APPLICATION OF REMOTE SENSING TO ENVIRONMENTAL MONITORING: THE 1996 SAGUENAY FLOOD IN QUÉBEC

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Abstract

Remote sensing has been used widely for monitoring natural resources over large territories. Recently, with advances in sensor technology and computation power, application of remote sensing has been extended to monitoring local situations that have been traditionally served by black and white survey aerial photographs. In 1996, after the flood in the Saguenay region, the Canada Centre for Remote Sensing mobilized a team to study the application of advanced remote sensing technology to assist the rehabilitation efforts by various groups and governments. Satellite and airborne sensors, including Landsat Thematic Mapper (TM), SPOT Haute Résolution Visible (HRV), Radarsat Synthetic Aperture Radar (SAR) imagery and multispectral airborne videography, were acquired after the flood in the Saguenay region. The black and white aerial photographs acquired at the same time as the videography were used as a visual reference for the study. The images were analyzed and interpreted with the assistance of scientists from the Geological Survey of Canada. This paper summarizes the flood information provided by the different datasets, moving from a regional to a local scale. It also discusses issues involved in flood monitoring and compares high resolution videography with optical and microwave satellite sensors.

Introduction

Remote sensing has been demonstrated as an effective technique for monitoring natural disasters. In Canada, optical and microwave remotely sensed images have been acquired from satellite and airborne platforms and have been used to monitor the progress of such events as floods and oil spills on a regional scale.

In the past decade, the refinement of remote sensing technology hardware and analysis techniques has made the airborne video camera an attractive, low-cost tool for local-scale applications. A history of the development of videography in remote sensing is provided by King (1995). Until the mid-1990s, most videographic studies had focussed on basic research, but more recently, videography has been applied to real-world problems such as pipeline monitoring (Jadlowski, 1994; Jadlowski et al., 1994), pipeline repair (Corbley, 1994) and flood monitoring (Rosenfeld, 1996). The flexibility and low cost of video equipment compared to other remote sensing technologies has enabled research groups and mapping companies to design and construct their own sensors and to acquire data cost-effectively (King, 1995).

Application of remote sensing technology to flood monitoring has attracted attention from organizations and institutions around the world. The recent demonstration of the use of satellite imagery to monitor the

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1997 Red River flood of Manitoba and 1996 California flood (Saper et al. 1996, 1997) reveals the cost effective ability of remote sensing for flood prediction, monitoring and management planning, floodwater diversion, impact assessment and reconstruction. Existing satellite sensors with spatial resolutions between approximately 5 m and 20 m can provide a regional-scale view for assessing the extent of the flood, and for monitoring the progress of floodwaters with a time series of images. On the other hand, the video camera, depending on the altitude of the platform, can provide the detailed spatial resolution (on the order of several metres to below a meter) necessary for planning of evacuation routes, distribution of medical aid, food and assistance to the affected population, emergency construction and repair of structures such as roads and dikes, as well as assessing the impact of the flooding, for example, for insurance purposes.

The July 1996 flood in the Saguenay region is one of the worst natural disasters to occur in the province of Québec in recorded history. It was the most severe flood to have occurred in Canadian history. Its toll included many landslides, ruptures in several of the region's private and public dams and extensive damage to buildings and structures located along river banks, including homes, industrial facilities, bridges and roads. Ten people lost their lives, 16,000 people were evacuated from the region and 1718 homes and 900 cottages were destroyed or damaged. $800 million in property damages were reported. The flood water deposited 25 to 50 centimetres of sediments in the Baie des Ha!Ha!, equivalent to approximately 75 to 150 years of deposition (Grescoe and Germain, 1997).

As it was urgent that the federal, provincial and local governments map the extent of flood damage and act to minimize the impact of the emergency on citizens and property, a number of surveys were carried out immediately in the affected areas (Comité interministériel de coordination sur l'environnement, 1998). The Canada Centre for Remote Sensing (CCRS) of Natural Resources Canada acquired satellite images dating from before and immediately after the flood, resulting in a general estimation of flood damage for the entire Saguenay region. Two weeks after the flood, CCRS scientists were dispatched to the site to document in detail the effects of the flood on a local scale. Videograph imagery was acquired on August 6 by Air Focus of Chicoutimi, Québec for CCRS. Air Focus then digitally processed the data, producing a geometrically corrected and radiometrically adjusted mosaic over several of the flooded rivers which drain into the Saguenay River.

