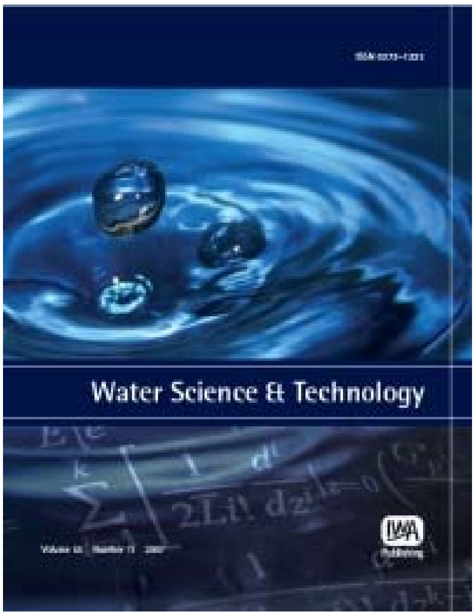
Water Science & Technology

Remote sensing of suspended solids concentration in a reservoir with frequent wildland fires on its watershed

M. Bonansea and R. L. Fernandez

ABSTRACT

Wildland fire is an important disturbance factor that can cause severe ecological and watershed damage. Depending on fire severity and watershed extension, reservoir suspended solids concentration (SSC), which arrives through river load, is expected to increase. Satellite remote sensing is an alternative technique to measure SSC in a reservoir. In this paper we evaluate the applicability of multitemporal Landsat data for mapping and monitoring of the SSC in a reservoir whose watershed was exposed to fires. Besides, we aim to identify catchment areas that have been burned, estimating the level of burn severity that occurred because of the fire. The Landsat images were radiometrically, atmospherically and geometrically corrected. Using the differenced normalized burn ratio (dNBR) algorithm, the perimeter and severity of fire was mapped. A theoretical model to characterize the distribution of SSC using multitemporal Landsat data was developed. The relationship between burn severity maps, rainfall and SSC maps improved our understanding of management actions on a reservoir which suffers frequent wildfires on its watershed. The theoretical model here developed may be considered as a low cost measurement tool for water management authorities, particularly when *in-situ* data are not available.

Key words | burn severity, Landsat 5 TM, Landsat 7 ETM +, reservoir, suspended solids concentration, theoretical model

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INTRODUCTION

Wildland fire is an ecologically important disturbance factor in many ecosystems, which can cause severe ecological and watershed damage. On the terrestrial side, catastrophic fire leads to changes in vegetative structure and soil properties, which increases the risk of huge biomass loss, runoff and erosion (Miller & Yool 2002). Because surface water systems are tightly linked to terrestrial systems, all the changes in the ground produced by fire can also have a direct impact on aquatic resources.

Depending on fire severity and watershed extension, the concentration of suspended solids in a reservoir, which arrives through river loads, is expected to increase. These instream flows are one of the most dramatic responses associated with fire, and play an important role in water quality management (Shukla *et al.* 2008). A variety of field-based methods have been developed to measure suspended solids concentration (SSC) in the aquatic environment. Satellite remote sensing is an alternative technique that allows mapping of spatial and temporal variation in SSC depending upon how sediment variations alter the optical properties or reflectivity of the water column (Pavelsky & Smith 2009). In contrast to conventional field methods for lake water management, these techniques are less expensive, low time-consuming, and easy to perform.

Most techniques for remote sensing of SSC construct empirical relationships between *in-situ* measurements and remotely sensed reflectance values (Schmugge *et al.* 2002). In the absence of a data field, as in the case of this study, a theoretical model is the best way to know the distribution of sediments. The simplest models for mapping SSC use reflectance values from a single band in the red portion of the spectrum (Hellweger *et al.* 2006). However, different studies suggest a combination of red reflectance with other visible bands in order to increase robustness when sediment color varies. While high sensitivity of the visible portion of the spectrum to variations in SSC is well documented, portions of near-infrared are also sensitive to SSC and have the advantage of being less influenced by waterbody

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bottom reflectance. Thereby, complex studies have successfully utilized infrared reflectance in combination with visible reflectance to produce a more robust SSC-reflectance relationship (Pavelsky & Smith 2009).

