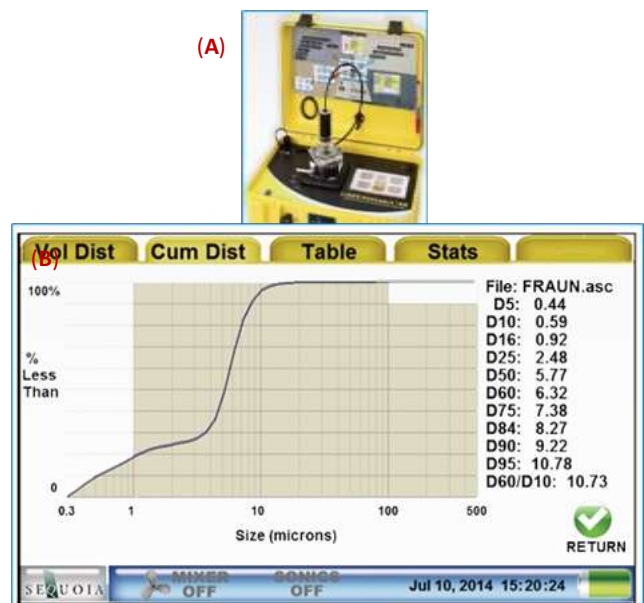


Figure 2. (A) LISST-Portable Low-Cost Particle Size Analyser (PSA); (B) Touch panel screenshot of size distribution [7]

An alternative approach is to measure a physical parameter that is strongly correlated with SSC and then estimate SSC from it by deriving correlation coefficients. A suitable physical parameter with simple measurement technology and cost-effectiveness is water turbidity (WT). WT can be measured in situ by installing an automated sensor at the desired location, with real-time data recorded in nephelometric turbidity units (NTU) [8, 9].

For better illustration, Figure 3 shows a satellite image of turbidity variation in the coastal waters of Nowshahr Port and at the mouths of the Mashalak and Moghadam Rivers. As can be seen, turbidity is highest at the river mouths and disperses into the surrounding coastal waters depending on the direction and magnitude of the current velocity vectors [10].



Figure 3. Satellite image of water turbidity variation due to suspended sediment concentration (SSC) in the coastal waters of Nowshahr Port

Accordingly, the higher the SSC in the water, the greater the WT, and vice versa. Thus, by measuring WT across a sufficiently dense monitoring network, the SSC distribution can be estimated.

This paper presents the research steps taken to determine the correlation coefficients between WT and SSC for water–sediment samples from coastal areas near Amirabad and Anzali ports, located on the eastern and western coasts of the Caspian Sea. The research approach is designed so that the results can be applied as a reference model for other northern and southern ports of the country, ultimately contributing to the creation of a comprehensive sediment monitoring database.

2. Materials and Methods

2.1. Water-sediment samples

As mentioned earlier, before measuring SSC in an aquatic basin, it is necessary to understand the spatial variation of sediment texture within the basin as well

as its seasonal changes. The NTU unit, as the measurement unit for WT, is not directly comparable across all aquatic basins and sensors. In other words, it cannot be assumed that a WT of 1000 NTU at two different ports (or at the same port with two different sensors) corresponds to the same SSC value in g/L. This is because turbidity depends not only on SSC but also on the particle size distribution (PSD), shape and physical properties of the particles—such as colour (reflectivity), density, refractive index, and surface roughness [11, 12].

Therefore, understanding the sediment texture of each aquatic environment and performing a calibration between WT and SSC using water–sediment samples collected from the same study site is of utmost importance.

In this study, the coastal waters of the Caspian Sea were selected as the research area, specifically Amirabad Port in the east and Anzali Port in the west. These sites were chosen based on the following:

The southern Caspian Sea, from a sedimentological perspective, shows variations in sediment composition and grain size from west to east. The southern shores (land area) are very gently sloped, which prevents large waves from reaching the coast. As a result, the coastal sediments are fine-grained and marshy, with indistinct shorelines in some areas [13].

The coastal sediments range mainly from sandy to muddy. The eastern part of Gorgan Bay toward the north is muddy, with local sandy deposits only at the mouth of the Gorgan River. Moving westward across the southern bay, sediments transition from muddy to sandy. The Miankaleh Peninsula coast is predominantly sandy [14, 15].

Based on this, two water–sediment samples were collected from inside the basins of Amirabad and Anzali Ports with geographical coordinates shown in Table 1 and red markers and yellow ovals in Figure 4 from the dredging contractor of the Ports and Maritime Organisation (PMO). Additionally, 100 litres of seawater were collected from the same sampling sites to ensure laboratory calibration conditions closely matched the field environment.

