ABSTRACT

The Peace-Athabasca Delta (PAD), Canada, has been the subject of much interest during the last 30 years, particularly with respect to apparent changes in flooding and potentially resulting changes in vegetation patterns and ecosystem function. Tracking these changes is exceedingly difficult using traditional hydrological and ecological monitoring techniques. This paper attempts to present a geomatics based approach for monitoring the spatio-temporal changes that occur within this productive wetland area. A combination of Radarsat SAR and visible-infrared satellite images was used to generate flood maps for the six-year period between 1996 and 2001. These maps clearly depict the extent of the 1996 and 1997 overland floods and the subsequent water level draw down. A spatial flood-duration map based on the flood maps of individual years was also generated, and shows regions in the delta where the frequency of flooding appears to be highest. Such maps are invaluable for any ecological change detection protocols that may be developed for this region. The general vegetation patterns in the PAD were also mapped using multi-temporal SPOT-4 images from the summer of 2001. The accuracy of the 2001 vegetation map was assessed to 86%. By comparing the vegetation and flood duration maps, the relationship between vegetation patterns and duration of flooding could be examined.

Airborne scanning LiDAR data from the summer of 2000 were also used to generate a Digital Elevation Model (DEM) of selected non-flooded areas. The LiDAR accuracy was satisfactory and the DEM proved to be quite detailed and useful for understanding the subtle topographic patterns in this relatively flat region. It was shown that a relationship existed between vegetation patterns and topography by comparing the vegetation map to the DEM. Because of the usefulness of these spatial databases, it is recommended that flood maps and vegetation maps are generated annually to monitor the changes that occur in the delta.

Key words: Peace-Athabasca Delta, wetland, remote sensing, flood mapping, vegetation mapping, LiDAR

* This report may be cited as:

INTRODUCTION

The Peace-Athabasca Delta (PAD) is a 3900 km$^2$ wetland complex that is located in northeastern Alberta at the confluence of the Peace and Athabasca Rivers (See Figure 1). The small wetland basins scattered within the delta provide important habitat for a large number of migrating waterfowl, numerous muskrats and other mammals. Since a major portion of the wetland basins is disconnected from the channel network, they rely on large, periodic overland floods to replenish and maintain their productivity. The hydrology of the Peace-Athabasca Delta has received much attention during the past 30 years (PAD-PG, 1973; PAD-IC, 1987; PAD-TS, 1996), mainly because of the concern that the construction of the W.A.C. Bennett Dam and Williston Reservoir on the Peace River in 1968 would affect the flood frequency and, thereby, also the productivity of the wetland complex. Based on the results from the PAD-PF (1973) and PAD-IC (1987), Prowse and Lalonde (1996) showed that the backwater effect caused by river ice-jams were the main reason for the large overland floods. Prowse et al. (1996) later observed that the Peace River flow regulation combined with a climate shift in the 1970’s resulted in a reduced frequency of ice-jam flooding. The PAD-TS (1996) concluded that regardless what the future climate variations may be, the effects of the dam on the frequency of ice-jam flooding will still persist. Since the ecology of the Peace-Athabasca Delta is driven by the hydrologic regime, many studies have also been undertaken to assess the effect of flood frequency on the vegetation patterns (PAD-PG, 1973; PAD-TS, 1996; Timoney, 2002). PAD-PG (1973) proposed that reduced flooding and declining water levels would allow encroaching willows to advance into the wetland basins and replace the productive emergent vegetation. Timoney (2002), on the other hand, suggested that the wetland ecology is much more resistant to change than previously believed. Although there is still considerable scientific debate on the role water plays in the encroachment or senescence of vegetation, it was clear that an effective means of assessing these changes both spatially and temporally was required. Because of this, our research focused on the mapping, monitoring and understanding of the extent, frequency and duration of flooding as well as mapping the general vegetation patterns within the Peace-Athabasca Delta for the purposes of ecosystem assessment and management. The large size, unique terrain and the remoteness of the delta along with lack of detailed and accurate topographic information and poor hydrometric records pose a challenge to understanding the hydrology. As such, it also presents an ideal opportunity for employing remote sensing as a hydrologic monitoring tool, an approach that is too often overlooked in many water-management studies (Kite and Pietroniro, 1996).

The use of remote sensing technologies in wetland studies is not new. It has been well understood that visible and infrared (VIR) sensors, such as SPOT and Landsat, are able to detect open water surfaces and distinguish wetland vegetation from upland vegetation. However, the visible and infrared wavelengths are not long enough to penetrate vegetation, which means that...
flood extents in vegetated areas are underestimated. Pietroniro et al. (1999) used a time series of Landsat MSS, Landsat TM and SPOT panchromatic data to document changes in open water extent in the Peace-Athabasca Delta between 1974 and 1990. The time-series of images highlighted the extent of open water change that occurred during a significant drying trend. However, the flooded areas obscured by vegetation went mostly undetected. Synthetic Aperture Radar (SAR) is useful for flood mapping because of its sensitivity to moisture differences, or rather differences in dielectric constant. The microwaves that are transmitted by SAR sensors also have the potential to penetrate clouds and vegetation. A smooth open water surface acts as a specular reflector in the microwave spectrum and yields a very low radar backscatter signal, while dry and flooded vegetation generally produce a medium strength and a strong return signal, respectively. Wang et al. (1995) suggested that the total backscatter for a non-flooded forest stand is dominated by surface scattering on the forest floor and volume scattering in the canopy. They also pointed out that the high returns of flooded forest stands is caused by the corner reflection between the tree trunks and the standing water surface, amplified by the high dielectric constant of the water. Töyrä et al. (2001; 2002) classified spring and summer Radarsat SAR scenes of the Peace-Athabasca Delta into open water, flooded vegetation and non-flooded land and achieved an accuracy of 76% and 56%, respectively. They found that for each vegetation type, the Radarsat could often distinguish if the area was flooded or non-flooded. However, there were often difficulties separating one type of flooded vegetation from another vegetation type that was non-flooded. Töyrä et al. (2001; 2002) also evaluated the complimentary information obtained from combining the Radarsat SAR scenes with multispectral SPOT scenes. The Radarsat and SPOT combination increased the classification accuracy significantly to 92% and 83% for spring and summer conditions, respectively. The VIR information helped in distinguishing between the different vegetation types, preventing misclassification between dry upland vegetation and flooded wetland vegetation.

