Mapping Underwater Bathymetry of a Shallow River from Satellite Multispectral Imagery

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Abstract: Rivers play an important role in water supply, waterway transport, and riverine species habitations. The underwater depth of a river channel is a fundamental geometric element and a key input to studies for the aforementioned and other applications. Traditional in-situ field surveys for flow depth measurements would incur high costs and encounter technical and/or logistical difficulties, particularly for river channels of large extents, very shallow channels, and remote, inaccessible channels. Recent advances in satellite remote sensing of inland water bodies like rivers, streams, and creeks have allowed mapping flow depth in an inexpensive, convenient, and efficient manner. The purpose of this paper is to demonstrate the retrieval of river flow depth from high-resolution (1.2 m) WorldView-3 satellite imagery. The depth retrieval methods are based on the ratio of top-of-atmosphere reflectance between two pairing wavelength bands of multispectral imagery. The originality of the methods lies in using analytical relationships without resorting to ground data of river flow depth for calibration, which improves from previous studies of remote sensing of river flow depth. The methods are successfully applied to mapping the underwater bathymetry of a 26 km reach of the Nicolet River in Quebec, Canada. This study shows the importance of geometric and radiometric corrections to the satellite images. The obtained flow depths using the ratio of reflectance of the red band (630–690 nm) to that of the green band (510–580 nm), among the eight bands in the visible spectrum, agree best with in-situ measurements. This study is perhaps the first use of the analytical approach for mapping river bathymetry. It is feasible to implement the approach to other river channels, with a good potential to reduce the costs and increase the efficiency of mapping river bathymetries.

Keywords: river flow depth; satellite remote sensing; underwater bathymetry; Nicolet River; WorldView-3 imagery

1. Introduction

Rivers evolve on the Earth and contribute to shaping landscape. River flows can erode and deposit sediments, creating canyons, valleys, and deltas. Accurate data of river bathymetry are essential for geomorphologists, hydrogeologists, hydro-environmental scientists, and river engineers to investigate river processes, evaluate their impacts, and improve river engineering design. Bathymetric data may be obtained through traditional field surveys using, e.g., a plumb line or sound navigation and ranging (sonar). Field surveys involve deploying operators and instruments at a river site, and thus are expensive, time-consuming, and inconvenient. Recent advances in satellite remote sensing technology have created a new approach to bathymetric data acquisition. The new approach is much more efficient than the traditional surveys. However, existing implementations of the new approach need some underwater depth measurements from the river site in question in order to estimate the correlations between optical variables and underwater depth. In many cases, no field measurements from a site are available. Therefore, it is desirable to
eliminate the reliance on field measurements, which has motivated this study. This study retrieves bathymetric data from fine resolution images, which are particularly useful for river restoration applications.

In many rivers, in-stream structures like deflectors, weirs, and spur dikes have been installed to restore fish habitats, improve flood controls, and stabilise channel geometries [1–3]. The installations cause spatial changes in underwater depth of the riverbed even if the discharge is the same. For example, in the Nicolet River in Quebec, Canada (Figure 1), deflectors were installed at a series of cross sections to create new pools or maintain excavated pools in the flow, as a measure to restore deteriorated habitats and declined fish populations [4–6]. An assessment of the suitability of such a measure needs hydro-information, particularly the change of flow depth before and after an installation. The traditional approach to acquiring flow depth is field surveys of a river channel. Field surveys are expensive and time consuming. They are oftenlogistically difficult for a remote river site and a river in a cold region like Canada.

![Figure 1](image_url)

**Figure 1.** (a) The Nicolet River watershed in the Province of Quebec, Canada. The river flows from Lake Nicolet through Victoriaville to the river mouth in Lake Saint-Pierre between Sorel-Tracy and Trois-Rivieres. (b) A 26 km section of the river channel as the site of this study.
The purpose of this study is to provide efficient estimates of underwater depth of the riverbed by means of satellite remote sensing. Digital imagery of river areas from archives and ongoing satellite measurements offers an ever increasing temporal and/or spatial resolution. A beam of solar light may penetrate the entire water column of a shallow river; the radiance reflected from the riverbed and transmitted back through the atmosphere is measured by the satellite sensor. This study uses reflectance from multispectral imagery to estimate underwater depth, without the need for field observations for calibration. This is new and more convenient compared to existing methods for generating depth from satellite imagery.

Other applications of satellite imagery are extensive and include riparian zone characterisation [7], shoreline change detection [8], river flood extent delineation [9], water quality monitoring [10,11], and river sediment load [12]. Such applications concern physical characteristics or phenomena observable above the water surface. WorldView-2 (WV-2) imagery was used to generate lake geometry [13]. This study uses WV-3 imagery to generate underwater depth of a river at the reach scale with details at the patch scale. In the context of monitoring, assessing, and restoring fish habitats, the scales are desirably on the order of $O(10^4)$ to $O(10^0)$ m. The obtained underwater depth may be converted to high-resolution channel bathymetry, which is fundamental input data in hydrodynamics and habitat modelling [14–16]. Note that some digital elevation models (DEMs) of rivers exist, but few provide a sufficiently high resolution, e.g., $O(10^0)$ m. The grid size of existing DEMs may exceed the channel width of a shallow river. It is not practical to generate high-resolution DEMs by means of classic field surveys.

