Application of a hydrodynamic model in a freshwater delta using remote sensing

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Abstract The Peace-Athabasca delta (PAD) is located in the northern extreme of Alberta, Canada and is one of the world's largest freshwater inland deltas. Inland areas surrounding the main flow system comprise a myriad of small lakes and wetlands, of which a large percentage are hydrologically disconnected or "perched" at elevations higher than adjacent lakes or channels. This large, complex and dynamic ecosystem has undergone substantial changes over the last 25 years. The remoteness of this site, along with a shortage of hydrological and ecological information, has necessitated the development of innovative methods to assess these changes. These methods include the analysis of Landsat, Radarsat and SPOT satellite imagery for verification and calibration of a hydrodynamic model to observed flood conditions. This unique coupling of imagery and a hydrodynamic model provides key validation points and initial conditions for model runs. The results of the techniques outlined in this paper provide a starting point to assess changes produced by flow regulation and climatic change.

Key words delta; flood mapping; hydraulic modelling; northern; Peace-Athabasca delta (Canada); wetland

BACKGROUND

The Peace-Athabasca Delta (PAD) is a large boreal, freshwater delta and lake system located in the northeast corner of Alberta, Canada, covering approximately 10 000 km^2. It is situated (59°N, 112°W) at the confluence of the Slave, Peace, Athabasca and Birch rivers at the western end of Lake Athabasca (Fig. 1). Inland areas surrounding the main PAD flow system comprise small lakes and wetlands, of which a large percentage are hydrologically disconnected or "perched" at elevations above adjacent lakes or channels. Summer evaporation is generally greater than annual precipitation (Prowse *et al.*, 1996) in this region and perched basins are dependent on floodwater contributions in order to maintain high primary plant production that provides food and

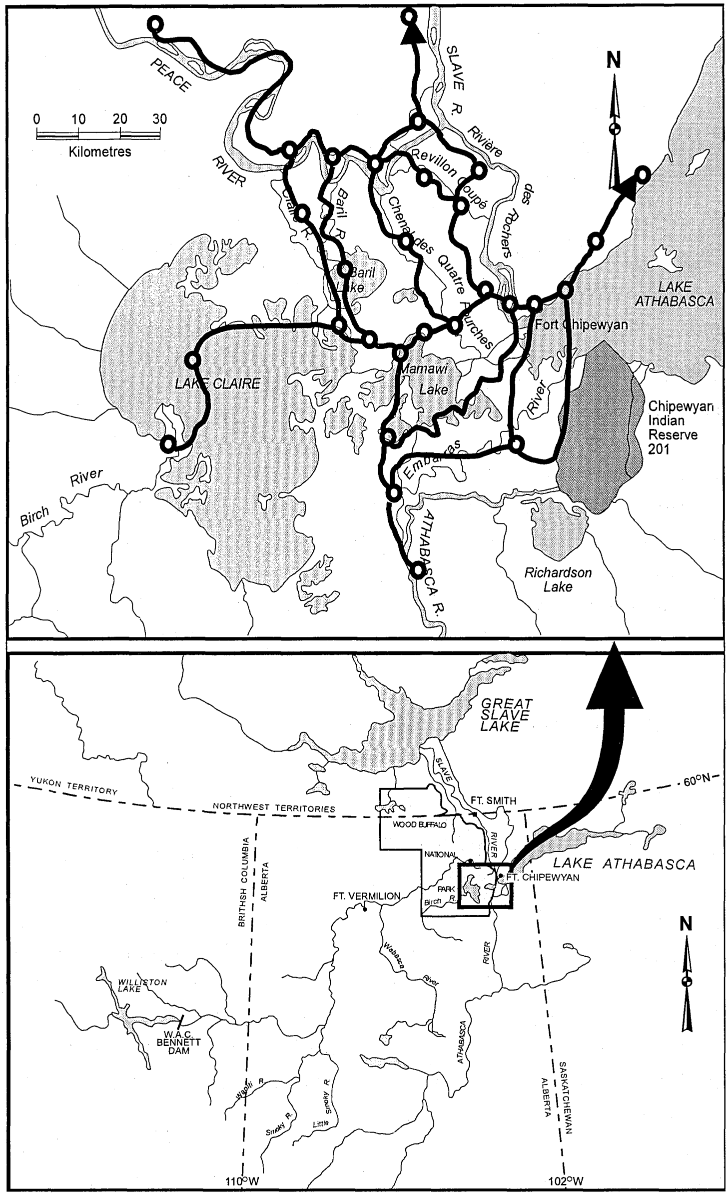

Fig. 1 Location map of the Peace-Athabsaca Rivers and the Peace-Athabasca delta.

shelter for wildlife (Carbyn *et al.*, 1993). Clearly, the flood regime is an important component of the region's ecology.