The Saguenay region and the 1997 flood

The Saguenay region (Figure 1) extends over an area of over 106,200 km^2 (Grescoe and Germain, 1997). It is located in the Grenville Province of the Canadian Shield in the province of Québec. The bedrock includes gneiss, granite, diorite and anorthosite, and is covered with pastureland and forestland. The Saguenay region straddles the Great Lakes-St. Lawrence and Boreal forest regions (Rowe, 1972). The bedrock was eroded by the retreating Wisconsin glaciers 10250 years ago. The resulting topography is rolling and rugged, characterized by steep hills and deeply incised valleys. To the south lie the mountains of the Réserve faunique des Laurentides (maximum elevation 1,143 metres), which extends to Québec City; to the north, the Valin plateaus rise to about a kilometer in elevation. The Saguenay valley lies in a graben between two parallel faults, one running along the rivière Sainte-Marguerite to the north, and the other near lac Kènogami to the south. Several communities, including

Alma, Jonquière, Chicoutimi and La Baie, are connected together on the south shore of the Saguenay River (Grescoe and Germain, 1997).

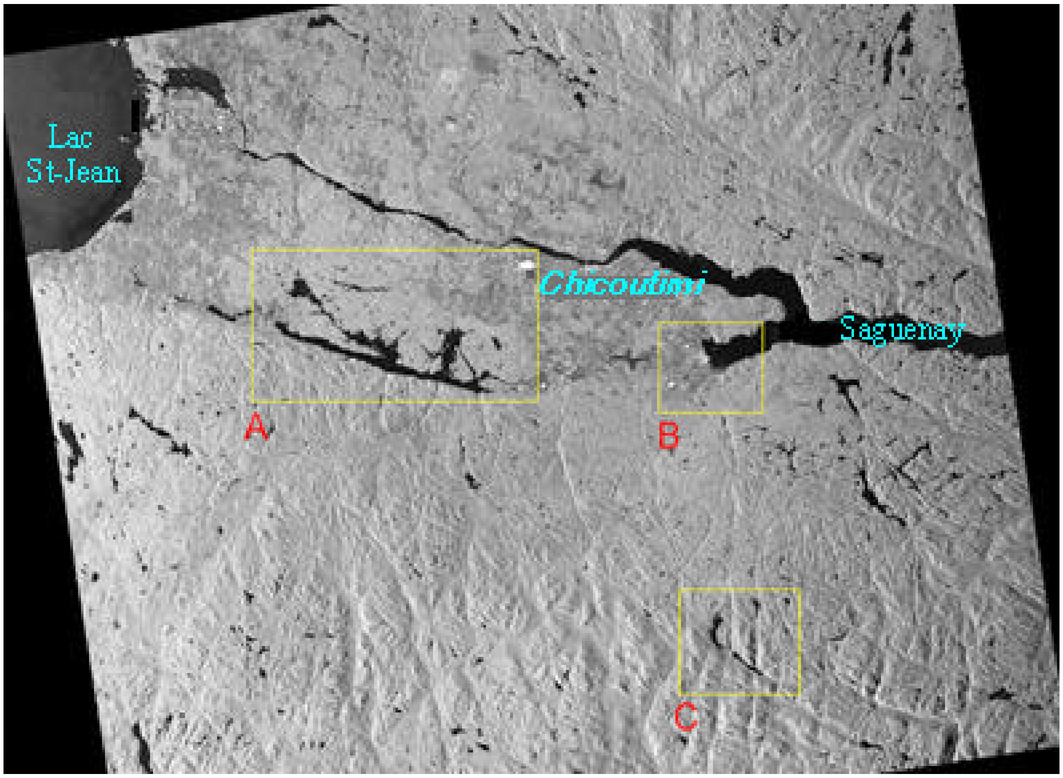


Figure 1. **A RADARSAT scene over the Saguenay region acquired on July 30, 1996. The box labeled A is Lac Kénogami, B is La baie des Ha! Ha!, and C is Lac Ha! Ha!.**

The watercourses of the Saguenay region are heavily regulated by dams and dikes for recreational and residential use, as well as for hydro-electric power. Most of the 2,000 structures were built before the1960s by 25 public and private organizations, with minimal environmental and technological controls (Grescoe and Germain, 1997).