A good alternative is measurements of underwater depth by satellite remote sensing. A linear relationship between river depth and the logarithm of the ratio between paired multispectral bands can be formulated [17], but it may be argued that the single ratio algorithm is inadequate due to complications of different riverbed types, suspended sediments, and water surface roughness [18]. Nevertheless, application of a single ratio algorithm [17] successfully retrieved river bathymetry from WV-2 imagery [19]. The application needs field-survey data of flow depth for calibration. This is a site-specific technique commonly used in river bathymetry studies [20–23]. The technique cannot be used when field data are not available or are not sufficient, which is often the case for inaccessible rivers, very shallow rivers, or large river extents. This limitation is significant.

Analytical techniques not relying on calibration data become attractive. Previously, analytical techniques have been developed, but they are mostly for marine applications [24–27]. Rivers differ from the marine environment in spatial gradients of depth, and possibly in bottom reflection and radiance absorption and scattering. The techniques developed for marine applications have not been applied to rivers. WV-3 imagery includes eight bands in the visible light spectrum. It is not known which pair of bands are the most suitable for use in ratio-based algorithms for river applications.

2. Methods
2.1. Site of Study

The site of this study is a section of the Nicolet River. This river section extends about 26 km upstream from Victoriaville, Quebec (Figure 1). The lands surrounding the river channel are mainly agricultural lands. Along the riverbanks, some locations have coniferous trees imposing a canopy on the river channel. The riverbed sediments are mainly dolomite, limestone, shale, clays, and sands. The Nicolet River has been at risk for losing biological diversity and fish populations. Wooden and boulder deflectors were installed at a series of locations along the river section [28,29] for restoration of fish habitats and populations. The in-stream structures aid in creating new pools and maintaining excavated pools in the river channel. Pools provide relatively large water depth; they may lower water temperature (summer) and velocity and may stabilise the bed with coarser sediments. Such features would improve fish habitats. Locating pools in the river section and quantifying their varying depths and water volumes are within the scope of this study.
Field measurements of underwater depth from a short (approximately 250 m) reach of the river section were available [28,30,31]. This reach has two sets of paired deflectors (Figure 1b), installed approximately 90 m apart in the streamwise direction. The upstream and downstream sets each created a pool. Using the field measurements, a digital elevation model (DEM) of the short reach was built for investigating the influence of the deflectors on water flow and sediment transport [30,31]. This DEM used a local vertical datum (Figure 2) instead of a standard datum (e.g., Canadian Geodetic Vertical Datum of 1928 or CGVD28). The field measurements allow data comparison.

Figure 2. Diagram of flow depth \( z = \eta \) below the water surface and riverbed elevation, \( H \), above a vertical datum; \( P \) is a point at the bed.

2.2. WV-3 Multispectral Image

This study acquired eight WV-3 scenes of the river site (Figure 1), captured on 20 May 2016, at an off-nadir of 26.5° and a solar zenith angle of \( \theta = 0.48192 \) radians, under clear sky conditions. The eight scenes were combined to form one digital image. The image was made of 1.2 m \( \times \) 1.2 m pixels. Pixel values or digital numbers, \( N \), in eight spectral bands of different wavelengths, \( \lambda \), (Table 1) are available. The eight bands are coastal blue (CB), blue (B), green (G), yellow (Y), red (R), red edge (RE), near-infrared 1 (NI1) and near-infrared 2 (NI2). The values of \( N \) have undergone relative radiometric corrections, which standardised multiple-satellite scenes to each other using supplementary information and removed such radiometric problems as stripe noises, defective lines, and non-uniformity [32]. The individual pixels in the image have coordinates within the image grid, but are not geo-referenced.

Table 1. Properties of the radiometric performance of WV-3 imagery.