Among several satellites that have been used for the study of surface water with relative accuracy, the Landsat Program is particularly useful for assessment of inland water. The resolutions of Landsat sensors make these data highly suitable to evaluate the concentration of waterborne constituents. Furthermore, using Landsat data, it is possible to map and infer the severity of fire. Although fire severity is difficult to quantify, a number of studies have assessed the influence of wildfire events using satellite remote sensing (Röder *et al*. 2008; Meng & Meentemeyer 2011).

Summarizing, there are not many studies that integrate a multi-temporal remotely sensed images series of different Landsat satellites as a snapshot solution to the fluid dynamic problem of SSC in a reservoir after a wildfire, and it is being carried out for the first time for the conditions of this study in Argentina. Thus, the present study involves a complete treatment of accurate time series Landsat imagery for the study of SSC when *in-situ* data are not available. The main objective is to evaluate the applicability of multitemporal Landsat data for mapping and monitoring the SSC in a reservoir whose watershed was exposed to fires. Further, the work intends to identify areas that have been burned, estimating the burn severity.

METHODS

Study case

During 2003, a string of blazes, considered the most serious of the decade, occurred in the mountains of Cordoba (Argentina). Some of the fires that occurred in November covered the watershed of Los Molinos reservoir, although the size of the area affected by fire and its severity was unknown. Los Molinos watershed (Figure 1) has an area of 978 km^2 and is divided into four watersheds. After fires, rainstorms were recorded, carrying ashes to the reservoir through the rivers. The consequence for the waterbody was an increment in SSC, leading to water filter plugging and a slight coloration in drinking water. Los Molinos reservoir is used to supply drinking water to Cordoba city (with 1.4 million inhabitants). This reservoir has a surface area of 21.1 km^2, a medium depth of 16.3 m and a maximum volume of 399 million m^3.

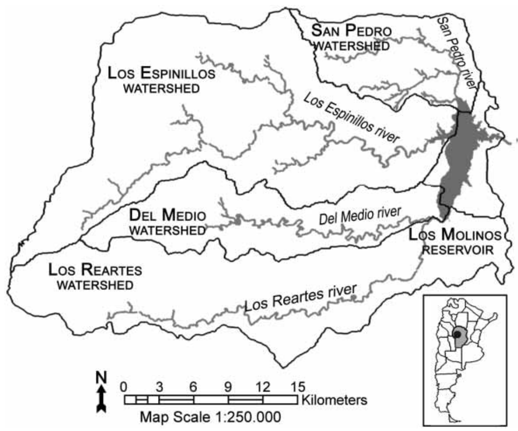

Figure 1 | Location of Los Molinos reservoir and its watershed in the central-west of Argentina.

Satellite data

The remote-sensing data source analyzed consisted of four Landsat 5 TM and four Landsat 7 ETM+ scenes that were downloaded from the USGS website (http://glovis.usgs.gov). The properties of these satellites are described in Table 1. All image processing steps were carried out using ENVI (version 4.2). To detect haze and cloud cover, an RGB band combination (1,6,6) was used. The images with cloud presence over the study area were not used (Table 2).

Pre-processing of Landsat images

To cross-calibrate TM images, the cross-calibration procedure and coefficients found by Vogelmann *et al*. (2001) were applied. To correct atmosphere effects, several algorithms have been developed. In this study we applied the widely used dark-object subtraction (DOS) model (Chavez 1996). Geometric corrections were applied with a root mean square error (RMSE) for positional accuracy less than 0.5 pixel for each scene, guaranteeing a precise geometric match among them. Since May 2003, ETM+ images have a failure known as Scan Line Corrector: off (SCL-off), characterized by wedge-shaped gaps (Chen *et al*. 2011). This failure was corrected predicting the best closest value of the missing pixels, using a methodology adapted from the SLC Gap-Filled Products, Phase One Methodology article (Scaramuzza *et al*. 2004).