As part of this overall strategy to assess changes in the PAD, it is also important to monitor the changes in vegetation patterns throughout the delta. Dirschl et al. (1974) used 1:37,000 black and white air photos from 1955 and 1956 to map eight terrestrial community types and seven water body types within four selected areas in the Peace-Athabasca Delta. The vegetation types were outlined by hand on uncontrolled air photo mosaics based on ground verification data in the field. Air photo mapping has the advantage and disadvantage of high resolution. More details can be picked out visually, but any computer-based classification is more complicated. A controlled air photo mosaic does also take longer time and is more costly to generate compared to producing an orthorectified satellite image. Visible and infrared satellite remote sensing has been utilized for wetland vegetation mapping since the launch of the first 80-m resolution Landsat MSS satellite in the early 1970’s. Jaques (1990) used MSS imagery from 1976 and 1989 and an unsupervised classification scheme to map the Peace-Athabasca Delta into six and eight
vegetation classes, respectively. The accuracy was assessed to be 82% for the 1976 image and 89% for the 1989 image based on the same ground truth sites that were initially used to group the classes (Jaques 1990). Wickware (1978) and Wickware and Howarth (1981) also utilized Landsat MSS data to map habitat types in the Peace-Athabasca Delta based on vegetation and moisture conditions. They concluded that the imagery gave satisfactory results, although some problems were encountered at the land-water fringe where the spatial mix of vegetation types was close. Rutchney and Vilcheck (1994) used SPOT multispectral data and a hybrid unsupervised/supervised classification algorithm to group the wetland vegetation in the Everglades, Florida, into 20 classes. The classes represented a few different vegetation types, which in turn were broken down into smaller classes according to specific vegetation densities. The reported accuracy for the 20 classes was 70.9%. Since much of the inaccuracy came from errors within the density classes of a single vegetation type, the 20-class map was grouped into 12 more general classes and the accuracy increased to 80.9%. As part of the Peace-Athabasca Delta Technical Studies, Terrain Resources Ltd. (1995) mapped the vegetation in the delta into 18 detailed classes using a Landsat TM image from 1992. An attempt was made to separate different meadow types and aquatic emergents, but the classification accuracy was much too low. May et al. (1997), found that Landsat TM and SPOT-1 imagery could discriminate shrub vegetation from meadows, while meadow sub-types could not be distinguished from one another.

Another important aspect of this work is to improve the understanding of flow patterns within this regime. Often, subtle differences in the landscape elevation can determine whether or not certain regions are inundated. In general, the Peace-Athabasca Delta has a very low relief, with the exception of the channel levees and some scattered bedrock outcrops. This presents a hydrological modelling problem since small water level changes can result in a large increase in water surface area. Elevation models derived from 1:50,000 National Topographic Survey (NTS) contour lines and survey points have been used up to date. These elevation models lack the detail and accuracy needed to truly model overland flow paths and basin contributing areas. Such information is tremendously important for water balance studies. Traditional in situ surveying is impossible for such a large area with such difficult terrain. Airborne stereophotography is possible, but is very time consuming and costly. A reasonable alternative is airborne scanning LiDAR (Light Detection and Ranging) sensors that have the potential to provide accurate data at high densities (Töyrä et al. 2003).

The objective of this paper was to describe the use of multi-sensor remotely sensed data in conjunction with ground-based observation to provide an efficient and plausible monitoring strategy that supplements traditional monitoring methods. Although remote sensing may not provide the high level of details obtained through in situ sampling, it does allow for spatial snapshots of the entire delta at timely intervals that are otherwise unavailable. Information such
as distributed flood-duration maps or relationship between distribution of shrubs and flood duration/depth can be established. The importance of flood frequency and vegetation/topography along selected transects or, in smaller areas within the Peace-Athabasca Delta has been studied and discussed by many projects (Townsend, 1972; Dirschl, 1974; Mueller, 1996; Timoney, 2002). This paper illustrates a cost-efficient, non-conventional and effective approach for monitoring and evaluating these spatio-temporal changes that should be adapted by monitoring and operational agencies interested in the ecosystem health of this very important region of Canada.

Figure 1. The Peace-Athabasca Delta (58º40’N, 111º15’W) in northeastern Alberta, Canada. The LiDAR flight lines and the extent of the vegetation map are also shown.
METHODOLOGY

As part of the overall geomatics-based management plan for the Peace-Athabasca Delta, the vegetation, flood extent and topography were mapped using remotely sensed data. The methodology is presented in four sections. The first three describe the techniques used for development of the flood maps, vegetation maps and the digital elevation model. The following section describes the procedure of analyzing these derived data sources.

