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Evaluation of Different Atmospheric Correction Methods Prior to the Estimation of Total Dissolved Solids Concentrations from Satellite Imagery

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Abstract- **Surface water quality is degraded by the presence of numerous types of pollution produced by anthropogenic activities. Hence, surface water quality monitoring and assessment is essential. Conventional approaches of surface water quality assessment are expensive, tedious, and labor-intensive. On the other hand, remote sensing techniques are an effective tool for determining the quality of surface water. Satellite images should be atmospherically corrected prior to using them in the determination of surface water quality parameters (SWQPs). Therefore, The purpose of this research is to assess the outputs from various atmospheric correction methods, such as Dark Object Subtraction (DOS), Fast Line of sight Atmospheric Analysis of Hypercubes (FLAASH), Quick Atmospheric Correction (QUAC), and Atmospheric Correction for OLI lite (ACOLITE) in order to estimate total dissolved solids concentrations (TDS) over the study area of the whole province of New Brunswick, Canada. A TDS acquisition model was evaluated and validated in order to obtain TDS concentrations from atmospherically corrected data. The results obtained from the TDS retrieval model demonstrated that the DOS method provided the most suitable remote sensing reflectance values for coastal blue, red, and shortwave infrared-2 spectral bands with a determination coefficient (R^2= 0.76), root mean square error (RMSE = 0.76 mg/l), and significant value (P-value < 0.001).**

Keywords- **Surface water quality, atmospheric correction, Dark object subtraction, Total dissolved solids.**

I. INTRODUCTION

The vast increase in human activity over the past few decades has had a negative impact on water bodies, particularly in industrial areas. As a result, it is anticipated that the water shortage, which has worsened over the past few years, will continue in the future. Therefore, updated information on water quality is crucial [1]. Water quality is a general description of the properties of water in terms of physical, chemical, and biological characteristics. Water bodies are degraded by the presence of junk, heavy metals, and suspended solids [2].

Bearing that in mind, the previous studies of estimating surface water quality parameters are reviewed. Traditional water quality assessment and evaluation techniques are expensive, tedious, and labor-intensive. Moreover, these techniques are accurate at discrete points. On the other hand, It is unable to offer instantaneous spatial and temporal overviews [3]. Accordingly, it is possible to estimate SWQP concentrations using satellite imagery. Hence, remote sensing techniques can be utilized for continuous surface water quality assessment by estimating SWQPS across an area rather than a single sampling site, without the need for field trips or sampling [4].

The presence of the atmosphere significantly degrades the surface of the earth as seen from an aircraft or spacecraft. This degradation involves a reduction of reflected light and loss of contrast due to the scattering of sunlight by aerosols and molecules in the atmosphere. For remote sensing implementations, such as the assessment of SWQPs, the atmospheric effects must be eliminated from the imagery in order to obtain the spectral reflectance of the materials. The process of eliminating atmospheric effects is called atmospheric correction [5].

Several atmospheric correction algorithms and codes have been applied to image processing softwares, however; there is disagreement regarding the best algorithm to use imagery data for assessing water quality. As a result, choosing the best method depends on reducing atmospheric interference with the minimum error and matching the corrected image reflectance with the actual ground reflectance [5].

II. METHODOLOGY

A. Study area

In the eastern part of Canada, New Brunswick is the largest and one of the three maritime provinces, as shown in Figure 1. The province is bordered to the north by Quebec, to the east by the Atlantic Ocean, to the south by the Bay of Fundy, and to the west by the US state of Maine. This province is about 83% forested, with the Appalachian Mountains occupying the northern half.

Figure 1. Boundaries of New Brunswick, Canada [7].

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Additionally, it has a continental climate with mild summers and cold winters. There are about 2,500 lakes and 60,000 kilometers of streams and rivers in the province, including three major rivers; Mirimichi, Petit Kodiak, and Saint John rivers [6].