This complex and dynamic ecosystem has undergone substantial change over the last 25 years, primarily as a result of alterations to the hydrological regime. The Peace River, which regulates northward drainage of the Lake Athabasca–Peace Athabasca delta (LA-PAD) complex, was altered with the completion of the W.A.C. Bennett hydroelectric dam and Williston Reservoir operated by the British Columbia Hydro-

Electricity and Power Authority (B.C. Hydro). There is also evidence of climate change impacts within the basin, which may be influencing the ice-jam flood frequency and magnitude (Prowse & Lalonde, 1996). A one-dimensional hydrodynamic model (ONE-D) has been used in the PAD to assess possible strategies for improved water management as well as to further the understanding of climatic and anthropogenic influences within the delta (Cheng, 1996). However, the remoteness of this region along with the unique terrain and poor hydrometric records poses a challenge to understanding the hydrology of the PAD and application of the model. As such, it also presents an ideal opportunity for employing remote sensing as a hydrological monitoring tool, an approach that is too often overlooked in many water-management studies (Kite & Pietroniro, 1996).

Considering the hydrological complexities and lack of data within the PAD, two objectives were defined for the use of satellite remote sensing records in conjunction with the hydrodynamic model for this region. The first focused on a need to establish a historical record of flood extent within the large lake system and to link this with historical flood elevation data. This type of information was a prerequisite for upgrading of the hydraulic flow model to properly deal with storage at higher elevations and to determine the spatial extent of extreme floods. The second objective was to evaluate whether satellite images could be used to monitor the spatial progression of a recent flood and provide validation of the hydrodynamic model.

HYDROLOGY OF THE PAD

The total drainage of the Peace River, referenced to the Peace Point hydrometric station located approximately 70 km upstream of the Peace delta (Fig. 1), is 293 000 km^2. The Williston Reservoir is located in British Columbia 1200 km upstream of the delta. The second largest tributary flowing into the LA-PAD complex is the Athabasca River. The river flows are distributed through its delta and into Lake Athabasca through a series of rivers and channels. The PAD and Lake Athabasca are connected to the northward flowing Peace and Slave rivers by three major channels, Rivière des Rochers, Révillon Coupé and the Chenal des Quatre Fourches. Discharge into these channels is proportional to the difference in water levels between the lake systems and the Peace River. Although flow is normally northward, it can reverse when water levels in the Peace River exceed those in Lake Athabasca, which normally occurs during the spring ice break-up period and during a period of sustained high flows produced by runoff from the Rocky Mountain headwaters. As a consequence, flow out of Lake Athabasca is reduced or even reversed resulting in a backwater effect in the lake. Three large and shallow (1–3 m) lakes (Claire, Mamawi and Baril) occupy a large proportion of the 3900 km^2 delta area, and are connected to Lake Athabasca by numerous active and inactive channels.

Application of ONE-D to the LA-PAD started in 1979 and employs a finite difference, fully implicit, numerical scheme to solve the St Venant complete mass balance and momentum equations for water level and discharge. The model treats the flow as one-dimensional and the resistance equations developed for steady flows, such as the Manning's equation, are assumed to also apply for unsteady flow. The model solves for flow in water depth at all interior nodes using input water level or flow information at all boundaries. Lake Claire and Mamawi cross-sections were based on below ice survey and were extended beyond the water line using photogrammetric aerial surveys (PAD-IC, 1985).

ANALYSIS OF LARGE LAKES FOR THE HYDRODYNAMIC MODEL

Given the dynamic nature of the large lakes as well as the lack of relief within the region, lake extent as a function of flood depth is difficult to retrieve from traditional sources. Remote sensing through analysis of historic satellite data along with archived lake-level data was used to provide a best estimate of lake hydraulic characteristics for input into the hydrodynamic model with the results implemented directly as cross sectional information for Lake Mamawi and Lake Claire in the ONE-D model.

The 16-year period following the last major flood (1974) of the PAD was selected for analysis. To ensure that the analysis covered a full range of water-level conditions during this period, it was necessary to compile a suitable inventory of satellite imagery. Eight images were selected for detailed analysis. The 1974 image was critical to the analyses because it displayed the early summer extent of a major ice-jam induced flood that affected the delta.