Flood Mapping

The purpose of the flood mapping component was to delineate the flood extents in the Peace-Athabasca Delta between 1996 and 2001 using the method previously developed and tested by Töyrä (2001; 2002). A combination of SAR and VIR imagery was suggested as a reliable approach. In this way, the classification procedure could benefit from the complementary information in the two image types and, thereby increase the accuracy of the flood maps. The Canadian Radarsat SAR was operational in the spring/summer of 1996, in time for the first major overland flood in the Peace-Athabasca Delta since 1974. The delta flood in the spring was due to backwater produced by ice-jams in the Peace, Athabasca and the Quatre Fourches rivers. An open water flood also occurred later in the summer of 1996 and another ice-jam spring flood took place in the spring of 1997. No other large overland floods occurred during the study period, meaning that the imagery acquired between 1998 and 2001 represented flood draw down. Detailed studies of the 1996 flooding were conducted by Peters et al. (1999). Between one and three Radarsat SAR images combined with either SPOT multispectral or Landsat TM imagery were obtained for each summer season subsequent to 1996, with the exception during the summer of 2000 when no useful VIR imagery were available due to cloud. Table 1 lists all the acquired satellite images.

SAR image acquisitions were limited, whenever possible, to shallower incidence angle modes. Many studies have shown that a lower incidence angle allows for better penetration of the vegetation layer, which results in a better detection of flooded vegetation (Crevier and Pultz, 1997; Adam et al. 1998; Töyrä et al. 2001). Therefore, Radarsat standard beam 1 and 2, which have incidence angles of 23.5 and 27.5 degrees, respectively, were selected in first hand. The high incidence angle Radarsat (S6) from May 1996 was deemed acceptable since it was acquired in the spring prior to foliation. Radarsat imagery were acquired for the 1997 season, but they were not useable due to the severe striping caused by the automatic gain control in the sensor (Töyrä et al. 2000). Other years were also affected by the striping (1996, 1998), but not as severely as the 1997 imagery and could, therefore, be restored (Vachon et al. 1997). The 1999 and 2001 Radarsat images were acquired using a fixed gain and did not have striping problems. In terms of VIR data, cloud-free scenes, preferably Landsat TM due to the large size of the delta,
were selected as close as possible to the Radarsat overpasses. For the occasions when no cloud-free Landsat scene was available, a SPOT scene or a partial Landsat scene (from a near-by track) was selected instead. However, these images did not cover the entire delta.

Table 1. The acquired flood mapping satellite images. The 1997 Radarsat images are not useable due to severe saturation caused by the Automatic Gain Control (AGC). The two images in bold letters were also used for the vegetation mapping. 

<table>
<thead>
<tr>
<th>Month &amp; Year</th>
<th>Radarsat</th>
<th>Radarsat Date</th>
<th>VIR</th>
<th>VIR Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 1996</td>
<td>S6</td>
<td>May 18</td>
<td>SPOT (P)</td>
<td>May 23</td>
</tr>
<tr>
<td>May/June 1997</td>
<td>AGC</td>
<td>May 13</td>
<td>Landsat TM (P)</td>
<td>June 09</td>
</tr>
<tr>
<td>Sept./Oct. 1997</td>
<td>AGC</td>
<td>October 3</td>
<td>SPOT (P)</td>
<td>September 24</td>
</tr>
<tr>
<td>May 1998</td>
<td>S2</td>
<td>May 17</td>
<td>SPOT (P)</td>
<td>May 16</td>
</tr>
<tr>
<td>July 1998</td>
<td>S1 &amp; S7</td>
<td>July 21 &amp; 22</td>
<td>SPOT (P)</td>
<td>July 26</td>
</tr>
<tr>
<td>Aug. 1998</td>
<td>S2</td>
<td>August 23</td>
<td>Landsat TM (F)</td>
<td>August 22</td>
</tr>
<tr>
<td>May 1999</td>
<td>S1</td>
<td>May 29</td>
<td>Landsat TM (P)</td>
<td>May 30</td>
</tr>
<tr>
<td>July 1999</td>
<td>S1</td>
<td>July 8</td>
<td>Landsat TM (F)</td>
<td>July 8</td>
</tr>
<tr>
<td>Aug. 1999</td>
<td>S2</td>
<td>August 18</td>
<td>Landsat ETM+ (F)</td>
<td>August 17</td>
</tr>
<tr>
<td>May 2001</td>
<td>S2</td>
<td>May 27</td>
<td>SPOT (P)</td>
<td>May 22</td>
</tr>
<tr>
<td>July/Aug. 2001</td>
<td>S2</td>
<td>July 14</td>
<td>SPOT (P)</td>
<td>August 17</td>
</tr>
</tbody>
</table>

Ground verification data were collected in May 1996, August 1997, October 1997, May 1998, July 1998, September 1998, May 1999, September 1999, and July 2001. Representative flooded and non-flooded areas of the main land-cover classes were visited in the field. Ground verification data were collected in the form of video footage and photographs taken from the ground or from a helicopter.