On July 18, 1996, Environment Canada issued several weather warnings for heavy rains over the Saguenay region (Nicolet et al, 1997). The rain started at 1 a.m. the next day and heavy rains continued for about 2 days, resulting in precipitation ranging from 150 mm to 280 mm over different areas of the Saguenay region. The Kénogami drainage basin received almost double the amount of rainfall as that recorded in the lowlands between Jonquière and La Baie. This amount of rainfall exceeded the average amount for the entire month of July (approximately 125 mm). In fact it exceeded the 120-year old record of maximum rate of rainfall in a day (94.5 mm on August 31, 1893). At the stations located at rivière aux Ecorces, rivière Pikauba and lac Ha!Ha! the rainfall set a record; it averaged 6 mm per hour and at times exceeded 12 mm per hour. This intense rainfall covered many thousands of square kilometers and occurred on soils already saturated from previous rains.

Five of the rivers in the Saguenay region were most affected by the rainfall: rivière aux Sables, rivière à Mars, rivière Chicoutimi, rivière du Moulin and rivière des Ha! Ha!. These rivers have headwaters located in a zone that experienced greater than 200 mm of rainfall during the storm (Brooks and Lawrence, 1997). The result of the heavy rainfall was catastrophic. The most noticeable change was observed at the lac des Ha!Ha! reservoir. A major downstream flood event was triggered at the northeast side of lac des Ha! Ha! when 30 million cubic meters of water ruptured an earth dike and, rather than emptying through the gates of the existing concrete dam, created a new outlet channel through the surrounding forest approximately 12 m deep and 2 km long, which rejoined the existing watercourse downstream. The resulting rapid outflow of water devastated the village of Boilleau and the town of Grand-Baie, where a trailer park was inundated by floodwaters and numerous buildings were washed into the Saguenay River.

The damage to the landscape and to property was by no means confined to the valley of rivière des Ha! Ha! Within the Saguenay region, many landslides were triggered by the heavy rains. Many roads, sections of railway and bridges were heavily damaged or destroyed by the landslides or by inundation. Some river reaches experienced severe inundation, bank erosion and widening of channels. Many homes, businesses (including many farms) and industrial areas located along the rivers were severely affected. The banks along rivière à Mars suffered major lateral erosion, resulting in broken roads and the disappearance of backyards behind homes. At the city of Chicoutimi, floodwaters overtopping a dam caused a flood covering two city blocks. The damage to properties at rivière aux Sables was mainly caused by erosion of the river bank.

Remote Sensing and Ancillary Data

Due to orbital restrictions and problems with cloud cover, the earliest cloud-free LANDSAT and SPOT images showing the Saguenay region after the flood were acquired on July 29, 1996 (see Table 1). SPOT and LANDSAT images acquired in late June, 1996 were the “before the flood” optical satellite images available for temporal study of the flood.

Satellite	Acquisition Date	Image Mode	Resolution
SPOT	June 25, 1993	Panchromatic	10 m
		Multispectral	20 m
SPOT	July 29, 1996	Panchromatic	10 m
		Multispectral	20 m
LANDSAT	June 27, 1996	Thematic Mapper	30 m
LANDSAT	July 29, 1996	Thematic Mapper	30 m

Table 1. Spaceborne optical images used in the Saguenay flood study.

Satellite	Acquisition Date	Image Mode	Resolution
RADARSAT	June 6, 1996	S6 (Descending)	25 x 28 m
RADARSAT	July 30, 1996	S4 (Ascending)	25 x 28 m
RADARSAT	August 2, 1996	S7 (Ascending)	25 x 28 m
RADARSAT	August 9, 1996	F4 (Ascending)	10 x 9 m
RADARSAT	August 13, 1996	S2 (Ascending and Descending)	25 x 28 m
RADARSAT	September 26, 1996	F4 (Ascending)	10 x 9 m
RADARSAT	October 20, 1996	F4 (Ascending)	10 x 9 m
ERS-1/2	March 16, 17, 1996	Tandem	30 m
ERS-1/2	April 20, 21, 1996	Tandem	30 m
ERS-1/2	August 1, 2, 1996	Tandem	30 m
ERS-1/2	August 3, 4, 1996	Tandem	30 m

Table 2. Spaceborne synthetic aperture radar data acquired over the Saguenay region. A subset of these images are used in the study reported by this paper.