The original data were received from satellite archives as level 5 systematic corrected and a subsequent affine transformation, based on a first-order polynomial using a cubic convolution re-sampling algorithm, was applied. Image classification was used to derive areas of these lakes from each of the eight corrected images. The first stage of the analysis involved classifying the images into water/no water regions by employing a parallelepiped scheme with a maximum-likelihood classifier. Training areas were confined to the large, well-defined lake areas. The ensuing classification resulted in a binary raster image containing two classes. The final stage of the analysis involved identification of continuous water-covered areas by creating vector polygons from the water/no water data set. As with most similar schemes, errors in pixel classification would have resulted in a noisy vector stream requiring manual editing. To circumvent this, a simple algorithm was applied to extract those areas that were hydrologically connected. After initiation with a seed point, the algorithm operates by finding all pixels satisfying a four-point connectivity with the seed and subsequent

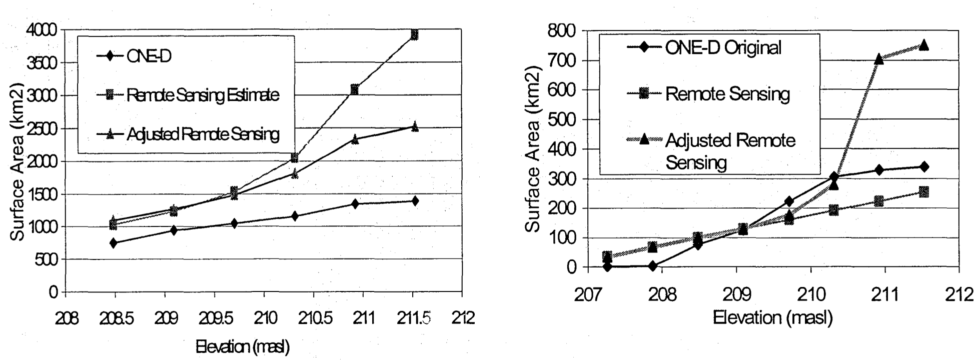

Fig. 2 Original and Landsat derived hydraulic characteristics of Lake Claire (left) and Lake Mamawi (right).

pixels. The result is a homogenous area requiring very little manual correction. Areas of Lake Mamawi and Lake Claire were then calculated from the final derived vectors. Water level data recorded on the lakes coincident with the day of each image acquisition are plotted with the satellite-derived areas in Fig. 2.

Because lakes Claire and Mamawi join at high water levels, the Landsat derived relationship was adjusted to account for this and this is represented in Fig. 2 as well. Differences in elevation and areal extent using the Landsat derived hydraulic characteristics and those of the traditional survey methods are clearly evident. Differences in water level estimates between model runs using the original hydraulic tables and the one derived from the imagery was between 10 and 13 cm on Lake Mamawi.

MAPPING THE 1996 PEACE-ATHABASCA DELTA FLOODS

In anticipation of a potential ice jam on the Peace River in 1996, the authors arranged for several Radarsat and SPOT satellite images to be acquired from April to October, to monitor the flooding and any subsequent recession during the summer and autumn months. Landsat imagery proved unsuitable due to cloud cover. A digital elevation model (DEM) was employed with the hydrodynamic model to assess overbank conditions. A combination of Radarsat and SPOT data was used to assess the flooding extent at the end of May using the algorithm developed by Töyrä *et al.* (2000). The resulting image is shown in Fig. 3(a). The ONE-D model was run for the entire open-water period from 21 May until 31 October 1996. Water elevations at all the nodes were entered into the DEM and interpolated to provide the flood map shown in Fig. 3(b). It is interesting to note that the ONE-D derived flood map does not include large tracts of flooded area north of Lake Mamawi and bordering the Révillon Coupé as shown in the imagery. The flood waters in this region were the remnant waters of an ice-jam-induced flood that occurred in late April of the same year.