B. Landsat 8 satellite imagery data

Landsat was developed by the United States Geological Survey (USGS) cooperated with the National Aeronautics and Space Administration (NASA). NASA develops spacecraft and remote sensing devices prior to satellite launch and performance verification, while USGS manages all ground reception, data distribution, and product generation [8]. The entire set of Landsat 8 scenes can be downloaded for free from the Landsat website maintained by the USGS. There are two instruments in the Landsat 8: the Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS), which give a spatial resolution of 30 m in visible, NIR, and SWIR bands; a spatial resolution of 100 m in thermal bands; and a spatial resolution of 15 m in a panchromatic band. In this study, Landsat 8 OLI sensor was used to monitor SWQPs due to the data quality and radiometric quantization (12 bits) [9]. In our study, seven Landsat 8 satellite images were collected at various dates and zones to present the maximum variation in the TDS concentrations, as depicted in Table 1 and Figure 2 USGS processed Landsat 8 OLI imagery using Standard Terrain Correction (Level 1T). The Level 1T product was geometrically corrected to the UTM projection and WGS 84 datum.

Table 1. The World Reference System (WRS), UTM zone, and date of the selected images over the study area.

C. WRS Path- Row	UTM zone	Date
Path 9 – Row 27	20	13-9-2017
Path 9 – Row 28	20	21-5-2016
Path 10 – Row 27	19	25-8-2019
Path 10 – Row 28	19	25-8-2019
Path 10 – Row 29	19	8-7-2019
Path 11 – Row 27	19	14-9-2018
Path 11 – Row 28	19	14-9-2018

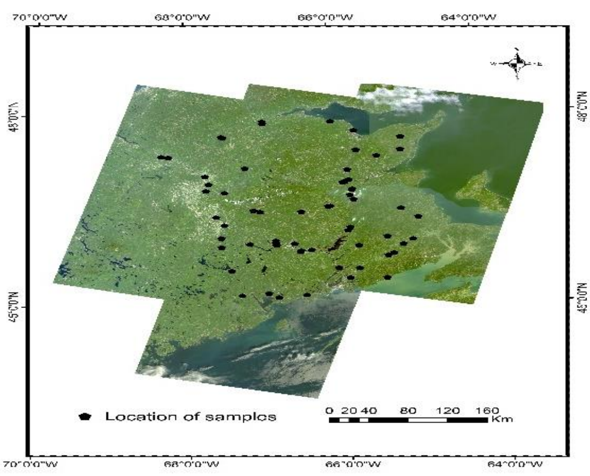

Figure 2. Landsat 8 images of the chosen study site and the locations of the samples [10].

The reflectance product is acquired from a wide range of digital numbers (0-65535). Therefore, the USGS scaled the obtained values by multiplying them with a factor of 0.0001 to get values ranging from 0 to 1. Following the geometric correction and rescaling values, the images were subjected to additional processing in order to remove the atmospheric distortions. This is called the atmospheric correction process and it will be described in the following section.

D. Assessment of atmospheric correction methods

Four atmospheric correction techniques, such as DOS, QUAC, FLAASH, and ACOLITE were performed and evaluated, in order to eliminate the atmospheric distortions. These methods are divided into two types: in-scene atmospheric correction methods and model-based methods. Atmospheric correction techniques, such as DOS, QUAC ACOLITE, and ACOLITE are in-scene methods, while FLAASH is a model-based method.

The DOS algorithm is very efficient, especially for visible wavelengths. The DOS approach assumes that the pixel with the lowest digital number should equal zero. According to the DOS principle, visible and near-infrared wavelengths are responsible for the majority of the signal from dark objects that reaches the sensor [11]. Therefore, dark target pixels are used as indicators for estimating the amount of upwelling radiance. To reduce this effect, the values from the darkest objects are deducted from every pixel in the image within the corresponding band, as shown in Equations (1) to (5) [12].

$$\rho_{sur} = (\pi * (L_\lambda - L_p) * d^2) / (T_v * E_{sun\lambda} * \cos\theta * T_z + E_{down}) \quad (1)$$

$$L_p = L_{\lambda\,\min} - L_{DO1\,\%} \quad (2)$$

$$L_{\lambda\,\min} = M_L * DN_{min} + A_L \quad (3)$$

$$L_{DO1\,\%} = (0.01 * T_v * E_{sun\lambda} * \cos\theta * T_z + E_{down}) / (\pi * d^2) \quad (4)$$

$$E_{sun\lambda} = (\pi * d^2 * RADIANCE_{max}) / (REFLECTANC_{max}) \quad (5)$$

Where L_λ is the sensor's aperture's spectral radiance; L_p is the path radiance; d is the distance between the sun and earth in astronomical units; T_z is the illumination-direction atmospheric transmittance; T_v is the viewing angle's atmospheric transmittance; $E_{sun\lambda}$ is the solar radiation; E_{down} is the downwelling diffuse irradiance; $L_{DO1\,\%}$ is the dark object radiance; $L_{\lambda\,\min}$ is the radiance corresponding to the minimum digital number; DN_{min} is the minimum pixel value; A_L is the additive scaling factor; and M_L is the multiplicative scaling factor.