All Radarsat scenes were calibrated to derive radar backscatter (σ°) values (Srivastava, 1998). The variations in local incidence angle were ignored because of the extremely flat topography of the Peace-Athabasca Delta region. The Radarsat speckle was reduced by applying a 7x7 pixel Kuan adaptive filter (Kuan et al. 1987). All imagery were orthorectified (Toutin, 1995) to a UTM (Zone 12) projection based on the NAD27 datum. To ensure a good fit between the Radarsat and the SPOT or Landsat scenes, the Radarsat scenes were re-registered to their respective SPOT or Landsat scene using eight GCPs (tiepoints), a first or second order polynomial equation, and a nearest neighbour re-sampling procedure.
The image channels were classified into open water, flooded vegetation, and non-flooded land using a Mahalanobis distance supervised classification scheme (Schott, 1997). Since some of the VIR and Radarsat images did not cover the entire delta, the classification was conducted in sections where the areas covered by both image types (combined image classification) were classified separately from the areas covered by only one of the image types (single image classification). The Radarsat and SPOT or Landsat channels were combined using the augmented vector approach (Schistad Solberg et al. 1994). Classification training areas were collected based on ground verification data. As indicated by Table 1, two different Radarsat images (S1 and S7) and a SPOT image were obtained for July 1998. In this case, all three images were combined when possible. The section that was not covered by the smaller SPOT scene was classified using a combination of the two Radarsat images. Töyrä et al. (2001) showed that there was a significant increase in classification accuracy of the open water class when combining a low incidence angle Radarsat (S1) with a high incidence angle Radarsat (S7). After completing the classifications, the combined image type and single image type classification results for each acquisition date were mosaicked together into one seamless flood map. Mosaicking was not needed for the acquisition dates where both image types covered the entire delta.

As the floodwater drained from the delta and levees began to emerge from beneath the flood water, water filled basins were cut-off from the drainage network. To map the flooded areas that were hydraulically connected to the drainage network, an image polygon growing algorithm was applied to each flood map. This algorithm finds all the 8-connected pixels belonging to the same class, or in this case, belonging to either the open water or flooded vegetation classes.

**Vegetation Mapping**

The vegetation mapping component focused on evaluating the use of SPOT-4 multispectral scenes for mapping general vegetation types in the Peace-Athabasca Delta. One of the important issues of this work was the concern that encroaching willows (*Salix spp.* ) could potentially overtake the productive graminoid covered areas in the delta. Therefore, the focus of the vegetation mapping was directed on outlining the shrubs. The vegetation classes used in this study are listed and described in Table 2. The vegetation mapping was limited to the centre portion of the delta (see Figure 1) as the field sampling was focused in this region. This area was selected because it includes active deltas in Mamawi Lake, many isolated and open wetland basins, and higher levees where the relationship between vegetation and elevation could be evaluated.

Reference data were collected in the field in June 2000 and July 2001. Selected areas were visited *in situ* and the vegetation cover was identified. To obtain more data while reducing the cost of field sampling, the vegetation cover was also video-filmed and photographed along helicopter transects. These transects were flown and recorded in slow speed at relatively low altitudes.
Table 2. The vegetation classes.

<table>
<thead>
<tr>
<th>Class</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>Open Water</td>
</tr>
<tr>
<td>Aquatic</td>
<td>Aquatic macrophytes and lake shore communities</td>
</tr>
<tr>
<td>Graminoid</td>
<td>Wet or dry sedges (<em>Carex spp.</em>) and grasses (<em>Calamagrostis spp.</em> and <em>Scolochloa spp.</em>), also immature meadows (recently mud fields). May contain scattered low shrubs</td>
</tr>
<tr>
<td>Shrub</td>
<td>Mainly willows (<em>Salix spp.</em>)</td>
</tr>
<tr>
<td>Deciduous</td>
<td>Deciduous trees, such as poplar (<em>Populus spp.</em>) and birch (<em>Betula spp.</em>)</td>
</tr>
<tr>
<td>Conifer</td>
<td>Coniferous trees, such as spruce (<em>Picea spp.</em>). Also includes mixed forest.</td>
</tr>
</tbody>
</table>

The May 2001 and August 2001 SPOT-4 images that were used for flood mapping (see Table 1) were also used for the vegetation mapping. It was noted that the differences between vegetation types were prominent when a combination of the two images were viewed as a false-colour composite (August mid-infrared, May mid-infrared and May near-infrared). This was due to phenological changes that occurred between May and August. Therefore, a combination of the two SPOT images was used for the vegetation mapping. To ensure a good fit between the already orthorectified images, the August scene was re-registered to the May scene using eight tie points, a first order polynomial and a nearest neighbour re-sampling algorithm (Schott, 1997). The area of interest in the centre of the delta was subsetted from the two images and used as classification input. The red, near-infrared and mid-infrared channels from each of the SPOT scenes were combined using the augmented vector approach and classified using a supervised Maximum Likelihood classifier (Schott, 1997). Classification training areas were collected based on field verification data. The six main classes (see Table 2) were divided into several sub-classes to reduce the standard deviation of the class signatures. These sub-classes were aggregated back into the main classes after completing the classification. The produced vegetation map was generalized with a 3x3 mode filter.

