Remote sensing of total suspended sediment within lakes Onoke and Wairarapa

Introduction
Remote sensing can provide synoptic monitoring of water quality and temperature (e.g., Kloiber et al. 2002, Dekker et al. 2002). It is highly suitable for providing comprehensive spatial coverage. Three-dimensional (3-D) and one-dimensional (1-D) hydrodynamic modelling of lake water quality and thermodynamics offers an opportunity to interpolate temporal gaps in data derived from satellite and traditional monitoring of water quality and temperature, and to extend the analysis to the vertical domain (Hedger et al., 2002). These models can also provide insights into the spatial variability of biogeochemical processes (Jorgensen, 2008) as well as being able to be coupled with biogeochemical models for quantitative predictions of state variables relevant to water quality.

While remote sensing can provide cost effective synoptic monitoring, limitations of this method must also be considered. Remote sensing using visible and infrared (IR) radiation is not possible during periods of extensive cloud cover, which are frequent in New Zealand. Remote sensing also does not allow derivation of non-optically active water constituents, such as nutrient concentrations. In optically complex Case 2 waters found in lakes, bio-optics are a function of at least three optically active constituents which can vary independently (Blondeau-Patissier et al., 2009), including total suspended solids (TSS), chlorophyll $a$ (chl $a$) and coloured dissolved organic matter (CDOM). The retrieval of water constituent concentrations from Case 2 waters (coastal and lake water) is more demanding in terms of algorithm complexity and the satellite sensor spectral resolution (Matthews, 2011). This is the case when using broadband sensors such as Landsat’s Enhanced Thematic Mapper (ETM), and estimations of water quality in optically complex waters can be limited to more water quality variables that are constituent in nature, such as Secchi depth, light attenuation, and TSS.

The aim of the remote sensing study of lakes Wairarapa and Onoke is to estimate TSS using the entire archive of Landsat 7 and 8 images, spanning a time period from 1999 until 2015. These images may provide useful background on the frequency and spatial variability in the lake of sediment resuspension or storm inflow events.

Method
United States Geological Survey (USGS) on demand atmospherically corrected Landsat imagery was ordered from http://espa.cr.usgs.gov/index/, including 91 images captured from 1999 - 2015. Atmospheric correction applies the radiative transfer model 6sv (Second Simulation of a Satellite Signal in the Solar Spectrum), which corrects for atmospheric scattering and absorption effects of gases, and aerosols (Kotchenova et al., 2008). All image processing routines were automated using scripts written in Interactive Data Language (IDL).

TSS was estimated from Landsat subsurface remote sensing reflectance ($r_{rs}$) using a similar semi-analytical algorithm to those found in Allan et al., (2015) and Dekker et al., (2002) except that only Landsat band 3 (b3) was applied to estimate TSS. Forward bio-optical modelling was used to quantify the physical processes responsible for relationships between
Landsat measured \( r_{rs} \) and TSS concentrations. These relationships were used to predict TSS from inverted \( r_{rs} \). The relationship between \( r_{rs}(\lambda) \) and the total backscattering coefficient \( (b_b) \) (m\(^{-1}\)) and total absorption \( a \) (m\(^{-1}\)) is (Gordon et al. 1988):

\[
r_{rs}(\lambda) = g_0 u(\lambda) + g_1 [u(\lambda)]^2
\]

where \( u \) is defined as (Dekker et al. 1997):

\[
u(\lambda) = \frac{b_b(\lambda)}{a(\lambda) + b_b(\lambda)}
\]

and \( g_0 \) and \( g_1 \) are empirical constants that depend on the anisotropy of the downwelling light field and scattering processes within the water. The constant \( g_0 \) is equivalent to \( f/Q \) where \( f \) represents geometrical light factors and \( Q \) represents the light distribution factor, which is defined as upwelling subsurface irradiance/upwelling subsurface radiance (Maritorena et al. 2002). It has been suggested that \( g_0 \) and \( g_1 \) should be considered as variables in optically complex inland waters (Aurin and Dierssen 2012; Li et al. 2013) therefore we used fitted values for \( g_0 \) and \( g_1 \) of 0.103 and 0.009 respectively, which were derived previously for Lake Ellesmere (Allan, 2014).

The absorption and backscattering coefficients are comprised of individual optically active constituents:

\[
b_b(\lambda) = b_{bw}(\lambda) + B b_{TSS} b_{TSS}^*(\lambda) C_{TSS}
\]

\[
a(\lambda) = a_{aw}(\lambda) + C_\phi a_{\phi}^*(\lambda) + a_{CDOMD}(\lambda)
\]

\[
a_{CDOMD}(\lambda) = a_{CDOMD}(\lambda_{440}) \exp[-S(\lambda - \lambda_{440})]
\]

where:

\( b_{bw}(\lambda) \) = backscattering coefficient of water

\( B b_{TSS} \) = backscattering ratio from TSS

\( b_{TSS}^*(\lambda) \) = specific scattering coefficient of TSS

\( C_{TSS} \) = concentration of TSS

\( b_{\phi}^*(\lambda) \) = specific scattering coefficient of phytoplankton

\( a_{aw}(\lambda) \) = absorption coefficient of pure water

\( C_\phi \) = concentration of chl \( a \)

\( a_{\phi}^*(\lambda) \) = specific absorption coefficient of phytoplankton

\( a_{CDOMD}(\lambda) \) = absorption coefficient for coloured dissolved organic matter (CDOM)