Burned areas detection

Using the normalized burn ratio (NBR) developed by Key & Benson (2006), burned areas were identified and mapped on

Table 1 | Principal resolutions of Landsat images

Sensor	Resolutions	Band 1	Band 2	Band 3	Band 4	Band 5	Band 6	Band 7	Band 8
TM	Spectral range (nm)	0.45–0.52	0.52–0.60	0.63–0.69	0.76–0.90	1.55–1.75	10.4–12.5	2.08–2.35	–
	Spatial	30 m					120 m	30 m	–
ETM +	Spectral range (nm)	0.45–0.52	0.53–0.61	0.63–0.69	0.78–0.90	1.55–1.75	10.4–12.5	2.09–2.35	0.52–0.90
	Spatial	30 m					60 m	30 m	15 m

Table 2 | Multitemporal Landsat dataset (path/row: 229/82)

Date	Sensor type	Sky condition
10/22/2003	ETM +	Free of clouds
11/07/2003	ETM +	Free of clouds
11/15/2003	TM	Presence of clouds
12/01/2003	TM	Presence of clouds
12/09/2003	ETM +	Free of clouds
12/17/2003	TM	Free of clouds
12/25/2003	ETM +	Free of clouds
01/02/2004	TM	Free of clouds

to the watershed (Equation (1)):

$$\text{NBR} = (\text{Band 4} - \text{Band 7})/(\text{Band 4} + \text{Band 7}) \quad (1)$$

The NBR algorithm was calculated for both pre-fire (10/22/2003) and post-fire (12/09/2003) scenes. A differenced NBR (dNBR) was applied by subtracting the post-fire NBR data from the pre-fire NBR data. This index was used to assess fire severity effects, from unburned areas to a complete canopy removal.

Spectral bands model to determinate SSC

To assess spatial and temporal patterns in SSC across the reservoir, the multitemporal Landsat dataset was analyzed. Due to the absence of *in-situ* SSC samples, a theoretical model was applied. In order to ensure robust SSC distribution, the processing techniques included an analysis of all Landsat images to select those individual or combined bands providing the best information on SSC distribution. Digital enhancement techniques were performed to develop a new distribution of the original reflectance values. Transects were elaborated to identify the suspended solids distribution across the reservoir.

Having found the best band combination which better characterized the distribution of SSC in the reservoir over time, a model (M) was created to differentiate between low, medium and high SSC. The thresholds of the model were generated based on the combined multitemporal dataset reflectance distribution (MDRD):

$$M\begin{cases} 0 \text{ (low SSC) if MDRD were from 0 to 50\%} \\ \quad \text{reflectance values} \\ 1 \text{ (medium SSC) if MDRD were from 50 to 80\%} \\ \quad \text{reflectance values} \\ 2 \text{ (high SSC) if MDRD were from 80 to 100\%} \\ \quad \text{reflectance values} \end{cases}$$

Using this model, we were able to generate qualitative SSC distribution maps which were related to wildfire maps and rainfall to determinate whether burned areas and their severity had a relationship to the SSC of the reservoir.

RESULTS

Mapping fire perimeter and burn severity

The burned areas covered a wide range of vegetation types, including forest, shrub, and some herb communities. The dNBR algorithm was an appropriate method for mapping the perimeter and severity of fire (Figure 2). Similar results were found by Miller & Thode (2007), and by Meng & Meentemeyer (2011). During November 2003, a total of 62.6 km^2 was burned, which represents 7.1% of Los Molinos watershed. The burned area was divided into two fires, the larger covering 49.4 km^2 and the smaller covering 13.2 km^2. The central zone of Los Espinillos watershed was the most affected area (37.9 km^2 burned). Compared with the rest of the catchments, this watershed had the highest values of high, moderate and low burn severity. This principal fire also affected 11.5 km^2 of the upper portion of the San Pedro watershed. The second fire was detected on the limit between the Del Medio and Los Reartes watersheds. In this case, 5.2 km^2 on Del Medio and 8.0 km^2