Table 2 lists the satellite SAR data acquired over the Saguenay region before and after the flood event. Unfortunately, at the time of the flood, RADARSAT was not available for image acquisition due to a satellite anomaly resulting from a loss of attitude control. It was July 30 when RADARSAT resumed its operation with the first image acquired over the Saguenay region at that time (Table 2).

In order to assess the capability of airborne multispectral video images for monitoring flood events, Air Focus of Chicoutimi, Québec was commissioned to acquire and generate a mosaic along the corridors (about 2 to 3 km in width) of the five most affected rivers at 1 m spatial resolution with three narrow spectral bands centred at 550 nm, 650 nm and 800 nm. The bandwidths for each band are 70 nm, 70 nm and 80 nm respectively. The videograph data were acquired on August 6, 1996. Air Focus acquired post-flood images of the same area on June 19, 1997, and created a geometrically corrected videograph mosaic that was geometrically registered to the 1996 mosaic using the same basemap.

Black and white aerial photographs at a 1:10,000 scale were also acquired in August 1996 along the corridors of the same five rivers. These B/W photographs were used to ascertain the validity of the airborne video mosaic. Field measurements such as accurate planimetric coordinates and elevations at specific locations were also taken as ground control points. In-situ 35 mm photographs were taken on the ground and from a helicopter to document different visible events along the rivers. These photographs were supplemented by hand held video camera images.

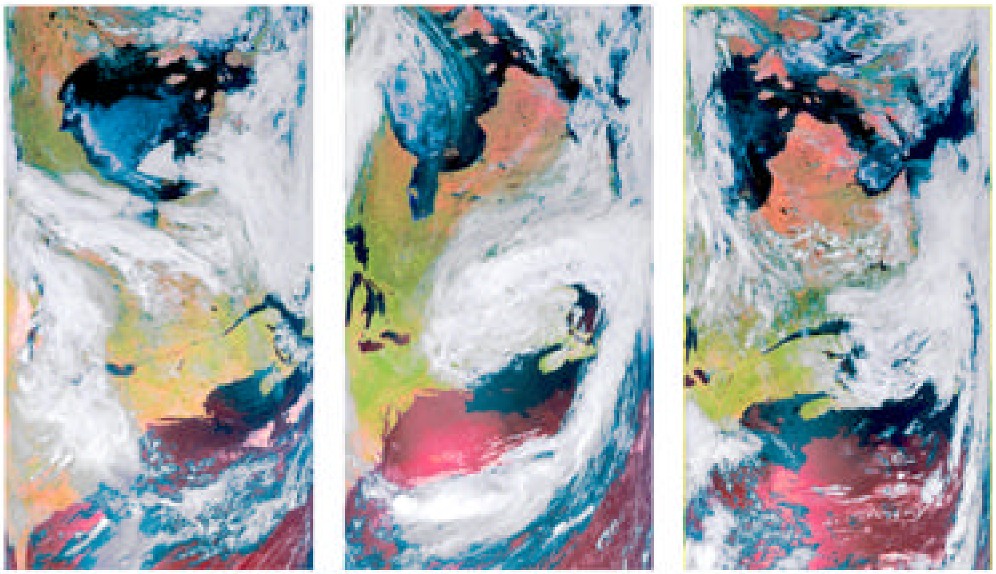


Figure 2. **The synoptic view of the flood event documented by the NOAA weather satellite images acquired on July 18, July 20 and July 22 of 1996.**

Seven regional weather images (including the days of the heavy rainfall) acquired by the National Oceanographic and Atmospheric Administration (NOAA) and processed by University of Québec at Chicoutimi, were included to provide a synoptic view. A set of topographic maps at 1:50,000 scale was used as reference for all the processing.

Digital Terrain Models (DEMs) are useful tools for sediment load estimation and geomorphic analysis within the flood plain. In order to study the impact and the cause of the flood, DEMs, which were generated by the Canada Centre for Topographic Information of Natural Resources Canada from 1:10,000 black and white aerial photographs at 1 m sampling space, were provided to the Dam Management Authority and the ministère des ressources naturelles. Topographic maps at 1:50,000 scale were used as reference for the processing.