The accuracy of the vegetation map was estimated using a semi-random sampling scheme. The training areas and the areas without any field data were masked out and 130 stratified random pixels were collected in the remaining portions of the image, that is, areas with field data that were not used to train the classifier. The classified data were compared to the ground verification data at each of the 130 sampled pixels. The Kappa coefficient (x100) was used as the measure of accuracy.
Topography

Seven areas were surveyed in the Peace-Athabasca Delta (see Figure 1) using airborne scanning LiDAR (Light Detection and Ranging) to retrieve detailed and accurate topographical information about the land surface. The LiDAR point data were used to generate a detailed Digital Elevation Model (DEM) for the seven sections of the delta. A detailed methodology regarding the processing and accuracy assessment of the LiDAR data can be found in Töyrä et al. (2003) and a summary will be provided here for sake of completeness.

As the river levees control the critical elevation needed for overland flooding, the LiDAR surveys were conducted along the levees of river channels and within the Jemis Lake basin (see Figure 1). Total station survey data were collected in situ in Jemis Lake (Area A) and Dog Camp (Area B) at the time of the LiDAR survey to be used as verification data. The horizontal survey coordinates were referenced to the UTM (Zone 12) projection based on the WGS84 datum. The orthometric heights were based on the GSD91 geoid model (Véronneau, 1993).

The LiDAR survey was conducted at the selected study sites on June 17, 2000, using an ALTM 1225 airborne scanner operating at a wavelength of 1064 nm. The position of the aircraft and LiDAR scanner was calculated based on data from an onboard geodetic grade GPS receiver and an inertial navigation system (INS). Another geodetic grade GPS receiver, located on a known benchmark, was used for differential correction of the aircraft GPS. Ground positional coordinates with orthometric heights were computed for each LiDAR pulse based on the position of the aircraft and the time it took for the transmitted LiDAR pulse to return from the ground. The coordinates were referenced to the UTM (Zone 12) projection based on the WGS84 datum. The elevation values were provided as WGS84 (G730) ellipsoid heights. The LiDAR survey was conducted at a flying altitude of 1300 m above ground level. Vegetation removal software was used to remove the points that did not completely penetrate the vegetation, leaving only the points that represented the ground surface. Data sets containing X-Y-Z ground data points were created for the seven survey areas, in which the horizontal distance between adjacent points ranged between 0.25 m along overlapping scan lines to several metres in dense vegetation.

Prior to evaluation, both the LiDAR and the survey elevations were converted to orthometric heights based on the CGG2000 geoid model (Véronneau et al. 2001; Véronneau, 2002) using conversion software developed by the Geodetic Survey Division (GSD), Natural Resources Canada. The LiDAR points were compared to the ground survey points to evaluate the vertical accuracy of the scanning LiDAR. The LiDAR points that were located closest to a survey point were selected and used for the evaluation. A horizontal threshold was set to 1 m, meaning that each LiDAR-survey pair that was more than one metre apart was excluded from the assessment.
To create a DEM, the LiDAR point data needed to be interpolated into an even grid where each pixel (or grid cell) contained an elevation value. The elevation values in a grid should be averaged when there are many data points within a pixel and interpolated from adjacent points when there are no data points within the pixel. Töyrä et al. 2003 achieved a combination of interpolation and averaging by using a Kriging algorithm (Cressie, 1993) to interpolate the LiDAR points into a grid with 0.25 m pixels, which was equal to the smallest input data spacing. Thereafter, the 0.25 m grid was aggregated (by averaging) up into 4 m pixels.

For this study, the 4 m LiDAR DEM was subsetted and aggregated (averaged) into 20 m pixels to match the extent (see Figure 1) and resolution of the vegetation map. The DEM was also re-projected into UTM (Zone 12) based on the NAD27 datum. As LiDAR pulses do not penetrate water, all areas that were flooded at the time of the LiDAR survey were excluded from the DEM. A flood map from the same date should preferably be used for this purpose. No flood maps were generated for the summer of 2000 and as a result the August 1999 and May 2001 flood maps were used instead. It was assumed that any area that was dry in both 1999 and 2001 should have been dry in 2000 as well. The DEM value was set to zero (background value) for any pixel that was covered by open water or flooded vegetation in either August 1999 or May 2001. Since the focus of this paper was on wetland vegetation, the areas representing bedrock outcrops were manually set to zero (background) elevation.

Evaluation of Vegetation, Flooding and Topography

The aim was to compare the spatial distribution of the vegetation classes to the duration of flooding and the topography. In order to display how long each area was classed as open water or flooded vegetation, a flood duration map was generated using the May flood maps from each year, with the exception of 1999 for which the July flood map was used instead. Since there were no flood maps for 1997 and 2000, any area that was covered by open water or flooded vegetation in 1998 and 2001 were assumed to have been flooded during the previous year as well. The spring flood maps were subsetted to match the extent of the vegetation map (see Figure 1). Based on the spring flood maps, the flood duration of each location could be calculated. The flood duration image channel was generated by assigning each pixel a value that represented how many seasons it had been flooded between 1996 and 2001. The vegetation map was compared to the flood duration map to see if there was a relationship between the spatial distribution of classes and the time that the area had been flooded.