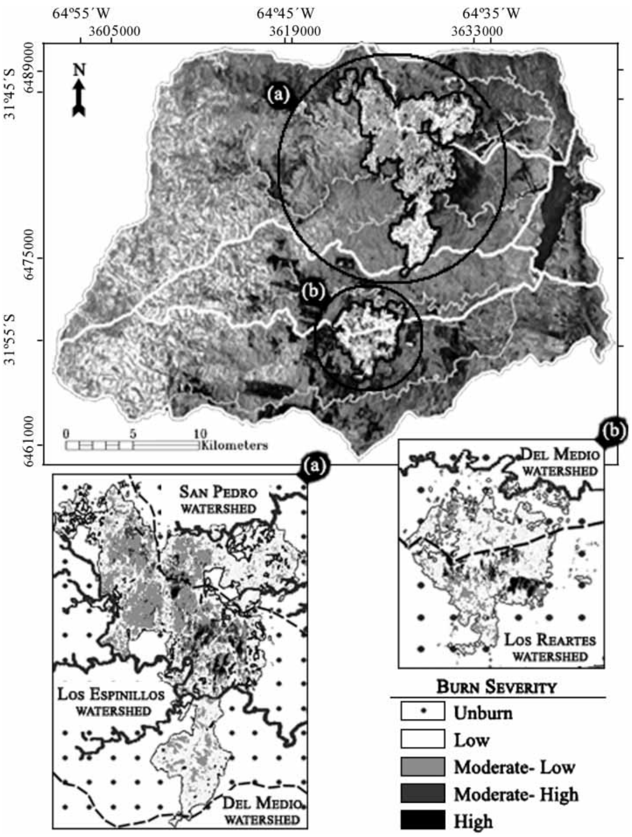

Figure 2 | Burn perimeter and fire severity map on Los Molinos watershed.

on Los Reartes watersheds were burned. In both catchment areas the most common category was low severity.

Multitemporal study of suspended solids concentration

The visual enhancement techniques applied to each band or band combination of multitemporal Landsat series showed that as wavelength increased, response values were higher for suspended solids in the water column. In addition, Pavelsky & Smith (2009) suggested that although visible portions of the spectrum are sensitive to SSC, portions of the near-infrared spectrum are also sensitive to these solids and they have the advantage of being less influenced by bottom reflectance in shallow water environments than shorter wavelengths. Previous studies have shown that for aquatic systems a combination between Landsat bands 3 and 4 can provide useful information when large sediment loads occur (Hellweger *et al.* 2006; Kulkarni 2011). However, in our study the combination or sum of spectral Landsat bands: 3, 4 and 5 proved to be a better method to clearly characterize areas of higher and lower SSC in Los Molinos reservoir. The methodology used here can strengthen the results for decision making in the management of reservoirs when SSC is a problem and *in-situ* data are not available. To illustrate these results, some band combinations are shown on the 9th December 2003 ETM+ image. Figure 3(a) represents the sum of bands 3, 4 and 5 applied on this ETM+ image. A zone with high reflectance values can be clearly identified in an area where a large number of particles in suspension were expected to be present. The generation of a transect on this zone (Figure 3(b)) showed that the band combination selected was the best method to differentiate the presence of a zone of high reflectance values, proving that this combination may potentially play a significant role in explaining the presence of solids in reservoirs. Although we only show the 9 December 2003 ETM+ image, the same results were found in all the images analyzed.