Observations:

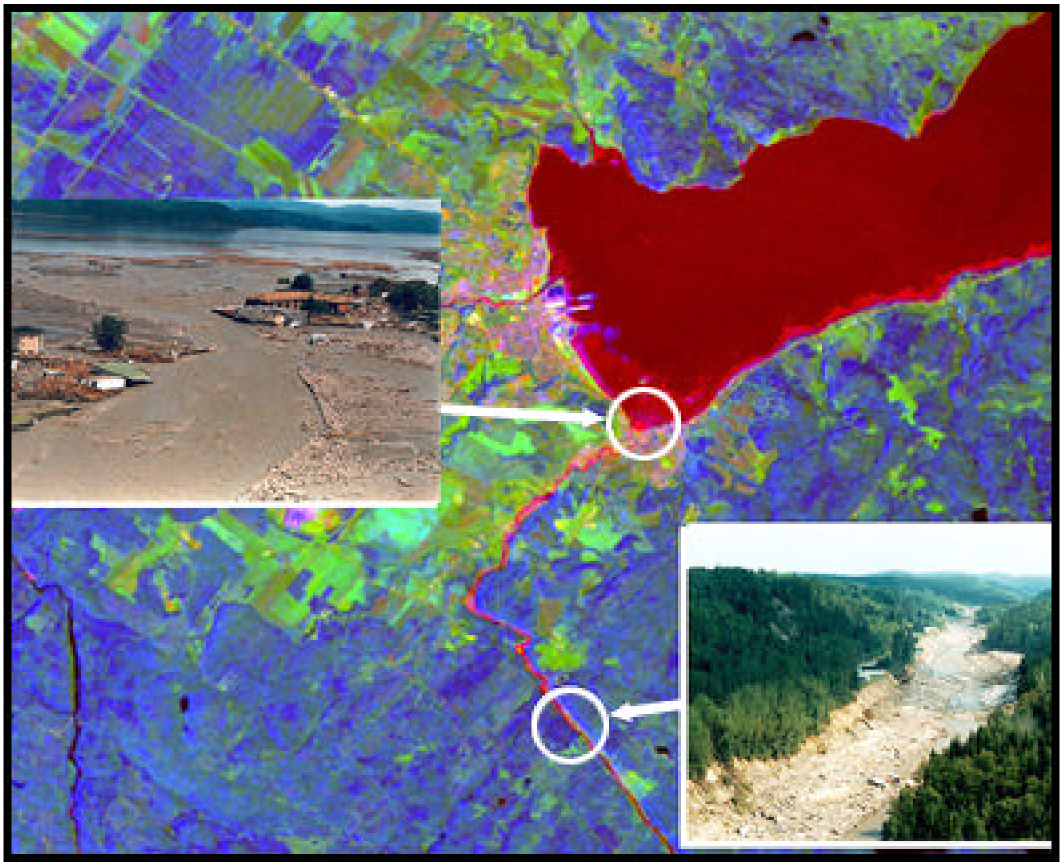


Figure 3. **Colour composite image showing LANDSAT Thematic Mapper channel 2 data acquired on July 29, 1996 (red), June 27, 1996 (green), and RADARSAT Fine Beam 4 on August 9, 1996 (blue). Red areas are exposed or suspended sediment resulting from the flood.**

The three NOAA images of July 18, 20 and 22, shown in Figure 2, are valuable as overviews of the storm that triggered the floods. The sequence of weather images shows the movement of the storm over eastern North America; the July 20 image, acquired during the most intense rainfall, provides a sense of its counter-clockwise movement and shows its location as it stalled over the headwaters of the rivers flowing northward into the Saguenay Valley. The July 22 image indicates that by that date, the Saguenay region was nearly cloudless.