The ACOLITE method was evaluated by the Royal Belgian Institute for Natural Sciences (RBINS). This method allows for quick and easy processing of Operational Land Imager (OLI) data for inland, coastal, and marine waters. ACOLITE computes mean values for solar irradiance, rayleigh optical thickness, ozone thickness, and water ingestion based on the OLI relative reflectance. However, the effects of foam and whitecap on reflective surfaces in water systems were unaffected by ACOLITE [13].

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QUAC is an in-scene technique. This method performs the correction on multispectral and hyperspectral imagery within visible and short wave near-infrared spectral range from 0.4 to 2.5 µm, and can also allow for any view angle or solar elevation angle. QUAC method is based on finding the average reflectance of various materials spectra, whereas the input data can be radiance, reflectance, or uncalibrated units. QUAC technique responds very well with scenes that contain diverse materials, such as water, greenery, soil, and man-made structures. On the other hand, scenes over oceans or other large bodies of water should not be rendered with QUAC [5]. The QUAC method can be expressed, as shown in Equations (6) and (7), whereas ρ_{sur} is the surface reflectance pixel; ρ_{ave} is the average reflectance of the nearby pixels, L_{obs} is the observed surface pixel's sensor radiance, offset is the minimum pixel value for each band, Gain equals 1 / B, and A, B, and C are parameters taken from the in-scene spectral data.

$$L_{obs} = (\mathrm{A} + \mathrm{C}\ \rho_{ave}) + \mathrm{B}\ \rho_{sur} \tag{6}$$

$$\rho_{sur} = \mathrm{Gain}\ (L_{obs} - \mathrm{offset}) \tag{7}$$

FLAASH is a model-based atmospheric correction method. It is an atmospheric correction technique, which fixes wavelengths in the visible, NIR, and SWIR bands. Its performance relies on the input data, such as optical depth, initial visibility, aerosol-type model, and the amount of water vapour. The FLAASH method attempts to solve a radioactive transfer equation to model atmospheric effects, as shown in Equations (8) and (9), whereas L is the light received by the sensor for the single pixel, ρ is the surface reflectance of the pixel, S is the accumulated sunlight reflection and diffusion by atmospheric particles, ρe is the pixel's and its surroundings' average surface reflectance, L_a is the backscattered radiance from the atmosphere, which penetrates the sensor, L_e is the average spatial radiance image, and A and B are the coefficients that are determined by atmospherical and geometrical conditions [12].

$$\mathrm{L} = (A\ \rho\ /\ 1 -\ \rho e\ S) + (B\ \rho e\ /\ 1 -\ \rho e\ S) + L_a \tag{8}$$

$$L_e = ((A + B)\rho e\ /\ 1 -\ \rho e\ S) + L_a \tag{9}$$

The term $(A\ \rho\ /\ 1 -\ \rho e\ S)$ represents the radiance that directly penetrates the sensor from the target surface, while the term $(B\ \rho e\ /\ 1 -\ \rho e\ S)$ represents the total radiation that penetrates the sensor from the surface through the atmosphere [12].

The DOS, QUAC, and FLAASH atmospheric correction techniques were successfully applied to the study area, however; the ACOLITE method failed in the atmospheric correction because the output bands were minimized to only four bands with geometric distortion. Therefore, this method has been excluded from the comparison.

E. In situ measurements of TDS concentration.

During 2016, 2017, 2018, and 2019, sixty-one water sampling points were collected and distributed randomly across the whole selected study site over several field trips during summer, spring, and autumn to represent the maximum variation of TDS concentrations. However, twelve water sample points were neglected due to cloud coverage. To effectively carry out this study, the water samples were gathered just underneath the water surface and at the closest acquisition time from Landsat 8 satellite imagery of the selected study site, as depicted in Figure 2. TDS concentration is the amount of dissolved matter in water that remains after all of the water has been evaporated. At each station, TDS concentrations were measured and analyzed using the recommended American Public Health Association standard procedures (APHA) [14].