2.2. Laboratory Devices and Equipment

The required devices and equipment for this study included:

Standard sieves and a hydrometer for generating grain-size distribution curves.

HATCH 2100N turbidimeter for measuring turbidity of sediment–water mixtures.

Magnetic stirrer for homogenizing sediment mixtures.

Auxiliary TSW-20 turbidity sensor for measuring turbidity of sediment samples in a 250 mL beaker.

The lab instruments and equipment mentioned above are shown in Figure 5.

In Amirabad port, six points are adjacent to the eastern and western arms of the pond; two points, 2 and 5, are adjacent to the coastal waters. In Bandar Anzali, five points are adjacent to the eastern and western arms of

Table 1. Geographical coordinates of sediment sampling locations (inside and outside basins)

Row	Location	Latitude	Longitude
A Port Amirabad			
2	AMA-1-In	36° 51' 41.01" N	53° 22' 23.91" E
3	AMA-2-In	36° 51' 29.61" N	53° 22' 28.78" E
4	AMA-2	36° 51' 28.44" N	53° 21' 07.20" E
5	AMA-5	36° 51' 45.60" N	53° 23' 10.68" E
B Port Anzali			
1	ANZ-1-In	37° 28' 45.60" N	49° 27' 37.24" E
2	ANZ-2	37° 29' 00.96" N	49° 26' 55.68" E
3	ANZ-8	37° 28' 35.04" N	49° 27' 00.72" E



Figure 4. (A) Satellite image of Amirabad Port sampling locations (outside basin – PMO project, inside basin – this study); (B) Satellite image of Anzali Port sampling locations (outside basin – PMO project, inside basin – this study)

2.3. Measurement data

National project reports from the Water Research Institute (WRI) in collaboration with PMO on Caspian Sea sediment field studies were used, containing sediment data from 12 sampling points in Amirabad and 8 points in Anzali. [16].

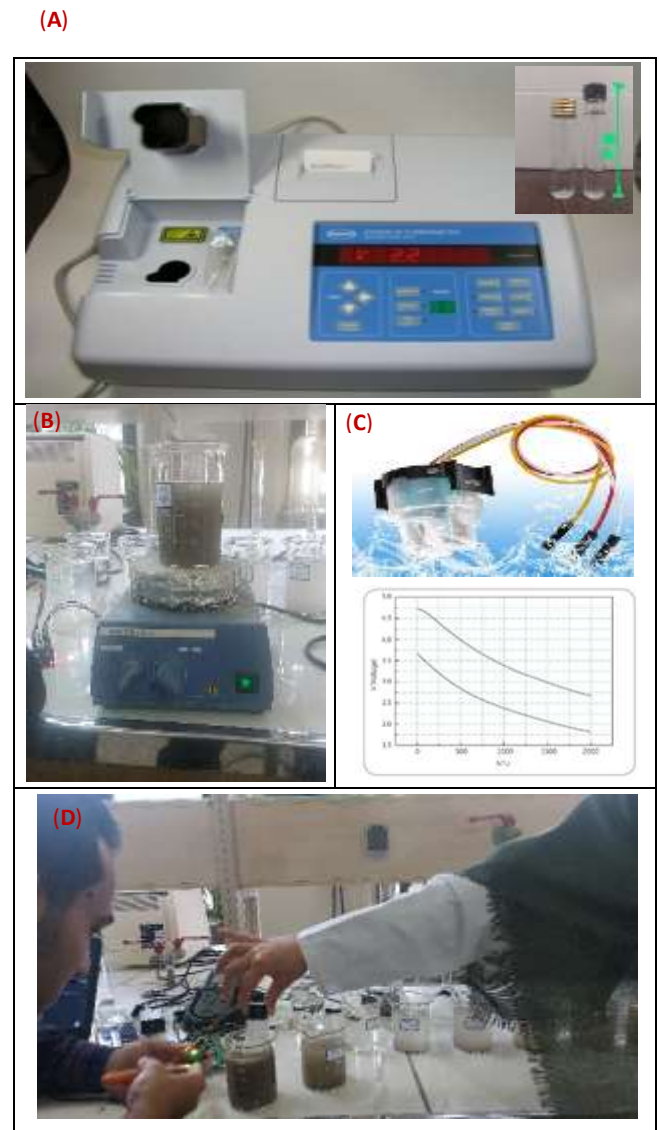


Figure 5. (A) HATCH 2100N turbidimeter; (B) Magnetic stirrer; (C) TSW-20 water turbidity sensor; (D) Data reading from TSW-20 sensor

in the pond, of which two points 2 and 8 are adjacent to the coastal waters. The geographical coordinates of two points 2 and 5 of Amirabad port and two points 2 and 8 of Anzali port are also shown in Table 1. They are shown in Figure 4 with a yellow indicator for the points outside the pond and a red indicator for the points inside the pond. In this study, the data of the points outside the pond from the WRI-PMO project and the results of the gradation test of the samples have been precisely investigated.