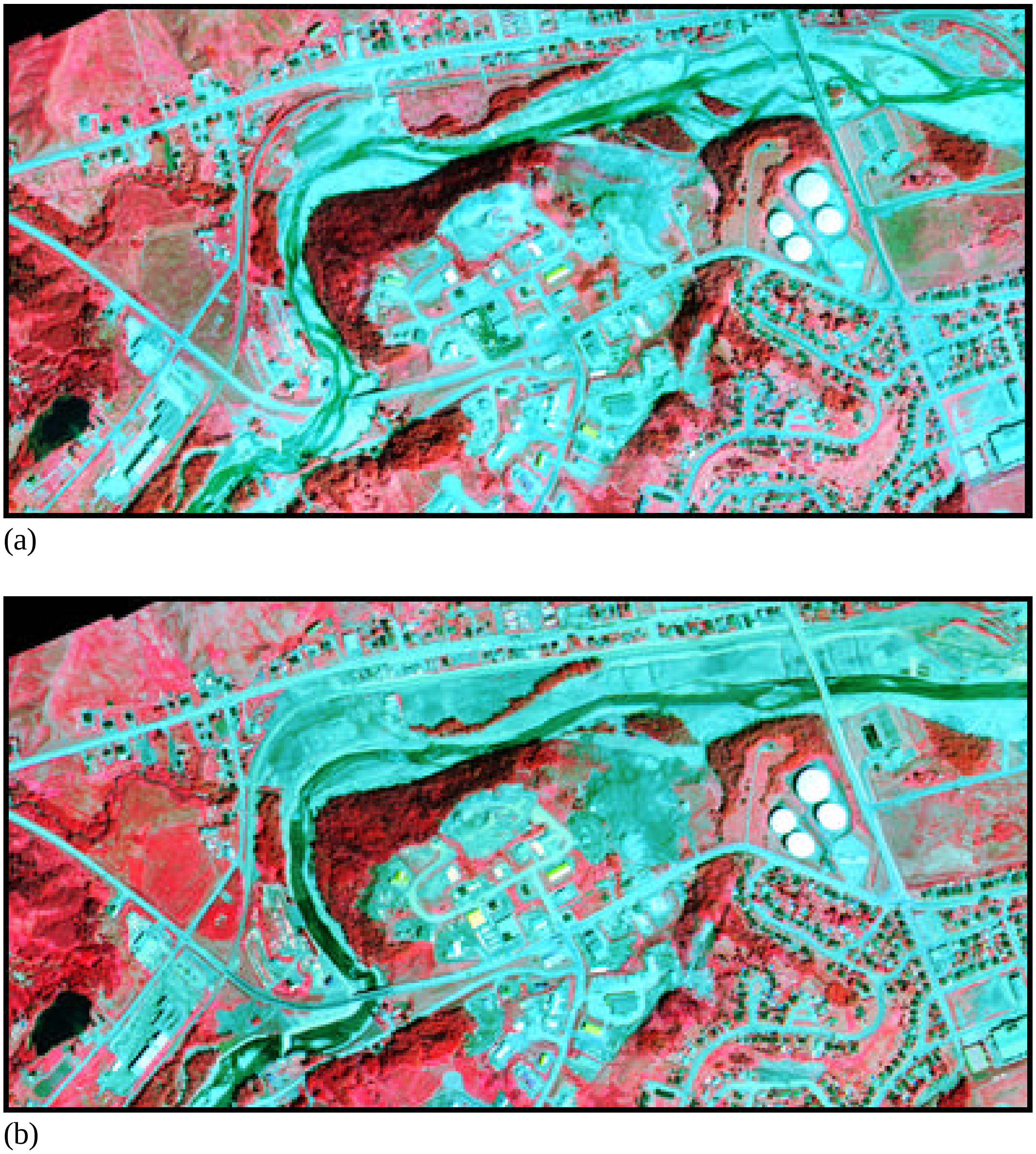


Figure 4. **Segments of the video image mosaic of the rivière a Mars (near La Baie). (a) image acquired early August 1996 two weeks after the flood; (b) image acquired in June 1997.**