<table>
<thead>
<tr>
<th>Band</th>
<th>( \lambda ) nm</th>
<th>( \Delta \lambda ) ( \mu m )</th>
<th>( \lambda_o ) nm</th>
<th>( E ) W/(m²( \mu m ))</th>
<th>( g )</th>
<th>( o ) W/(m²sr-Count)</th>
<th>( c ) W/(m²sr-Count)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB</td>
<td>400–450</td>
<td>0.0405</td>
<td>427.4</td>
<td>1743.8</td>
<td>0.2909</td>
<td>−7.070</td>
<td>0.0139747</td>
</tr>
<tr>
<td>B</td>
<td>450–510</td>
<td>0.054</td>
<td>481.9</td>
<td>1971.5</td>
<td>0.3052</td>
<td>−4.253</td>
<td>0.0177236</td>
</tr>
<tr>
<td>G</td>
<td>510–580</td>
<td>0.0618</td>
<td>555</td>
<td>1856.3</td>
<td>0.1955</td>
<td>−2.633</td>
<td>0.0131636</td>
</tr>
<tr>
<td>Y</td>
<td>585–625</td>
<td>0.0381</td>
<td>604.3</td>
<td>1749.4</td>
<td>0.1679</td>
<td>−2.074</td>
<td>0.0067200</td>
</tr>
<tr>
<td>R</td>
<td>630–690</td>
<td>0.0585</td>
<td>660.1</td>
<td>1555.1</td>
<td>0.1695</td>
<td>−1.807</td>
<td>0.0102036</td>
</tr>
<tr>
<td>RE</td>
<td>705–745</td>
<td>0.0387</td>
<td>1344.0</td>
<td>1344.0</td>
<td>0.1560</td>
<td>−2.633</td>
<td>0.0060632</td>
</tr>
<tr>
<td>NI1</td>
<td>770–895</td>
<td>0.1004</td>
<td>1072.0</td>
<td>1072.0</td>
<td>0.1159</td>
<td>−3.406</td>
<td>0.0117091</td>
</tr>
<tr>
<td>NI2</td>
<td>860–1040</td>
<td>0.0899</td>
<td>863.3</td>
<td>863.3</td>
<td>0.1193</td>
<td>−2.258</td>
<td>0.0103495</td>
</tr>
</tbody>
</table>

2.3. Calculation of Top-of-Atmosphere Spectral Radiance

The value of the digital number \( N \) in each band can be converted to top-of-atmosphere (TOA) radiance, \( L \), as [33]

\[
L = \frac{c}{\Delta \lambda} N + o,
\]
where $g$ is the gain (or the slope of the sensor response line); $c$ is an absolute radiometric calibration factor; $\Delta \lambda$ is the effective bandwidth; $o$ is the offset (Table 1). The offset handles the situation where a histogram of the obtained $L$ values for a specific band does not start from zero, and thus the offset from zero needs to be subtracted from the values. The offset is partly due to atmospheric interference. It is understood that the digital numbers themselves are without the aforementioned corrections.

2.4. Calculation of TOA Reflectance

The reflectance is the ratio of light leaving materials to the amount of light striking them. It is an inherent property of the materials and does not depend on light illumination or the position of objects. NASA proposed a model for TOA reflectance (in percentage)

$$\rho = \frac{L_{\text{es}} \pi}{E \cos \theta}$$

where $d_{\text{es}}$ is an Earth-Sun distance, and $E$ is the band-averaged solar exoatmospheric irradiance (Table 1). For the time of the WV-3 image, $d_{\text{es}} = 0.985$ AU, being within the acceptable range of 0.983 to 1.017 AU [33]. Values of $E$ were determined using an irradiance model, developed by the World Radiation Center on the basis of a series of measurements. According to this model, the solar irradiance peaks around wavelength $\lambda = 450$ nm (Table 1) and then declines towards longer $\lambda$.

2.5. Identification of River Water Pixels

Let $\omega$ denote the normalised difference water index (NDWI). It is calculated as

$$\omega = \frac{\rho(\lambda_G) - \rho(\lambda_{\text{NI1}})}{\rho(\lambda_G) + \rho(\lambda_{\text{NI1}})},$$

where the subscripts G and NI1 refer to the green and near infrared 1 bands, respectively (Table 1). Values of $\omega$ range from –1 to +1, with $\omega = +1$ representing water pixels. The reason is that river water strongly absorbs radiance in the NI1 band, whereas vegetation and soil highly reflect radiance in the NI1 band [34]. River water gives the maximum $\rho$ in the G band and minimum reflectance in the NI1 band.

A threshold of $\rho$ between G and NI1 may be used to discriminate water pixels from the rest. This study identifies water features by a positive value of $\omega$. The identification reduces the number of pixels in water depth calculations and hence computing costs. More importantly, it avoids some ambiguities and thus enhances the accuracy of calculations.

2.6. Geo-Reference of Pixels in the WV-3 Image

The pixels need to be geo-referenced in order to establish their coordinates on the ground. This was achieved by using two topographic DEMs from the U.S. Geological Survey. They were constructed from the shuttle radar topography mission on 23 September 2014. The combined DEM covered the river watershed (Figure 3). Mapping the WV-3 image to the combined DEM associated each pixel with ground coordinates (Figure 3).

An issue in geo-referencing arose due to mismatching dates between the 2014 DEMs and the 2016 WV-3 image. Over the two years, the river path has shifted position to some extent (Figure 4). The coordinates of the pixels on the ground were corrected using Google Earth data. This study acquired a Google Earth image of the river site from the same date as the WV-3 image. The Google Earth image provides river channel position as a benchmark. The coordinates of the pixels on the ground (Figure 4) were translated to match the benchmark (Figure 5). It is understood that the geo-reference of pixels and corrections have no impacts on the calculations of underwater depths but are important for comparing the calculated depths with data from other independent sources.
Figure 3. Mapping of the river section (Figure 1b) to the USGS topographic DEM.