\( S \) = spectral slope coefficient

Values of \( a_{aw}(\lambda) \) and \( b_{bw}(\lambda) \) were prescribed from the literature (Morel 1974; Pope and Fry 1997). The backscattering ratio of TSS, \( B_{pTSS} \), was set to 0.019 (Petzold 1972). The specific
scattering coefficient of TSS at the Landsat b3 wavelength was estimated using a power function (Morel and Prieur 1977):

\[ b_{SP}^*(\lambda) = b_{SP}^*(555) \left( \frac{555}{\lambda} \right)^n \]  

(6)

where the value \( b_{TSS}^*(555) \) was set to 0.6 m² g⁻¹. The hyperbolic exponent \( n \) was set to 0.63, equating to a value measured in Lake Taupo, New Zealand (Belzile et al. 2004). The \( a_{\phi}(662) \) was 0.0136 m² mg⁻¹, equal to the average value measured in eight Dutch lakes (Dekker et al., 2002). The bio-optical simulations were run by varying TSS concentration from 0.1 to 417.6 mg L⁻¹ in increments of 0.5 mg L⁻¹ while \( a_{CDOM(440)} \) was fixed at a value of 0.042 m⁻¹, which is the average in situ of measurement in Lakes Wairarapa and Onoke, with chl \( a \) (μg L⁻¹) taken to increase with TSS (chl \( a \) (μg L⁻¹) = TSS (mg L⁻¹)/6) ranging from 0.017 to 67.6 μg L⁻¹ (encompassing a similar range to that measured in situ in Lakes Onoke and Wairarapa). This was designed to represent the often co-varying concentrations of chl \( a \) and TSS often found in inland waters.

Results

The semi-analytical relationship between TSS concentrations as a function of Landsat b3 remote sensing reflectance (\( r_{rb3} \)) was approximated via exponential relationships (Fig. 1a). Two exponential relationships were used to approximate the analytical relationship. At values of \( r_{rb3} < 0.06 \) the exponential function intercept was set to 0 in order to improve model accuracy at low reflectance (Fig. 1b).

![Figure 1](image)

Figure 1. (a) The analytical relationship between total suspended sediment (TSS) concentrations as a function of Landsat band 3 subsurface remote sensing reflectance (\( r_{rb3} \)). The analytical relationship is approximated using an exponential relationship. (b) For \( r_{rb3} < 0.06 \) this exponential relationship is applied using a zero intercept, which improves TSS estimations at low values of \( r_{rb3} \).

Nine in situ samples captured on the same day as Landsat images (within Lakes Onoke and Wairarapa) were used to calibrate and validate the model (Fig. 2). The relationship between observed and estimated TSS produced an \( r^2 \) of 0.97, RMSE 16.62 mg L⁻¹, and 32% RMSE, over a range of in situ TSS from 3 - 239 mg L⁻¹.
The spatially resolved estimates of TSS clearly demonstrate the highly heterogeneous distribution of TSS within and between lakes Wairarapa and Onoke. A common feature of the spatial distributions of TSS was generally higher concentrations within western regions of Lake Wairarapa. Also, there was often period when TSS concentrations in Alsop’s Bay were much lower than in the main lake basin. Time series of TSS from Landsat data at Lake Wairarapa Site 1 gave TSS concentrations of similar range to those measured in situ, demonstrating the high temporal variability in TSS concentrations (Fig. 3).

Landsat time series of TSS within Lake Onoke also demonstrate a similar range to those observed in situ, and again displaying high temporal variation (Fig. 4).
Figure 4. Time series estimation of total suspended solids (TSS) at Lake Onoke using Landsat (black filled circles), compared to those measured *in situ* (grey filled circles).
Figure 5. Spatially resolved total suspended sediments (TSS) in Lakes Onoke and Wairarapa derived from a semi-analytical algorithm for Landsat band three subsurface remote sensing reflectance data. Images displayed here represent a subset of the 91 images generated. Displayed images were selected to represent different magnitudes and spatial variations of TSS and were cloud free images.

Conclusions
The spatially resolved estimations of TSS will be useful for the calibration and validation of 3-D hydrodynamic models. Modelling provides the opportunity for interpretation of remotely sensed imagery through the quantification of the physical and biogeochemical fluxes that redistribute variables and lead to the spatial distributions observed in remote sensing imagery.
For example, the generally lower concentrations of TSS observed in western area of Lake Wairarapa may be due to the influence of lower concentrations TSS in inflows in this area. The often observed lower concentration of TSS in Alsop’s Bay is likely due to a lower energy environment owing to the shorter wind fetch and associated lower levels of wave and current energy for sediment resuspension in this area.

Future work
The Landsat remote sensing imagery and derivation of horizontal variations in TSS has provided a sound basis for comparisons with output from hydrodynamic-ecological models of Lake Wairarapa and Lake Onoke. These models have similar or slightly coarser resolution to Landsat but provide much more highly resolved temporal resolution, allowing more detailed exploration of the processes leading to the remote sensing TSS snapshots across the two lakes. The combination of remote sensing and hydrodynamic-ecological modelling can provide a powerful tool to improve predictions of TSS in Lake Wairarapa and Lake Onoke, and contribute to greater confidence in modelling of various management scenarios.

References
Allan, M.G., 2014. Remote sensing, numerical modelling and ground truthing for analysis of lake water quality and temperature. The University of Waikato, NZ.