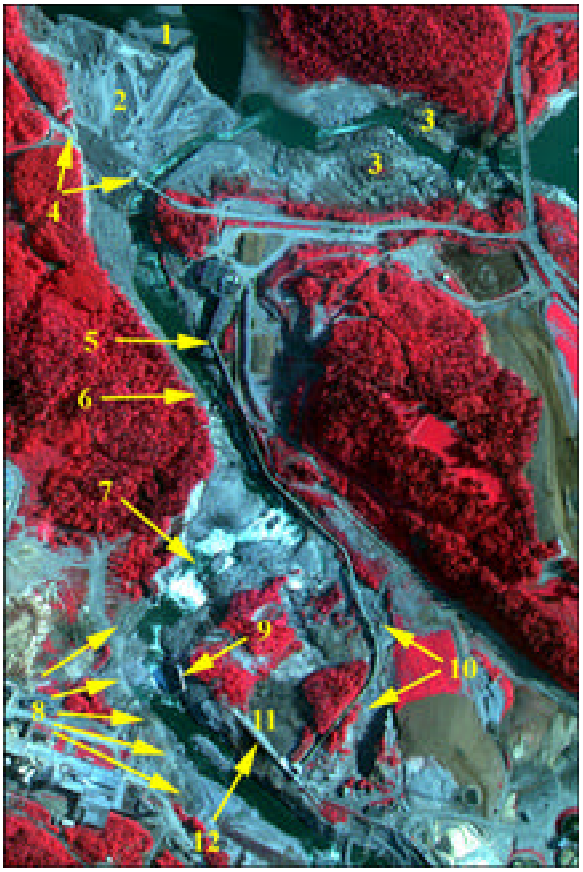
In a medium scale resolution image (such as the RADARSAT/Landsat composite in Figure 3), the damage caused at the mouth of the R. des Ha! Ha! following the emptying of the reservoir is clearly visible. The red colour indicates sediment that was either exposed or suspended due to the flood. The upper inset shows the estuary into which the rivière des Ha!Ha! empties into the Saguenay River. The old riverbed used to be about 25 m wide here but after the flood it was eroded laterally, resulting in a post-flood channel between 90 m and 280 m wide (Nicolet et al., 1997). The immense amount of sediment derived from upstream erosion, that was dumped over a wide area on the tidal flat, is visible in the background. The lower inset shows a portion of the river valley that was strongly incised and laterally eroded by the floodwaters. The flood plain shown here is three times the original width and now 7.5 m deeper than before the flood.

The 1 m spatial resolution of the videograph images (**Figure 4**a and 4b) results in far more detailed local information than that provided by the TM and RADARSAT satellite images. For instance, the smallest resolvable features are individual young trees, individual cars in parking lots, and the centrelines of highways and roads, all-terrain-vehicle (ATV) trails and small sheds in backyards. Homes, commercial buildings, and industrial facilities can be easily differentiated and identified. Roads ranging in size from ATV trails to farm roads, residential streets and major highways can also be distinguished.

The 1996 videograph image shown in Figure 4a provides information on the after-effects of the flood, including: locations where roads and railways have been severed, damaged, undermined, inundated or have disappeared; collapse of a bridge over the rivière à Mars, massive lateral and vertical erosion of land surrounding the river; undermining, damage, inundation or disappearance of buildings; areas of extensive deposition of sand, gravel and boulders by floodwaters; creation of temporary floodwater channels; and deposits of flood debris left along the floodplain.

Other videograph images acquired on the same date but not displayed here showed other evidence of damage and destruction. In the estuary of the rivière des Ha!Ha!, at the town of La Baie, large deposits of debris, including logs and remains of damaged homes, were visible. Tidal flats, created from the newly deposited sediment, were visible in the estuary. Along the rivière des Ha!Ha!, downstream from the emptied reservoir, large areas of trees knocked down in situ by the floodwaters were visible, as were scour pits that had been quickly eroded into the flood plain. At the lac Ha!Ha! reservoir, the newly exposed lakebed and new outlet channel could be seen, as well as the abandoned former outlet channel of the reservoir. **Figure 5** is an example of a geomorphological interpretation by GSC staff of a scene of 1996 videography. The area shown in Figure 5 is located near Jonquière, along the Saguenay River, and shows the erosive after-effects of the flood on roads, buildings, a bridge, a powerhouse, slopes and riverbanks. A dam structure, labelled as 12 in Figure 5, no longer retains water since the formation during the flood of a new overflow channel on the east side of the dam.

Even at the 1 m resolution of the videograph data, it is very difficult to see actual flood damage to individual homes (except for those homes that were wrenched from their foundations and were moved by the flood into the river or estuary). However, there were many secondary signs that damage had occurred, including the deposition of sand, disappearance of vegetation from yards and undermining of properties. It is also very difficult at this scale to distinguish sand from gravel or boulders. However, as the 1 m resolution is appropriate for depicting accurately the location of flood damage, the videograph images could be used as reference maps to help rebuild bridges, roads and facilities.