The vegetation map was also compared to the DEM. It should be noted that only certain areas were surveyed with the scanning LiDAR (see Figure 1) and that the flooded areas, which also were the low-lying areas, were excluded from the DEM. Elevation data were extracted for each vegetation class where the topographical information was available. As the DEM provided absolute elevations, the northern portion of the study area (LiDAR areas A, B and E) was analysed separately from the southern portion of the study area (LiDAR areas F and G).
RESULTS AND DISCUSSION

Flood Mapping

Classification accuracies obtained by Töyrä et al. (2001) were used as a guideline for estimating and understanding accuracies for all years since the same study area, methodology and data types were used in this study. Table 3 lists the classification accuracies that can be expected for the various image combinations. Waves on water surfaces often increase the radar backscatter due to the Bragg effect, sometimes to the point where the open water is mixed up with dry vegetated areas. Radarsat S1 and S2 images are especially sensitive to waves because of their low incidence angle. Wind induced waves on the large lakes in the Peace-Athabasca Delta quite frequently cause problems with increased backscatter, whereas most of the medium and smaller lakes remain unaffected. On most dates, the VIR image covered the large lakes and the infrared channels, which detect open water very well, would compensate for this problem. In May 2001 and July-August 2001, the SPOT images did not include Lake Claire, which is the largest of the delta lakes. As a result, the generated flood map contained many non-flooded land pixels in the middle of the lake. Since it was quite obvious that those areas were part of the lake, all pixels within Lake Claire were manually changed to open water. In July 1998, this problem was avoided by classifying a combination of the Radarsat S1 and S7 images. Radarsat S7 is acquired at a much higher incidence angle and is not as sensitive to wave action. The May 1999 Radarsat scene was of very poor quality and produced very poor classification results. The May 1999 flood map was, therefore, excluded from any further analysis. Other problem areas were saturated mud flats that were classified as flooded vegetation by the Radarsat channel although there was no standing water present. The final flood maps are illustrated in Figure 2.

Table 3. Classification accuracies (Kappa-coefficient x 100) obtained by Töyrä et al. (2001; 2002) for mapping open water, flooded vegetation and non-flooded land in the Peace-Athabasca Delta during spring (no leaves) and summer conditions (leaves).

<table>
<thead>
<tr>
<th>Time of Year</th>
<th>Radarsat S1 or S2 Only</th>
<th>Combination of Radarsat S1 and S7</th>
<th>VIR Only</th>
<th>Combination of Radarsat and VIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring</td>
<td>76%</td>
<td>-</td>
<td>80%</td>
<td>92%</td>
</tr>
<tr>
<td>Summer</td>
<td>56%</td>
<td>69%</td>
<td>67%</td>
<td>83%</td>
</tr>
</tbody>
</table>
Figure 2. The generated Peace-Athabasca Delta flood maps. Note that none of the July 1998 images covered the western edge of the area.
As mentioned, the delta was subjected to major overland flooding in the spring and summer of 1996 and in the spring of 1997. During the following years, the delta went through a drying trend with receding water levels. The May 1996 imagery were acquired after the peak of the 1996 spring flood and it seems like a larger area should have been classified as flooded. For example, the strip of non-flooded land just southeast of Lake Claire probably should have been classified as flooded vegetation. This area is part of the section that was classified using Radarsat alone. It is believed that ice could have caused the Radarsat backscatter to resemble that of non-flooded land. The drying trend can be followed from May 1998 to July-August 2001. The open water and flooded vegetation classes were reduced in size. The levees emerged and many basins became isolated from the drainage network. Since the evaporation is higher than the precipitation in the Peace-Athabasca Delta, the water in the isolated basins is lowered by an average of 90 mm per year (Peters, Pers. Comm., National Water Research Institute, Victoria, BC, 2003).

The percentage of open water, flooded vegetation and non-flooded land was calculated for each acquisition date and shown in Figure 3. The figure illustrates that much of the open water in May 1998 was replaced by flooded vegetation by July 1998. After that point, the open water class fluctuated around 40%, while the flooded vegetation class was slowly replaced by non-flooded vegetation. The non-flooded land class increased from 21% in May 1998 to 57% in July-August 2001.

Figure 4 delineates the flooded areas that were hydraulically connected to the Peace River and could drain freely. It should be noted that some basins might have been incorrectly included or excluded from the open drainage category because of classification errors. Several of the levees that initially emerged as the water levels decreased were relatively narrow compared to the 20-30 m resolution of

Figure 3. The percentage of total area covered by open water, flooded vegetation and non-flooded land based on the flood maps.
Figure 4. The hydraulically connected areas (black) based on the flood maps.

the satellite imagery. Because of this, the satellite sensors may not have detected some of the dry levees. The basin directly north of Jemis Lake and the area west of Richardson Lake (south of Athabasca River) are two examples of areas that were considered questionable as they were classed as isolated on one date and freely draining on the following acquisition. Despite these problems, Figure 4 illustrates how the freely draining areas gradually reduce as the levees emerge. It also highlights the areas that remained connected to the drainage network the longest as the delta continued to dry up.
Vegetation Mapping

The generated vegetation map is illustrated in Figure 5a. The accuracy assessment produced a Kappa –coefficient (x100) of 86%. May et al. (1997) obtained the same level of accuracy when classifying shrubs and meadows using Landsat TM data. The general vegetation patterns seemed to be captured well when compared to in situ sampling and photographs taken from the air. Some of the mixed pixels along river channels were classified as aquatic vegetation. There was also some confusion between willows and graminoids. A few of the narrow willow bands were classified as graminoid and some graminoid covered areas, especially along the fringe between wet and dry sections, were classified as willow. The Kappa –coefficients (x100) for the graminoid and shrub classes were 75% and 86%, respectively.