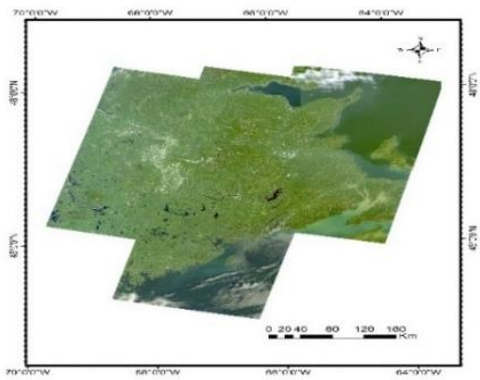
III. RESULTS AND DISCUSSION

A. Generating atmospherically corrected images

Three atmospheric correction techniques were successfully performed in the study area. The necessary input for all methods was prepared, then the different models were run independently. As shown in Figure 3, the DOS and QUAC images were found brighter than the FLAASH image. Additionally, the variance between the spectral values of vegetation and water bodies is clear in the DOS images compared to the other atmospherically corrected methods.

B. Measuring concentrations of TDS

Forty-seven sampling points were selected to measure quantities of TDS according to standard methods suggested by APHA. To model the study area, water samples were divided into two datasets: a calibration dataset (70% of the selected samples) and a validation dataset (30% of the selected samples). In this context, thirty-four samples were utilized for the model development, whereas 13 samples were utilized for the validation process. The concentration of TDS was found to be ranged from 12.401 to 382 mg/l with an average of 61.7 mg/l.



(A)

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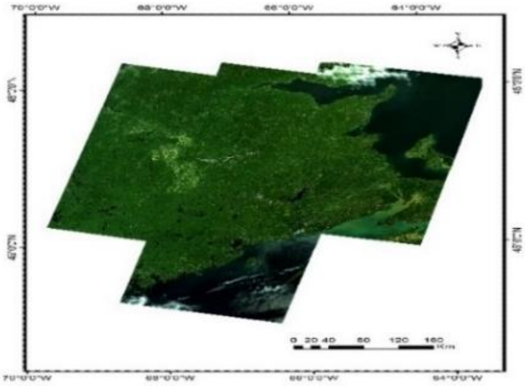

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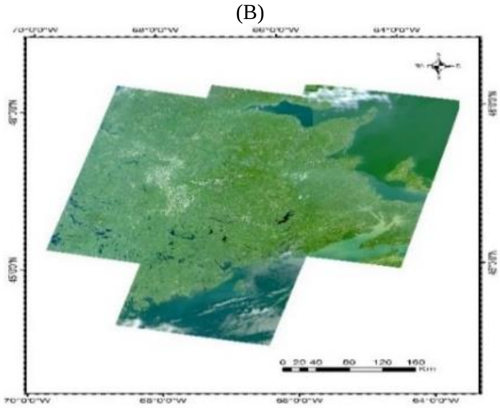

(C)

Figure 3. The atmospherically corrected images (A) for the DOS method, (B) for the FLAASH method, and (C) for the QUAC method.

C. TDS calibration and validation model

In this study, the stepwise regression method (SWR) was applied to develop models for estimating TDS concentrations from atmospherically corrected satellite imagery. The SWR method was chosen for its ability to optimize the developed model by choosing the most important independent variables from the obtainable dataset.

The entire study site was modeled using (70% of the collected dataset) for the calibration model and the rest (30% of the collected dataset) for the validation model. The best-fitting models for the statical relationships between TDS concentrations and various atmospheric correction methods data were explained in Table 2. The reliability of the developed models was examined using various statistical parameters, such as the R^2, RMSE, P-value, and the equation of the regression line.

The Landsat 8 surface reflectance data obtained from each atmospheric correction method, which showed the highest correlation with TDS concentrations, were included in the mathematical modelling process. The developed models between TDS concentrations and each atmospheric correction data were illustrated in Figure 4. The TDS concentrations were found to be significantly correlated to the DOS method compared to the other methods. The results from the DOS model were: (R^2 = 0.76, RMSE = 19.58 mg/l, and P-value < 0.001). On the other hand, the results of the QUAC model were: (R^2 = 0.36, RMSE = 52.53 mg/l, and P-value < 0.001), while the results of the FLAASH model were found to be the least correlated model to the TDS concentrations with (R^2 = 0.25, RMSE = 52.50 mg/l, and P-value < 0.001).