2.4. Laboratory Calibration Method

2.4.1. Laboratory Main Tests

Two main tests were performed: (1) grain-size analysis to determine sediment texture, and (2) turbidity measurements for prepared sediment–water mixtures. Grain-size analysis followed ASTM D422-63 (Reapproved 2002), combining standard sieve analysis for particles >75 µm and hydrometer analysis for particles <75 µm.

2.4.2. Proposed Six-step Calibration Method

When a certified reference turbidity sensor is available, placing it in the sediment–water mixture allows direct calibration of other sensors. In this study, due to the unavailability of an affordable certified reference, an alternative six-step calibration method was used:

Step-1: Collect fine sediment (<75 µm) from the target site and prepare in 25 g and 50 g portions.

Step-2: Place 50 litres of seawater from the same site into an 80 L container, install a magnetic stirrer and the target turbidity sensor.

Step-3: Prepare sediment mixtures with concentrations from 0.25 g/L to 8 g/L, keeping the stirrer running at optimal speed.

Step-4: At each step, take a 10 mL sample, place it in the HATCH 2100N turbidimeter cell, and record WT in NTU.

Step-5: Simultaneously record WT from the TSW-20 sensor in the stirred mixture.

Step-6: Plot SSC–Turbidity curves based on HATCH 2100N measurements.

3. Results and Discussion

3.1. Grain-Size Analysis and Coastal Sediment Texture

Grain-size distribution curves for samples taken from Points 1 and 2 inside the Amirabad Port basin and Points 2 and 5 outside the basin (adjacent coastal waters) are shown in Figures 6 and 7. These data were extracted from the PMO–WRI sediment study report.

From these curves, the grain-size percentiles D₁₀, D₃₀, D₅₀, D₆₀, and D₉₀ were calculated for each sample and are presented in Table 2.

Analysis of these values shows that more than 90% of the sediment inside the basin at points AMA-1-In and AMA-2-In consists of silt and silty sand, with only about 10% clay-silt at AMA-1-In. In contrast, more than 98% of the coastal sediment at AMA-2 consists of sand (with <2% silt), and the AMA-5 sample is nearly 100% sand.

Thus, the southern Caspian coast in the Amirabad study area consists mainly (up to 90%) of non-cohesive silty-sand sediments, with particle sizes ranging from 63 to 285 µm inside the basin and 70 to 290 µm outside the basin. These ranges can be divided into two

subranges—63–150 µm and 150–290 µm—for further calibration analysis.

Grain-size curves for one sample inside Anzali Port (ANZ-1-In) and two samples from coastal waters

Row	Sample	D ₁₀ (µm)	D ₃₀	D ₅₀	D ₆₀	D ₉₀
1	AMA-1-In	10	69	105	129	236
2	AMA-2-In	18	137	207	229	285
3	AMA-2	90	140	180	290	290
4	AMA-5	70	90	100	170	170

outside the basin (ANZ-2 and ANZ-8) are shown in Table 3 and Figure 8.

Results show that over 90% of the sediment inside Anzali basin at ANZ-1-In is silt and silty sand, with ~10% clay-silt. Coastal sediment at ANZ-2 is >98% sand, while ANZ-8 is almost 100% sand.