Figure 4. River path (red plus sign) extracted from a Google Earth image captured on 20 May 2016, overlaid on the WV-3 image. The ground coordinates of the WV-3 pixels were geo-referenced using the 2014 USGS DEMs. For clarity, only a portion of the 26 km river section is shown.
Figure 5. The ground coordinates of pixels in Figure 4 translated some units to the west and to the north until the river path from the WV-3 image matched the red plus signs.

2.7. Calculation of River Flow Depth

Let \( z \) denote the depth of a point below the water surface (Figure 2). On the basis of the Beer–Lambert law, a beam of light travelling through the depth toward the riverbed attenuates in intensity:

\[
I_o(z) = e^{-kz},
\]

(4)

where \( I_o \) is the incident intensity before entering water (Watt/m\(^2\)); \( I \) is the transmitted intensity; and \( k \) is an attenuation coefficient (in m\(^{-1}\)). The attenuation results from absorption and scattering of radiance energy and depends on \( \lambda \), i.e., \( I \) is a function of \( \lambda \). Attenuation also occurs as the radiance reflected from the bed transmits upward towards the water surface. The value of \( I_o \) is not recorded by the satellite sensor but can be eliminated by taking the ratio of transmitted intensities between a pair of bands (say \( i \) and \( j \)) listed in Table 1. This yields

\[
\frac{I_i}{I_j} = e^{-k_i z + k_j z}.
\]

(5)

Substitutions of \( I_i \) by \( \rho_i \) and \( I_j \) by \( \rho_j \) give

\[
z = \frac{1}{k_e} \ln \frac{\rho_i}{\rho_j},
\]

(6)

where \( k_e = k_j - k_i \) is an effective attenuation coefficient. Values of the reflection were obtained from Equation (2). For a given band, the attenuation coefficient was approximated as \( k \approx k_d \), where \( k_d \) is the diffuse attenuation coefficient.

The coefficient \( k_d \) was estimated on the basis of radiative transfer theories. It is expressed as [35]

\[
k_d = m_0 a + m_1 (1 - m_2 e^{-m_3 a}) b,
\]

(7)
where \( a \) is an absorption coefficient; \( b \) is a backscattering coefficient; \( m_0, m_1, \) and \( m_2 \) are constants. It is assumed that \( a \) and \( b \) are dependent of \( \lambda \) but not \( z \); \( m_0, m_1, \) and \( m_2 \) are independent of \( \lambda \) and \( z \). The constants are given by \( m_0 = 1 + 0.005\theta; m_1 = 4.18; m_2 = 0.52; m_3 = 10.8 \). The aforementioned methods of estimation avoid the need for ground data from the site to evaluate \( k_e \). It is understood that ground data are expensive and often difficult to obtain.

The coefficient \( a \) is given by

\[
a = a_w + \Delta a, \tag{8}
\]

where \( a_w \) is the absorption coefficient of pure water; \( \Delta a \) is the absorption coefficient of suspended loads [36]. A reference wavelength, \( \lambda_r \) (equal to 555 nm) was selected, and \( a(\lambda_r) \) was determined for \( \lambda = \lambda_r \). For other wavelengths (Table 1), values of \( a \) were based on \( a(\lambda_r) \). The selection of \( \lambda_r = 555 \) nm was due to little contribution from wavelengths \( \lambda \geq 550 \) nm to radiance energy absorbed by suspended loads. The foregoing steps give an empirical relation for \( a_w \) as a function of \( \lambda \).

The coefficient \( b \) is defined as the differential scattering cross-section per unit volume for a 180° scattering angle [37]. It is expressed as

\[
b = b_w + b_p, \tag{9}
\]

where \( b_w \) is the backscattering coefficient of pure seawater; \( b_p \) is the backscattering coefficient of suspended particles. A model for \( b_w \) was adopted [38]:

\[
b_w = 0.0035\left(\frac{\lambda_0}{450}\right)^{-4.32}, \tag{10}
\]

where \( \lambda_0 \) is the centre wavelength (Table 1) at standard atmospheric pressure and water temperature of 20°C. The model has been experimentally validated [39]. Dissolved and suspended particles, typically present in rivers, affect \( b_p \). More details about the calculations of \( a, b_p, \) and \( b_w \) can be found in the literature [36]. The methods for estimating \( z \) are summarised in Figure 6.

**Figure 6.** Flow chart for calculations of flow depth.
3. Results

3.1. Digital Number and TOA Reflectance

In Figures A1–A4, values of the digital number, \( N \), in a given band varied among pixels in the image. Take a wet (water) pixel in a pool (marked as ‘Deflector \( \times \)’ in Figure 1b) as an example. The values were \( N = 233, 225, \) and 152 in the CB band (Figure A1), G band (Figure A2), and R band (Figure A4), respectively, differing from values of \( N \) in surrounding pixels. Among all the dry and wet pixels, \( N \) ranged from 0 to 1525 in the G band and from 0 to 1928 in the R band. A zero value of \( N \) in a band represents the target of remote sensing completely absorbing the reaching radiance in that band and leading to zero reflected radiance. A larger \( N \) means higher reflected radiance in a band. For a water pixel, the lower the \( N \) value in a band, the larger the water depth, assuming that the riverbed-reflected radiance is dominant and radiance attenuation is due to the effect of water depth. In Figures A1–A4, darker pixels in the river path mean larger depths below the water surface.