The same band combination was applied to the multitemporal Landsat series. Figure 4, shows the pixel distribution of each satellite image. Based on this reflectance distribution the threshold classes generated with the *M* model were applied. A qualitative image for SSC categories on the reservoir during the study period was created (Figure 5(a)). The reservoir surface percentage of the

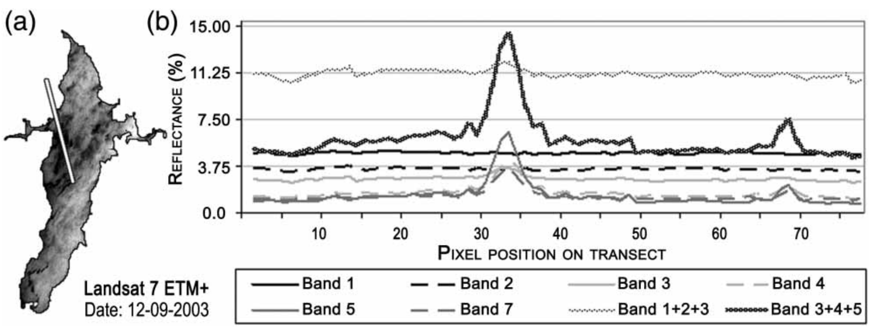

Figure 3 | (a) Transect which includes the higher reflectance values on Los Molinos reservoir for the 9 December 2003 ETM+ image. Land has been masked out as white. (b) Reflectance profiles of some of the bands and combinations tested. Because clear waters have less reflectance than turbid waters, higher reflectivity areas represent higher SSC.

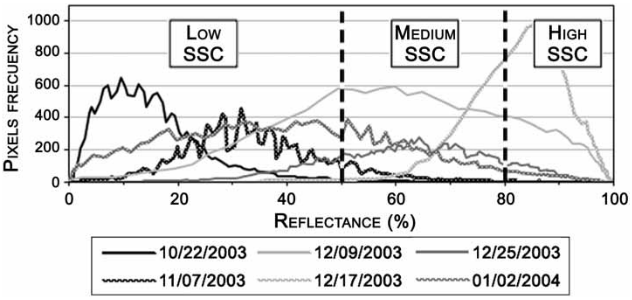

Figure 4 | Radiometric distribution of Landsat images used in this study. The vertical lines represent the threshold of each SSC category.

analyzed Landsat images was related to the rainfall registered on the watershed (Figure 5(b)).

The management of fire is particularly relevant to the aquatic ecosystems. The pre-fire image showed a low and homogeneous SSC category. After the fires the SSC category began to increase. This increase was greater after the beginning of the rainstorms. Thus, since December, high reflectance inflows through Los Espinillos river were observed. According to Robichaud *et al.* (2007), high soil burning leads to much more soil runoff and erosion compared with unburned and lightly burned areas. The burn severity map (Figure 2), reveals that Los Espinillos watershed suffered the most severe fires, with its burned areas in direct contact with its river and its affluents. Therefore the elevated influxes were related with runoff ashes by rainfall, producing an increase in SSC in the reservoir. Less intense influxes were observed through the rest of the rivers as the burned areas of these watersheds were smaller. On 9th December 2003, after the highest rainfall, an increase was observed in SSC, with half of the waterbody