Table 2. The regression equations between the measured TDS concentrations and the corresponding reflectance values of each atmospheric correction method.

Atmospheric correction methods	TDS concentration models
DOS method	$Y = 48.59 - 3.61 * \frac{B_5}{B_4} + 7111.50 * B_1 * B_7 - 4324.90 * B_7 * B_4$
QUAC method	$Y = -68.45 + 455.117 * \frac{B_2}{B_5} - 148.35 * \frac{B_4}{B_6} + 93.88 * \frac{B_3}{B_1}$
FLAASH method	$Y = 65.28 - 19.30 * \frac{B_3}{B_1}$

Using the validation dataset, the predicted values of TDS concentrations were validated to ensure the robustness of the developed models., as shown in Figure 4. The validation model for the DOS method remained very stable with (R^2 = 0.72, RMSE = 11.97 mg/l, and P-value < 0.001). On the other hand, the QUAC model was found to be (R^2 = 0.25, RMSE = 29.55 mg/l, and P-value = 0.07), and the FLAASH model was found to be (R^2 = 0.01, RMSE = 28.00 mg/l, and P-value = 0.73). The significant value for QUAC and FLAASH models were found to be more than 0.05; therefore, these models are not significant.

IV. CONCLUSION

In this study, several atmospheric correction techniques, such as ACOLITE, DOS, FLAASH, and QUAC methods were applied and tested to estimate TDS concentrations. The TDS retrieval errors from atmospheric correction images were computed using various models in order to explain the most relevant atmospheric correction method prior to their use in water quality assessment. Considering the achieved TDS predictions, The DOS method demonstrated the best performance in terms of TDS predictions. Other atmospheric correction methods failed to produce a significant model for determining TDS concentration.

Despite the fact that this study evaluated various atmospheric correction methods applied to an inland waterbody, the conclusions presented that the DOS method is applicable to all water systems. Atmospheric correction methods were confirmed to play an important role in TDS concentration retrieval. For this reason, prior to mapping TDS concentrations, atmospheric correction techniques should be tested to minimize atmospheric distortion.

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Conflicts of Interest: The authors declare that there is no conflict of interest.

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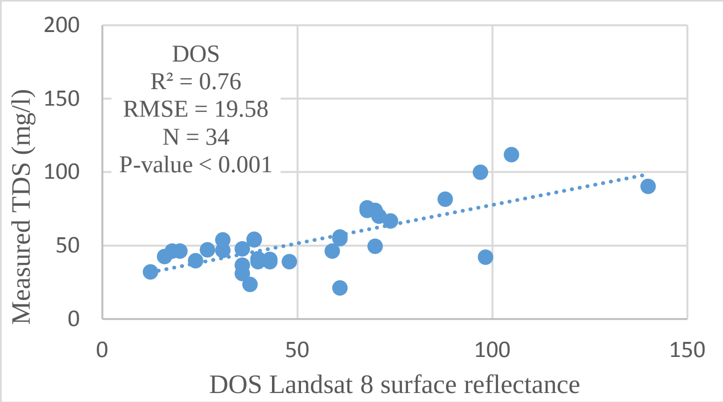
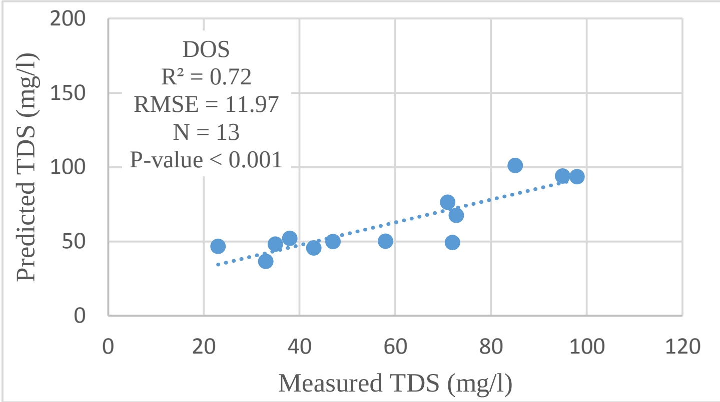