As calculated (Equation (1)) from the \( N \) values in Figures A1–A4, values of reflected TOA radiance, \( L \), are plotted in Figures A5–A8. The calculation allowed for radiometric corrections. Thus, the values of \( L \) represent corrected radiance numbers of the pixels in the image. An examination of the \( L \) values in the wet (river) pixels shows that out of a total of 609,485 river pixels (Equation (3)), only two pixels in the G band and three pixels in the R band had negative values of \( L \). For these few pixels in the image, the digital records were damaged.

For the sample water pixel noted above, with the values of offset, gain, effective bandwidth, solar exoatmospheric irradiation, and \( c \) given in Table 1, the calculated values of radiance (Equation (1)) were \( L = 15.3126, 6.7383, \) and 2.6878 W/(m\(^2\)\(\mu m\)) in the CB, G, and R bands, respectively. The corresponding values of reflectance (Equation (4)) were \( \rho(\lambda_{CB}) = 0.0302, \rho(\lambda_G) = 0.0125, \) and \( \rho(\lambda_R) = 0.0059 \). The ratio of the R band reflectance to the G bank reflectance was \( \rho(\lambda_R)/\rho(\lambda_G) = 0.472 \), and a logarithm of the ratio was \( \ln[\rho(\lambda_R)/\rho(\lambda_G)] = -0.7508 \). It is understood that the ratio \( \rho(\lambda_R)/\rho(\lambda_G) \) varied greatly among the river pixels, depending on the local water depth. This paper selected the ratio \( \rho(\lambda_R)/\rho(\lambda_G) \) for estimates of the varying flow depths (Equation (4)) from the WV-3 image.

3.2. Effective Attenuation Coefficient

Both the absorption coefficient, \( a \), (Equation (6)) and the backscattering coefficient, \( b \), (Equation (7)) varied with wavelength. Calculations of \( a \) gave a value of 0.0677 m\(^{-1}\) for the G band and 1.1398 m\(^{-1}\) for the R band. These values gave the e-folding depth-scales for the transmitted radiances in the G and R bands to attenuate by the factor \( e \) (or approximately 2.718). The values indicated that due to absorption, the radiance in the R band attenuated more rapidly than that in the G band during their transmission, which is expected as \( \lambda_R > \lambda_G \) (Table 1).

The backscattering coefficient of pure water, \( b_w \), had a value of 0.0014 m\(^{-1}\) for the CB and G bands and 0.0007 m\(^{-1}\) for the R band. The backscattering coefficient of suspended particles, \( b_p \), had a value of 8.0533 m\(^{-1}\) for the G band and 5.8585 m\(^{-1}\) for the R band [36]. Thus, the total backscattering coefficient, \( b_t \) (Equation (7)) had a value of 8.0547 m\(^{-1}\) for the G band and 5.8592 m\(^{-1}\) for the R band. The rate of radiance attenuation by backscattering was lower for the R band than for the G band. The attenuation coefficients for the G and R bands were \( k_G = 25.7892 \) m\(^{-1}\) and \( k_R = 25.3232 \) m\(^{-1}\), respectively. Between these two bands, the effective attenuation coefficient was \( k_e = k_G - k_R = 0.466 \) m\(^{-1}\). For the sample water pixel \( w_p \) (Figure 1), the calculation of the flow depth (Equation (4)) gave \( z = 1.611 \) m.

3.3. Flow Depth

Calculations of the NDWI (Equation (3)) returned 609,485 water pixels in the WV-3 image. The river section (Figure 1b) covered by these pixels had a total water surface area of 0.877658 km\(^2\), a thalweg length of 26 km, and an average cross-channel width of approximately 34 m. The calculated depths (Equation (4)) have an average value of
2.44 m and a median value of 2.51 m. The distribution of varying depths shows pools and very shallow areas. It is understood that the aforesaid results correspond to the river discharge on the date of the image (20 May 2016). Note that the pixel size of 1.2 m × 1.2 m appropriately resolves cross-channel variations of underwater depth (or cross-channel profiles of the riverbed) as well as variations of depth in pools.

The river section of this study (Figure 1b) has many bends. Typically, the underwater depth in a river bend has very complicated variations. An example of depth variations in a 120° bend is shown in Figure 7. From upstream, water flows in a northeast direction, passes between a pair of deflectors, continues to the apex of the bend, and turns in a west direction. The spatial variations of underwater depth show a pool located immediately downstream of the paired deflectors, a very shallow flow on the inner bank, and a relatively deep flow on the outer bank downstream of the apex. These features are consistent with typical flow behaviours in a river bend.

It is well-known that in a river bend, the flow is the slowest on the inside of the bend and fastest on the outside. Such flow conditions tend to cause sediment deposition on the inside and erosion on the outside. For this reason, one expects a shallow inner bank and a deeper outer bank. In Figure 7, the outer bank at the apex is not as deep due to the influence of the paired deflector and the resulting pool. In the figure, the thalweg appears to hug the inner bank upstream of the apex, return to the centre at the apex, and turn to hug the outer bank downstream of the apex. This is as expected.