Figure 5. The generated a) vegetation map and b) flood duration map. The location of this area within the Peace-Athabasca Delta is shown in Figure 1.
Topography

Based on comparisons of LiDAR point data to survey points on bare non-vegetated areas, Töyrä et al. (2003) found that the LiDAR elevations had a negative bias of 0.21 m. The LiDAR elevations were block-adjusted (raised) by this amount to compensate for the bias. Table 4 summarizes the findings from the LiDAR accuracy evaluation by Töyrä et al. (2003). As Table 4 indicates, the LiDAR elevations were on average higher than surveyed when the vegetation was tall and the Leaf Area Index (LAI) was high. For example, the LiDAR elevations in areas covered by graminoids and willow shrubs were on average 0.07 m and 0.15 m too high, respectively. The vegetation dependant bias was caused by LiDAR pulses that did not completely penetrate the canopy and bounced off prior to reaching the ground. A taller and/or denser vegetation cover simply produces increased opportunity for the pulse to bounce off branches, stems or understory. The Root Mean Square Error (RMSE) also increased with increased vegetation height and thickness. The RMSE varied between 0.07 m for bare ground and 0.26 m for willow covered areas. The accuracy of the 20 m DEM was not estimated.

The vegetation dependant bias would probably have been lower if the LiDAR survey was conducted in early spring when the shrubs were completely non-foliated. Many areas were still flooded in June 2000 and seeing as the LiDAR pulse does not penetrate water, many of the low-lying sections ended up being excluded from the DEM.

Table 4. The average difference (LiDAR-survey) and Root Mean Square Error (RMSE) of the block adjusted LiDAR data for different land cover types. A positive average difference indicates that the LiDAR elevations are on average higher than surveyed. The average Leaf Area Index (LAI) and height of the vegetation as well as the sample size (N) are provided. Adapted from Töyrä et al. (2003).

<table>
<thead>
<tr>
<th>Land cover</th>
<th>LAI</th>
<th>Height (m)</th>
<th>Average Difference (m)</th>
<th>RMSE (m)</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare</td>
<td>n/a</td>
<td>n/a</td>
<td>0.00</td>
<td>0.07</td>
<td>11</td>
</tr>
<tr>
<td>Graminoid (grass, sedge)</td>
<td>1.3</td>
<td>0.3-0.4</td>
<td>0.07</td>
<td>0.15</td>
<td>64</td>
</tr>
<tr>
<td>Willow</td>
<td>2.2</td>
<td>4-7</td>
<td>0.15</td>
<td>0.26</td>
<td>22</td>
</tr>
<tr>
<td>Dead Willow</td>
<td>1.0</td>
<td>2-5</td>
<td>0.14</td>
<td>0.17</td>
<td>6</td>
</tr>
</tbody>
</table>
Evaluation of Ecosystem Response

The flood duration map is shown in Figure 5b and clearly shows that the rivers and lakes as well as many of the wetland basins became isolated as the floodwater receded. Many of these basins were classed as being flooded for all six seasons. The map also highlights the levees and other elevated sections that did not flood at all or only flooded for a short period of time, making such a map an invaluable tool for assessing flood-duration considerations in this regime. It is clear that operation dissemination of such maps on a consistent annual basis could easily provide the basis for an ecological monitoring program. Such a spatial time-series would be invaluable in future years to assess ecological impacts of a changing flood regime within the Peace-Athabasca Delta.

Figure 6.  The relationships between vegetation patterns and flood duration between 1996 and 2001.
The comparison between the 2001 vegetation classes and flood duration is provided in Figure 6a. As expected, the water and aquatic classes were mostly located in areas where persistent flooding had occurred, whereas the majority of the deciduous and coniferous trees were located in areas that were not flooded. Almost 60% of the graminoid class was found in basins that were flooded for four seasons or more. Twenty percent of the graminoids were flooded for all six years. Slightly less than 30% of the shrubs were flooded for four seasons or longer, while only 8% of the shrubs were flooded during the whole six-year period. It was also noted that 22% of the shrubs that were flooded for all six years did not have any foliage at the time of the vegetation mapping. Figure 6b is an inverted view of the previous figure and illustrates that basins that were flooded for three to five years were dominated by graminoids, while the areas that were flooded for less than two years were mostly covered by shrubs.

**Table 5.** The average, minimum and maximum elevation (cm) for each vegetation class in the north (LiDAR areas A, B, and E) and the south (LiDAR areas F and G) section of the study area. The standard deviation (stdv) is also provided.

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Graminoid</th>
<th>Shrub</th>
<th>Deciduous</th>
<th>Graminoid</th>
<th>Shrub</th>
<th>Deciduous</th>
<th>Conifer</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>20909</td>
<td>20982</td>
<td>21071</td>
<td>21014</td>
<td>21064</td>
<td>21210</td>
<td>21243</td>
</tr>
<tr>
<td>Stdv</td>
<td>42</td>
<td>43</td>
<td>59</td>
<td>104</td>
<td>83</td>
<td>91</td>
<td>82</td>
</tr>
<tr>
<td>Minimum</td>
<td>20781</td>
<td>20747</td>
<td>20801</td>
<td>20834</td>
<td>20822</td>
<td>20835</td>
<td>20945</td>
</tr>
<tr>
<td>Maximum</td>
<td>21139</td>
<td>21217</td>
<td>21305</td>
<td>21486</td>
<td>21475</td>
<td>21488</td>
<td>21512</td>
</tr>
</tbody>
</table>

| South      |           |       |           |           |       |           |         |