(A)



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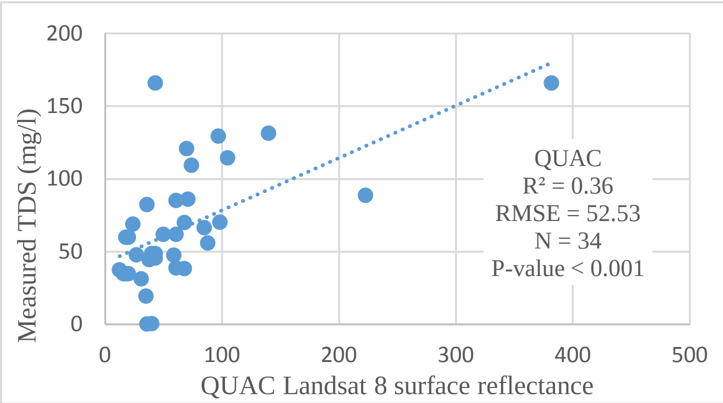
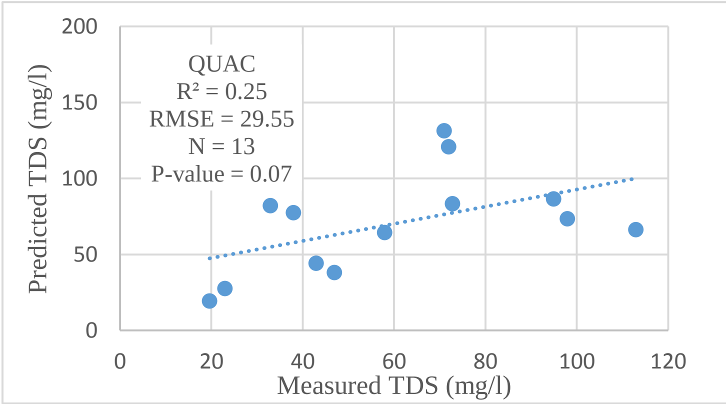
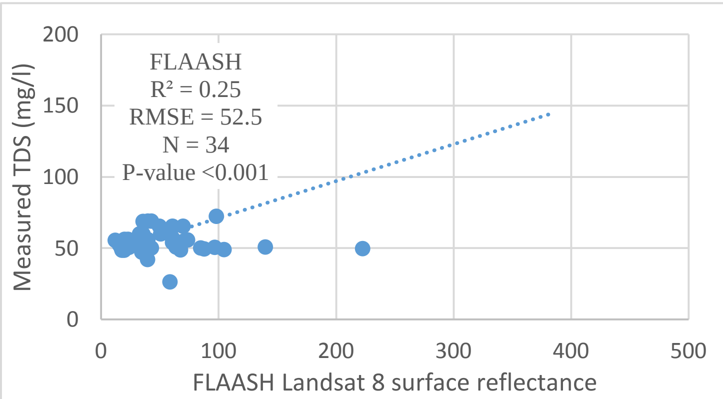


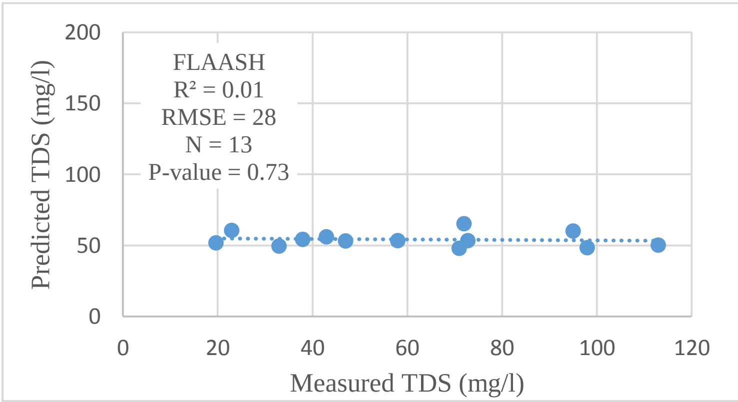
(C)



(D)



(E)



(F)

Figure 4. The calibration and validation models for each atmospheric correction method (A and B) for the DOS method, (C and D) for the QUAC method, and (E and F) for the FLAASH method, respectively.

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