In Figure 8, the river flows through a 60° bend. The key features of depth variations seen in the 120° bend (Figure 7) are also visible in this 60° bend. Without installation of artificial in-stream structures in the vicinity, the natural depth variations closely match the classic description of a river bend. In the river section (Figure 1b), many cross sections are only a few pixels (or a few metres) wide, and a large percentage of the pixels have a depth smaller than 2 m. For a shallow river, retrieving underwater depth from satellite imagery without relying on ground data for calibration appears to be a reliable alternative to field surveys.

For application to habitat restoration and improvement, it is relevant to locate pools. The locations of 19 pools along the thalweg of the river section are plotted in Figure 9. The locations of these pools closely match the data from reported field surveys [29]. For an individual pool associated with an installed in-stream structure, it is straightforward to track the pool volume evolving from year to year, using archived satellite images or newly collected images.

A limited amount of field data of depth from the site of study (Figure 1b) are available for comparison. An earlier study [4] reported field observations of depths of a deflector area, marked in Figure 1b as 'Deflector ×'. The observation area includes two pools, marked in Figure 9 as p1 and p2, in the vicinity of paired deflectors installed on the riverbanks. In the earlier study [4], the observed depths of the riverbed are presented as bed elevations above a local vertical datum. To allow for a direct data comparison, the obtained underwater depths from this study are converted to bed elevations (Figure 10a). The observed bed elevations vary between 99.7 m near the banks and 96.5 m in pool p2. For a good number of pixels (59 pixels) covering the pool area, bed elevations are extracted from the results in Figure 10a, and 85% of data points show elevations within the range from 96.5 to 97 m (Figure 10b). The comparison is reasonable.
Figure 7. Variation of underwater depth in a 120° bend.

Figure 8. Variation of underwater depth in a 60° bend.
**Figure 9.** Positions of the river thalweg and of deep pools along the thalweg. Pools marked by an open circle have a maximum underwater depth of $d > 5$ m, and pools marked by an open square have a maximum depth of $4.5 < d < 5$ m.

**Figure 10.** Cont.
4. Discussion

Researchers have explored several methods for generating river bathymetry [18,40]. Some researchers combine remote sensing data with field measurements from the site in question. The combined methods cannot easily be applied to a remote river site, as field measurements are typically not available. Others combine physical laws with field measurements. It is well-known that physical laws introduce approximations and thus have their own uncertainties. It is desirable to develop new methods for mapping river bathymetry that do not rely on the availability of field measurements. This study introduces much more efficient and less expensive methods in comparison to field surveys.

Analytical methods exist in ocean applications, but it is not known how well they work in river applications. The river environment features much stronger spatial variations in bathymetry than the ocean environment. Inspired by successful studies of oceanic and coastal water bathymetry, this study follows a set of analytical relationships for calculations of river depth. The calculations start from a general equation from Lambert–Beer’s law and select a pair of wavelengths as input to a ratio algorithm. The key challenge encountered in river applications is the determination of the attenuation coefficient and relevant parameters. This study initiated the quest for reliable relationships for determining the coefficient. Applications to oceans and coastal waters have produced some analytical or semi-analytical relationships, expressed by a set of equations for calculating the attenuation coefficient. However, these equations involve many technical factors (e.g., parameters of satellite’s optical sensor for recording solar radiances, offset and gain of wavelengths, solar angle, and so on) and/or environmental factors (e.g., turbidity of river water, riverbed condition, cloud coverage, tree canopy, and so on) that can cause errors in the results of bathymetry.

This study explored possible ways to eliminate/reduce error factors through a non-field-based approach. As sunlight passes through the atmosphere and water column, it is subject to the effects of absorption and scattering in these environments. Therefore, these effects must be considered in the calculation to increase the accuracy of bathymetry results. This study addressed the issue of atmospheric effects through radiometric corrections and the issue of water effects through a series of equations.

Radiometric corrections are fundamental corrections that are applied to all pixels of a satellite image. These corrections affect not only the value of band ratio in the ratio algorithm directly but also the attenuation coefficient indirectly. Radiometric corrections can be divided into two main categories: relative corrections and absolute corrections. The relative radiometric corrections consider climate data and illumination geometry to remove
stripe noises, defective lines, and non-uniformity [32]. The absolute radiometric corrections improve the raw physical scale of digital numbers. The images from the WorldView-3 satellites covering the Nicolet River are delivered with relatively corrected radiance. Only the absolute radiometric corrections are applied to each band of images in this study. The corrections correlate with the date of that scene and the sensor properties of satellites. Absolute radiometric calibration factor and effective bandwidth are common parameters with different values for the calculation of absolute radiometric corrections. It is possible to consider the offset and gain effects for the WorldView-3 images [33,41].