The results from the comparison of vegetation types to elevation data are provided in Table 5 and Figure 7. Since there were no elevation data in the flooded areas, the water and the aquatic classes could not be evaluated. The vegetation patterns in the flooded low-lying sections also could not be assessed. The coniferous vegetation was not included in the comparison in the north section since all of the conifers were located on the bedrock outcrops, which had previously been removed from the DEM. According to Table 5, the shrubs were located in areas that were, on average, between 0.5 m (in south) and 0.73 m (in north) higher than the graminoid covered regions. The vegetation dependant bias in the DEM accounted for a small portion of this difference (0.08 m). As indicated by Figure 7, the elevation ranges overlapped for the graminoid and shrub classes, especially in the southern portion. There was also much overlap between the deciduous and coniferous trees in the south. The wide overlap and the high standard deviations for the vegetation classes in the south were most likely caused by the elevation gradient along the Embarrass River and the Fletcher Channel down to Lake Athabasca. The standard deviations would probably be reduced if the comparisons were made on smaller sections.
CONCLUSIONS

A time series of flood maps were generated for the Peace-Athabasca Delta using a combination of SAR and VIR satellite imagery. The derived flood maps provide a useful quantitative estimate of the flooding extent and the subsequent drying of the delta. When the flood maps are compared, the drainage patterns and the duration of flooding within certain areas can be observed. This information is important for assessing the influence of flooding or absence of flooding on vegetation and wildlife. Satellite remote sensing affords the only reliable means of assessing flood extent in this region. The mapping of general vegetation classes in the central portion of the delta was achieved using multi-temporal SPOT-4 data to an accuracy of 86%. The vegetation patterns within the entire delta could be mapped using either Landsat TM data or a mosaic of SPOT-4 data. A spatio-temporal vegetation database could easily be generated if the vegetation mapping would be conducted in timely intervals. In addition, the vegetation maps from previous studies (Dirschl et al. 1974; Wickware, 1978; Wickware and Howarth, 1981; Jaques, 1990; Terrain Resources Ltd., 1995) should be assembled to generate a database that included past conditions.
The scanning LiDAR technology provided relatively accurate, very useful and highly detailed topographic information. However, to further expand the DEM in the Peace-Athabasca Delta, it is recommended that the LiDAR survey is conducted in a low water year and early in the spring when no leaves are present in the shrubs and deciduous trees to maximize the data coverage and accuracy.

The study showed that the generated spatio-temporal databases were very useful in discovering delta-wide relationships. This type of geomatics approach allows for a more consistent and complete view of this region. For example, the vegetation patterns could also be compared to the flood duration of areas that were hydraulically open versus closed to the drainage network. Although the results indicated that there was a relationship between the vegetation patterns and both elevation and flood duration, it is also important to know that there are many other parameters that influence the distribution of vegetation types. One of the drawbacks regarding the flood maps is that the water level is not obtained, only flood extent. However, if a scanning LiDAR survey was conducted in a low water year, the bathymetry of the basins would be obtained and an approximate water level could be extracted based on the flood outlines. Such a technique was shown to be quite effective in the past for a small perched basin water studies.

This study shows that a geomatics-based approach to understand the function of this large ecosystem can provide invaluable data that is otherwise unavailable. Remote sensing does not and will never completely replace detailed vegetation and ground surveys, but rather complements the in situ analysis with a more generalized delta wide view. Such a comprehensive approach to hydro-ecological monitoring must be considered for all future monitoring strategies. Increasingly, our view of the world is as a complex non-linear system. Only a geomatics-based remote sensing approach offers repeatable and consistent coverage, particularly for northern regions such as the Peace-Athabasca Delta.

ACKNOWLEDGEMENTS

This work could not have been completed without the help and support of many people. The authors would like to acknowledge Northern River Ecosystem Initiative (NREI) for funding the satellite remote sensing study and BC Hydro for funding the LiDAR study. Wood Buffalo National Park provided field logistics and Kelly Best (National Water Research Institute), Tom Carter (National Water Research Institute), Krysha Dukacz (formerly at National Water Research Institute), Jay Joyner (BC Hydro), Graham Lang (BC Hydro), Steve Adam (formerly at University of Calgary), and Robert Grandjambe (Ft. Chipewyan) contributed with field support. Terry Pultz (Canada Centre for Remote Sensing) supplied some of the Radarsat imagery and Paris Vachon (Canada Centre for Remote Sensing) calibrated the Radarsat data. Dan Peters and Pietroniro and Töyrä Monitoring Delta Ecosystem Response to Water-Level Restoration 21
Tom Carter (both at National Water Research Institute) shared their knowledge about the delta and its hydrology. Tom Carter also provided additional survey points in Jemis Lake, and Optech Inc. conducted the LiDAR data acquisition and LiDAR point data processing. William Kalbfleisch (Optech Inc.) and Christopher Hopkinson (currently at Queen’s University) personally carried out the LiDAR processing and helped with the understanding of LiDAR data. Marc Véronneau, Patrick Legree and J.C. Lavergne at the Geodetic Survey Division (GSD), Natural Resources Canada, provided invaluable and much appreciated help with geoid models and height transformations. The authors also thank Stephen Gibbard (Prairie Farm Rehabilitation Administration) for processing GPS data and Sheri Korpess and Sheela Selvarasan for data editing and gridding.

REFERENCES