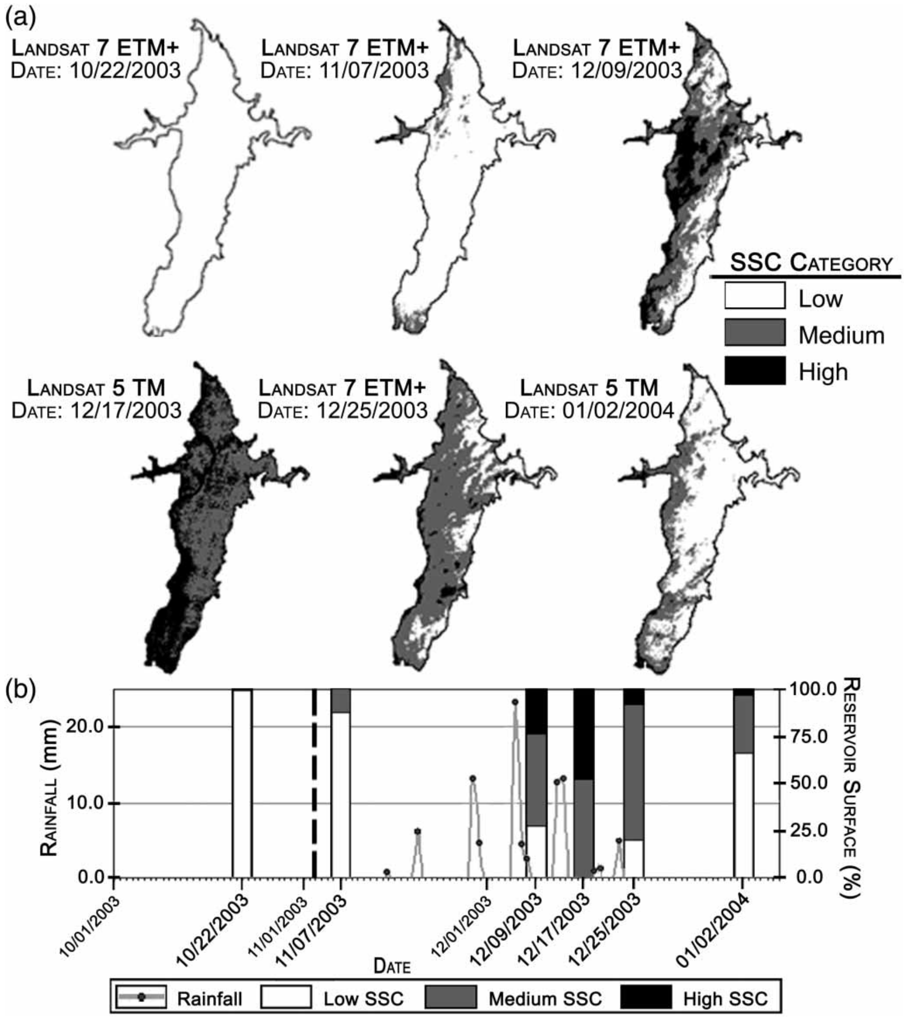

Figure 5 | (a) Qualitative SSC maps derived from multitemporal Landsat images after application of the *M* model. (b) Rainfall over Los Molinos watershed and bar graph of reservoir surface percentage on the Landsat images. The vertical line represents the beginning of the fires.

surface classified as medium SSC category. The SSC increased until 17 December 2003, when 47.8% of the reservoir surface was classified as high SSC and 51.7% classified as medium SSC category. On this date the highest SSC was observed in the southwest coast, while a second input of suspended solids was registered by Los Espinillos river, which could be related with the rainfall of previous days. On 25 December 2003, a mixture over the entire surface of the lake was observed, which may be related to strong winds with sedimentation processes. This resulted in a predominance of the medium SSC category. In early 2004, due to the sedimentation of suspended matter and the absence of rainfall, the reflectance values and heterogeneity decreased, resulting in a decrease of SSC.

CONCLUSIONS

Remote sensing provides suitable information concerning water quality and aquatic systems management. Landsat imagery allows the evaluation of different environments affected by natural or anthropic disturbances. In this study, we demonstrated the potential of time series Landsat imagery to characterize an increase of SSC events and its dynamics in a reservoir whose watershed was exposed to fires. Besides, we could identify the perimeter of the fire burned areas, estimating the level of burn severity. This kind of information could be useful for both fire and basin managers who require standard and reliable techniques for efficient mapping and monitoring of wildfire effects.

The sum of Landsat bands 3, 4 and 5 allowed us to clearly identify the presence of suspended elements in Los Molinos reservoir. This band combination may potentially play a significant role in mapping changes in the SSC, allowing the discrimination of even slight changes in water reflectivity, both to the center of the reservoir and towards the coastline. Although we acknowledge that it would be better to have *in situ* SSC measurement coinciding with satellite overpass to generate an empirical analysis, in the absence of a data field, the theoretical model presented here proved to be useful to generate and compare qualitative SSC maps that demonstrated the dynamics of the suspended elements in Los Molinos reservoir.