As water depth increases, the reflectance of bands decreases. For a wavelength band with higher absorption, the natural logarithm of the reflected band decreases faster compared to a wavelength band with lower absorption [26]. This feature, along with Lambert–Beer’s law, helps generate a natural ratio algorithm that can remove the reflectance of the bottom effect [26]. For the band ratio algorithm, it is necessary to use the reflectance of each band. Therefore, the corrected radiance of bands has to be transformed to top-of-atmosphere reflectance. This transformation can be achieved through calculating parameters like solar zenith angle, the Earth-Sun distance, and solar irradiance. These parameters can be different from one image satellite to another.

Paired bands for use in the ratio algorithm should be visible bands. They include coastal blue, blue, green, red, and yellow. In coastal blue and blue bands, the wavelengths are lower than 550 nm. They cannot be a suitable option because these bands must consider the absorption by suspended particles. As ocean studies recommend using 555 nm as a reference band in analytical equations, we selected the green band as one of the pair bands in the ratio algorithm. Investigations in this study show that in the case of WorldView-3 images, the band that provides the best match between retrieved and measured depths is the red band.

For the Nicolet River, the implementation of radiometric corrections leads to significantly improved results of riverbed elevations. In the pool area between a pair of deflectors, there are 59 pixels in the WorldView-3 image. Before radiometric corrections, 22 pixels give elevations outside the range of measured values; after radiometric corrections, only 9 pixels give values outside the range. Thus, the radiometric corrections reduce the percentage of out-of-range data points from 37.3% to 15.3%.

The effects of water on reflected wavelengths are considered in series of semi-analytical equations. Similar to coastal and oceans bathymetry studies, this study investigates the effects of backscattering and absorption of river water through the attenuation coefficient [35]. A multiband quasi-analytical algorithm for open coastal waters allows for backscattering and absorption effects in pure water and the presence of suspended loads [36]. This study uses wavelengths longer than 550 nm. In these wavelengths, the absorption effect of suspended loads is quite small. Only the absorption effect of pure water needs to be considered.

With regard to backscattering effects, the total backscattering is the sum of the backscattering of pure water and suspended loads. This research uses Equation (10) [38], which calculates the backscattering coefficient of pure water based on wavelengths. There are several possible wavelengths in each band for use in the equation. This study uses the centre wavelength of each band as the input wavelength to the equation. The results are compared to the experimental values of backscattering coefficient [39]. We show an excellent comparison between our analytical results and their experimental data. In conclusion, the backscattering coefficient of pure water is valid as calculated based on centre wavelengths.

It is worth noting that light detection and ranging (LiDAR) is also a remote sensing method for examining the surface of the Earth. Similar to other methods, LiDAR requires operators and flights over a target area. This study explores methods without involving operators at a river site and in-situ equipment for depth measurements. This is useful, especially for remote locations of inconvenient accessibility. This also reduces operational costs and time, which are important issues in mapping river bathymetry. The conventional methods may have lengthy times for mobilisation to and demobilisation from a river site.
Thus, they are not feasible for mapping the bathymetry of an extensive region because of the time-consuming process. Even the LiDAR methods are not sufficient enough to cover a large target region.

In the near future, the joint Surface Water and Ocean Topography (SWOT) mission by NASA and the National Centre for Space Studies of French (CNES), in partnership with the Canadian Space Agency and the UK Space Agency, will provide surface water data. SWOT operations will be able to capture images from rivers, and the images will offer an excellent opportunity to efficiently map river bathymetry. Previously, a comparison between optical bathymetry from WorldView-2 images of a lake and in-situ measurement of depth gave correction coefficients of 0.59 to 0.81 [42]. In this study, the retrieved bathymetry achieves acceptable accuracy; 85% of data points are within the range of measured values.

It is desirable to use satellite images captured under low river discharge conditions. This would help avoid significant issues related to suspended sediments and their variations from section to section in an alluvial river channel. Under high river discharge conditions, sediment transport may be active and vary spatially when the flow-induced shear stress exceeds a critical threshold for sediment mobilisation and prevents sediment grains from settling. It is also desirable to divide a river channel of interest into uninterrupted stretches at a reach scale, which are relatively short and homogeneous in geological structure, morphology, and drainage characteristics.

The methods discussed in this paper make use of empirical coefficients, including the absorption coefficient, \(a\), and the backscattering coefficient, \(b\). It is constructive to perform a sensitivity analysis of the attenuation coefficient \(k_d\) (Equation (7)) in response to slightly changes in \(a\) and \(b\). Table 2 presents the results for four cases in comparison to the base case. The results indicate that slight changes to the intermediate coefficients will not result in large changes to calculated underwater depths.