Table 2. D₁₀, D₃₀, D₅₀, D₆₀, and D₉₀ of Amirabad sediment samples

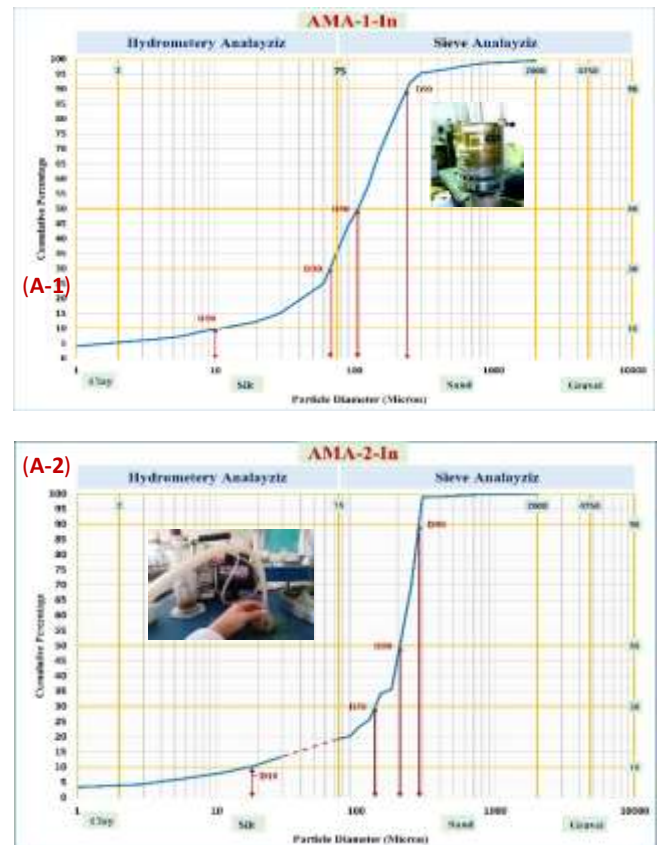


Figure 6. Grain-size distribution curves of two sediment samples inside the Amirabad Port basin

3.2. Calibration of WT and SSC

3.2.1 Selection of Regression Relationship

For estimating SSC from WT, various empirical relationships have been used in previous studies. The SSC–WT relationship varies with particle size, PSD,

and site-specific water properties. An example of this dependency on mean grain size (D_{50}) is shown in Figure 9 [17, 18].

Sometimes, a single regression equation is insufficient for the full WT range, requiring separate fits for different WT or SSC intervals, as shown in Table 4.



Figure 7. Grain-size distribution curves of two sediment samples outside the Amirabad Port basin (from PMO sediment project – WRI [16])

Table 3. D_{10} , D_{30} , D_{50} , D_{60} , and D_{90} of Anzali sediment samples



Figure 8. (A) Grain-size distribution curve of the sample inside the Anzali Port basin (this study)



Figure 8. (B)-Outside the Anzali basin (from PMO sediment project – WRI [16])

Although there is still no uniform proposed method for a formal and specific relationship for SSC-WT, nevertheless, in a number of recent studies, the relationships presented in Table 5 have been more sought after [17, 18, 19, 20, 21, 22, 23].

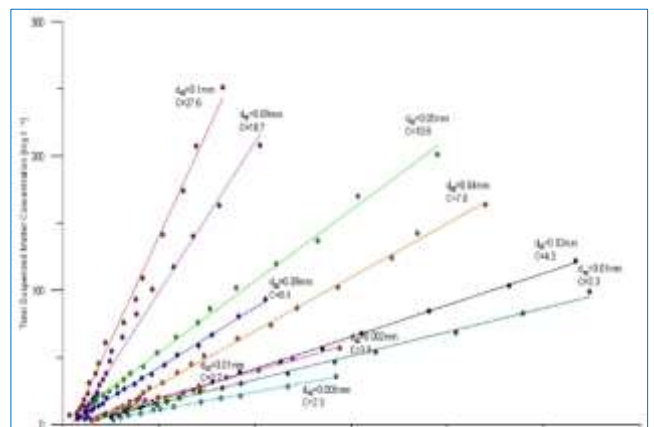


Figure 9. Increase in regression slope with increasing mean grain size (D_{50}) [18]

Table 4. WT and SSC intervals for SSC–WT regression

Row	SSC intervals (grm/L)	WT intervals (NTU)
1	1 < SSC < 5	0 < WT < 10
2	5 < SSC < 10	10 < WT < 100
3	10 < SSC < 30	100 < WT < 1000
4	SSC > 30	1000 < WT < 4000

Table 5. Several regression equations for SSC-WT

(1)	$SSC = f(WT)$	One variable
Linear	$SSC = a \cdot (WT) + b$	
Polynomial	$SSC = a \cdot (WT)^2 + b \cdot (WT) + c$	
Polynomial	$SSC = a \cdot (WT)^3 + b \cdot (WT)^2 + c \cdot (WT) + d$	
Power	$SSC = a \cdot (WT)^b$	
(2)	More than one variable	
	$SSC = f(WT, Color, D_{50})$	
	Note: SSC in ppm, WT in NTU, D_{50} in micron	

3.2.2 Calibration and Pearson Correlation Coefficients

Following the proposed six-step method, sediment–water mixtures for samples from Amirabad and Anzali were prepared at concentrations of 250 mg/L, 500 mg/L, and 1–8 g/L. WT was measured with both the HATCH 2100N turbidimeter and the auxiliary TSW-20 sensor.