Overall, our results demonstrated the relationship between burn severity maps, rainfall and SSC maps, which could help to improve the understanding of management action on a reservoir which suffers wildfires on its watershed. The theoretical model developed could become an independent, low additional training and low cost measurement tool for water management authorities when *in-situ* data is not available.

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REFERENCES

Chavez, P. 1996 Image-based atmospheric corrections revisited and improved. *Photogrammetric Engineering and Remote Sensing* **62**, 1025–1036.

Chen, J., Zhu, X., Vogelmann, J., Gao, F. & Jin, S. 2011 A simple and effective method for filling gaps in Landsat ETM+ SLC-off images. *Remote Sensing of Environment* **115** (4), 1053–1064.

Hellweger, F., Miller, W. & Oshodi, K. 2006 Mapping turbidity in the Charles River, Boston using a high resolution satellite. *Environmental Monitoring and Assessment* **132** (1–3), 311–320.

Key, C. & Benson, N. 2006 Landscape assessment: remote sensing of severity, the Normalized Burn Ratio. In: *FIREMON: Fire Effects Monitoring and Inventory System* (D. Lutes, R. Keane, J. Caratti, C. Key, N. Benson & L. Gangi, eds). USDA Forest Service, Rocky Mountain Research Station, Ogden, UT.

Kulkarni, A. 2011 Water quality retrieval from Landsat TM imagery. *Procedia Computer Science* **6**, 475–480.

Meng, Q. & Meentemeyer, R. 2011 Modeling of multi-strata forest fire severity using Landsat TM Data. *International Journal of Applied Earth Observation and Geoinformation* **13** (1), 120–126.

Miller, J. & Thode, A. 2007 Quantifying burn severity in a heterogeneous landscape with a relative version of the delta Normalized Burn Ratio (dNBR). *Remote Sensing of Environment* **109** (1), 66–80.

Miller, J. & Yool, S. 2002 Mapping forest post-fire canopy consumption in several overstory types using multi-temporal Landsat TM and ETM data. *Remote Sensing of Environment* **82** (2–3), 481–496.

Pavelsky, T. & Smith, L. 2009 Remote sensing of suspended sediment concentration, flow velocity, and lake recharge in the Peace-Athabasca Delta, Canada. *Water Resources Research* **45**, W11417.

Robichaud, P., Lewis, S., Laes, D., Hudak, A., Kokaly, R. & Zamudio, J. 2007 Postfire soil burn severity mapping with hyperspectral image unmixing. *Remote Sensing of Environment* **108** (4), 467–480.

Röder, A., Hill, J., Duguy, B., Alloza, J. & Vallejo, R. 2008 Using long time series of Landsat data to monitor fire events and post-fire dynamics and identify driving factors. A case study in the Ayora region (eastern Spain). *Remote Sensing of Environment* **112** (1), 259–273.

Scaramuzza, P., Micijevic, E. & Chander, G. 2004 *SLC Gap-Filled Products, Phase One Methodology*.

Available from: http://landsat.usgs.gov/documents/SLC_Gap_Fill_Methodology.pdf (accessed 26 April 2012).

Schmugge, T., Kustas, W., Ritchie, J., Jackson, T. & Rango, A. 2002 Remote sensing in hydrology. *Advances in Water Resources* **25** (8–12), 1367–1385.

Shukla, J., Misra, A. & Chandra, P. 2008 Modeling and analysis of the algal bloom in a lake caused by discharge of nutrients. *Applied Mathematics and Computation* **196** (2), 782–790.

Vogelmann, J., Helder, D., Morfitt, R., Choate, M., Merchant, J. & Bulley, H. 2001 Effects of Landsat 5 Thematic Mapper and Landsat 7 Enhanced Thematic Mapper Plus radiometric and geometric calibrations and corrections on landscape characterization. *Remote Sensing of Environment* **78** (1–2), 55–70.

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