<table>
<thead>
<tr>
<th>Case</th>
<th>(a) (m(^{-1}))</th>
<th>(b) (m(^{-1}))</th>
<th>(k_d) (m(^{-1}))</th>
<th>(\Delta k_d/k_d) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base case</td>
<td>0.0677</td>
<td>8.0533</td>
<td>25.3232</td>
<td>0%</td>
</tr>
<tr>
<td>Case 1</td>
<td>0.0684</td>
<td>8.0533</td>
<td>25.3853</td>
<td>0.25%</td>
</tr>
<tr>
<td>Case 2</td>
<td>0.0711</td>
<td>8.0533</td>
<td>25.6296</td>
<td>1.21%</td>
</tr>
<tr>
<td>Case 3</td>
<td>0.0677</td>
<td>8.1353</td>
<td>25.5756</td>
<td>1.00%</td>
</tr>
<tr>
<td>Case 4</td>
<td>0.0677</td>
<td>8.4575</td>
<td>26.5855</td>
<td>4.98%</td>
</tr>
</tbody>
</table>

5. Conclusions

This paper explores new methods for mapping underwater bathymetry of a shallow river from satellite multispectral imagery. The methods are applied to a 26 km reach of the Nicolet River in Quebec, Canada. The following conclusions have been reached. The new methods differ from previous methods for retrieving river bathymetric data from satellite images. The previous methods rely on field measurements for the calibration of regression relationships, whereas the new methods do not. Therefore, the new methods can be applied to a remote river reach, which satellite images may cover and from which field measurements may not be available. One way to enhance the accuracy of the new methods is to use data of radiance coming from wet pixels only, as demonstrated in the application to the Nicolet River. The wet pixels of satellite images covering the river are separated from the rest of pixels, and the radiance of each frequency band is determined for further analysis. Using radiance records from satellite sensors directly to derive river bathymetry does not produce the most accurate results. This is because sunlight is absorbed and scattered during its journey through the atmosphere and water column. The radiance records should be corrected in order to remove atmospheric effects by considering gain, offset, and absolute radiometric calibration factors. The records should be converted to values at the top of
atmosphere reflectance. The reason is that the ratio band algorithm uses band reflectance as pixel value. A general equation for the light attenuation coefficient is adopted from ocean studies. The coefficient allows for the effects of absorption and backscattering by water on wavelengths. With this equation, it is possible to correct radiances that come out of water column in the ratio algorithm. This idea is new in river studies. A comparison of results between before and after radiometric correction of visible bands shows noticeable changes to band pixel values. Without radiometric correction, the results of bathymetry derived are less comparable with available field measurements than with the radiometric correction. A shortcoming of deriving river bathymetry from satellite images is the discontinuity in flow depths across a channel cross-section from one riverbank to the other. The depths do not always start from zero value at one riverbank and end with zero value at the other. The river bathymetry is mapped by connecting discreet pixel values.

**Author Contributions:** Conceptualization, S.S.L.; methodology, S.S.; software, S.S.; validation, S.S.L., S.S. and B.L.; investigation, S.S.; writing—original draft preparation, S.S.L. and S.S.; writing—review and editing, S.S.L.; visualization, S.S.; supervision, S.S.L.; funding acquisition, S.S.L. All authors have read and agreed to the published version of the manuscript.

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**Conflicts of Interest:** The authors declare no conflict of interest.

**Abbreviations**

The following abbreviations are used in this manuscript:

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>Blue</td>
</tr>
<tr>
<td>CB</td>
<td>Coastal blue</td>
</tr>
<tr>
<td>CGVD28</td>
<td>Canadian Geodetic Vertical Datum of 1928</td>
</tr>
<tr>
<td>DEM</td>
<td>Digital elevation model</td>
</tr>
<tr>
<td>LiDAR</td>
<td>Light detection and ranging</td>
</tr>
<tr>
<td>NI1</td>
<td>Near infrared 1</td>
</tr>
<tr>
<td>NI2</td>
<td>Near infrared 2</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration of the United States</td>
</tr>
<tr>
<td>NDWI</td>
<td>Normalised difference water index</td>
</tr>
<tr>
<td>G</td>
<td>Green</td>
</tr>
<tr>
<td>R</td>
<td>Red</td>
</tr>
<tr>
<td>RE</td>
<td>Red edge</td>
</tr>
<tr>
<td>TOA</td>
<td>Top of atmosphere</td>
</tr>
<tr>
<td>USGS</td>
<td>United States Geological Survey</td>
</tr>
<tr>
<td>WV-3</td>
<td>World View 3</td>
</tr>
<tr>
<td>Y</td>
<td>Yellow</td>
</tr>
</tbody>
</table>

**Appendix A**

Values of the digital number, \( N \), in the coastal blue, green, yellow, and red bands (Table 1) are shown in Figures A1–A4. Values of the radiance, \( L \), (after correction) in the coastal blue, green, yellow, and red bands are shown in Figures A5–A8.
Figure A1. Values of the digital number N (or pixel values) in the coastal blue band (Table 1).
Figure A2. Values of the digital number N (or pixel values) in the green (G) band (Table 1).
Figure A3. Values of the digital number N (or pixel values) in the yellow (Y) band (Table 1).
Figure A4. Values of the digital number N (or pixel values) in the red (R) band (Table 1).
Figure A5. Corrected radiance in the coastal blue (CB) band.
Figure A6. Corrected radiance in the green (G) band.
Figure A7. Corrected radiance in the yellow (Y) band.
Figure A8. Corrected radiance in the red (R) band.

References