Pearson correlation coefficients for linear, quadratic, cubic, and power-law regressions were calculated using relationship (1):

$$PCC = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n s_{qr} \cdot (x_i - \bar{x}) \sum_{i=1}^n s_{qr} \cdot (y_i - \bar{y})}} \quad (1)$$

for SSC–WT relationships (see Table 6). Calibration curves are shown in Figure 10.

4. Conclusion

A step-by-step laboratory method was developed for estimating SSC based on WT measurements using a turbidimeter and an auxiliary sensor. Applying this method to samples from Amirabad and Anzali ports produced high Pearson correlation coefficients for linear, quadratic, cubic, and power-law regressions. The proposed approach is suitable for integration into a real-time and continuous sediment monitoring network, where WT serves as a surrogate parameter for SSC in national monitoring programs.

Table 6. Pearson correlation coefficients for SSC–WT regressions

Sample	SSC-WT Pierson correlation coefficients			
	Linear	Polynomial -Order2	Polynomial-Order3	Power
AMA-1-In	0.966	0.984	0.986	0.980
AMA-2-In	0.972	0.995	0.995	0.984
ANZ-1-In	0.959	0.998	0.998	0.964

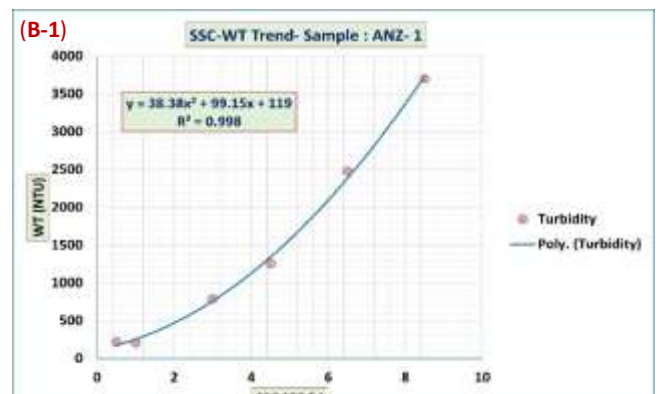
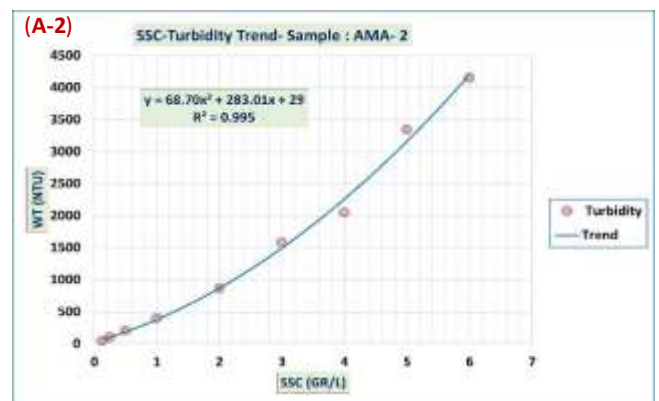
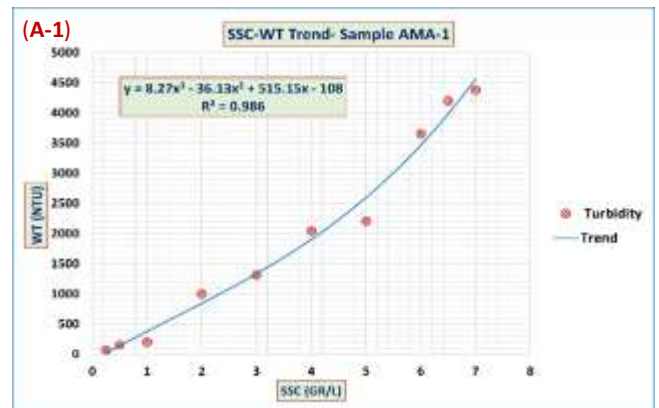


Figure 10. (A) Calibration curves for AMA-1-In and AMA-2-In and (B) ANZ-1-In samples

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