Although problems on board the Radarsat satellite precluded image acquisition during the summer and autumn months of 1996, the variable field of view of the SPOT satellite permitted the acquisition of seven suitable images. A supervised procedure

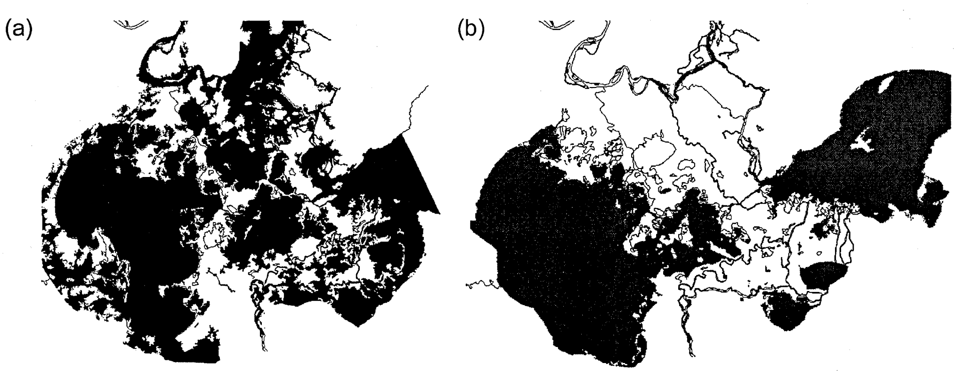

Fig. 3 Comparison between (a) image-derived, and (b) hydrodynamic model derived flood estimates for 23 May 1996. Note the area north of Mamawi Lake was inundated prior to 23 May by an ice-jam flood on the Peace River and residual water had not drained from the perched basin region.

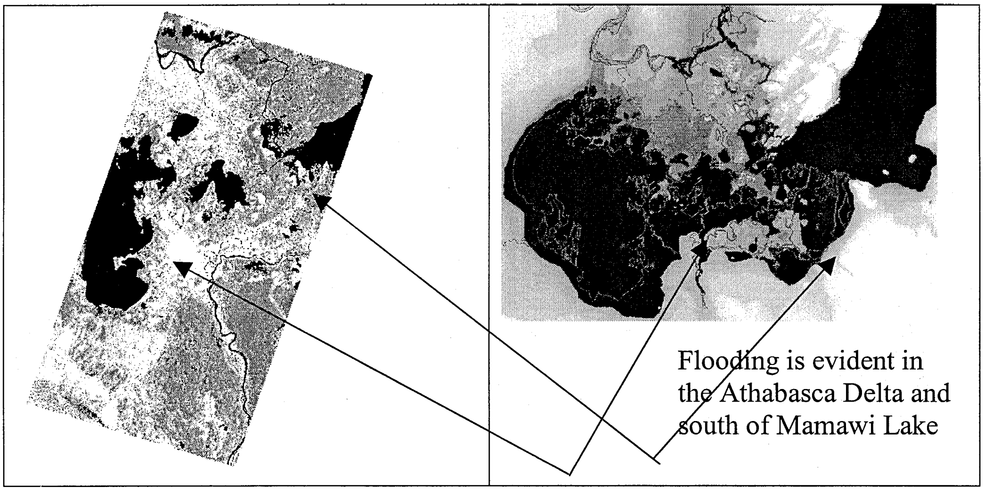

Fig. 4 Qualitative comparison of Landsat derived flood extent and ONE-D flood extent for 14 August 1996.

using a Mahalanobis classifier was used to classify these scenes into open water, wet vegetation, dry vegetation and clouds. The final classification of the 14 August imagery is presented in Fig. 4. In the absence of a Radarsat scene, the classification accuracy for SPOT imagery during the summer period is in the order of 60% due to the inability of the sensor to penetrate vegetation layers (Töyrä *et al.*, 2000). The imagery shows open water and flooded vegetation changes in the Athabasca Delta and south of Lake Mamawi as noted in this Figure. This is confirmed qualitatively by the ONE-D analysis also shown in Fig. 4. Although the results are preliminary, the feasibility of using satellite imagery as verification of the hydrodynamic model is possible. Obviously, increased confidence in the image classification would assist in providing quantitative assessment of flood extent in this region. As was shown by Töyrä *et al.* (2000), increased classification accuracy for the purposes of flood monitoring can be achieved in this region using a combination of both visible and active radar data. This could greatly assist in model verification and calibration at some future date.

CONCLUSIONS

The remoteness of the PAD, along with a shortage of hydrological and ecological information, has necessitated the development of innovative methods, based on the use of satellite imagery, to assess hydrological changes. Landsat derived time series have been shown to be able to provide provided key hydraulic information that is difficult to obtain from existing sources. The 1996 flood imagery provides a useful qualitative estimate of the summer-time flooding extent and a verification method of the ONE-D model. Unfortunately, lack of coverage due to cloud cover and the Radarsat satellite acquisition problems have limited the ability to fully quantify the flood extent in the region during the summer period. Such monitoring is entirely feasible from a technical standpoint and should be attempted in future flooding events.

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