1. Fresh bar deposit
2. Large gravel fan splayed into channel of Saguenay River
3. Scoured bedrock along Saguenay River
4. Washed-out road and west abutment of bridge
5. Powerhouse undermined by lateral bank erosion
6. Fluvially-scoured bedrock/banks along widened channel
7. Fluvially-scoured bedrock along new channel
8. Major lateral valley-side erosion
9. Destroyed building
10. New channel formed by overflow of east wing of dam
11. Former spillway
12. Intact dam structure, now non-functional

Figure 5. **Geological interpretation by Dr. Greg Brooks and Dr. Ted Lawrence of the Geological Survey of Canada.**

The 1997 videograph images, such as the one displayed in **Figure 4**b, were acquired in order to identify indications of recovery along the rivière des Mars and rivière des Ha!Ha! from the effects of the flood. Examples of such changes, visible in **Figure 4**b, include: artificial and natural straightening of the formerly braided channel of the rivière à Mars; repairs and changes to slopes, bridges, roads and railway tracks; areas of new commercial and residential construction; places where severely damaged homes had to be leveled and removed; and the removal of flood debris deposits from the flood plain. Temporary roads and bridges that were constructed at the estuary following the flood have now been dismantled and replaced by permanent roads and bridges. The mudflats in the estuary have increased in size due to additional sediment that has been dumped in the estuary during the 10 months after the flood. Because of their geometric accuracy, high spatial resolution and relatively low cost, the images can serve as a useful tool for monitoring the rehabilitation of a region after a natural disaster such as a flood.

Discussion

The illustrations in this paper include a number of digital images related to the Saguenay flood at several scales, from the synoptic, regional views provided by satellites to the very local scale scenes obtained from high resolution videography. Images of flooding can be used as a visual record to evaluate and report damage at regional and local scales, including property damage, disruption of communication and transportation and to portray the extent of physical impacts. The videograph data have been geometrically corrected using a 1:20,000 NAD83 basemap by Air Focus, resulting in a 3 m RMS error based on several control points. Therefore the videography can be used to make large scale measurements such as the area impacted by the flooding, the size of geomorphic features along the river and changes in the riparian and human environment between 1996 and 1997. Experience gained in the processing and interpretation of videograph data at the high resolution of the Saguenay dataset can be applied to the high-resolution commercial satellite data which are expected to be available within the next two years from companies such as EarthWatch, Space Imaging and OrbImage.

There remain, however, many problems that the user will experience when compiling a set of images at the various scales offered by remote sensing technology. Satellite images may only be obtained according to the repeat cycle of the satellite. For instance, the Landsat satellite acquires imagery over a given area of Canada every 16 days. In addition, atmospheric conditions at the time of acquisition may often limit the quality of the imagery. There are many places in the country where it is very difficult to find a cloud-free Landsat image. The RADARSAT satellite can provide images that are unaffected by clouds, but for some applications, the optical data offered by the Landsat sensor are preferable to radar data. Furthermore, the user must also understand the complicated effects of the viewing angle, season and various environmental factors on radar images when specifying the configuration of RADARSAT data. Other technical problems may hinder the acquisition of a given image; for instance, the RADARSAT satellite experienced a loss of attitude control during July 1996. It was not until July 30, ten days after the flood, that RADARSAT resumed its operation and an image could be acquired.

Some of the advantages of videography became apparent during the course of this study. The video camera can be rapidly and easily deployed on platforms such as helicopters and light aircraft, often in conjunction with GPS technology. The data are particularly useful for surveying long corridors such as pipeline rights of way and river beds because video provides a continuous imaging record (Corbley, 1994). Video data have several advantages over black and white photographs at the same scale, such as the multispectral nature of the data. A single image mosaic provides a more convenient and synoptic view of a region than do multiple separate photographs. Video data are suitable for digital image processing but do not require photographic processing and per-picture calibration like aerial photographs.

Can videography be used for scientific measurements? The answer depends on the accuracy required. For example, one might want to determine if the video mosaic can be used to compute an absolute measure of the health of vegetation which could be monitored annually. For such an application and others demanding a high degree of accuracy, videography would likely be unsuitable because of radiometric and geometric distortions which influence the digital data. It is however, useful as a qualitative measure of vegetation condition.

In a natural environment, the energy reflected and generated from an object differs according to the viewing angle. The reflectance intensity recorded on the video image depends on the viewing angle of the instrument, which is influenced by the orientation of the aircraft platform and the mounting of the instrument. Since reflectance energy depends on the orientation of the source and the secondary reflectance from its surroundings, the recorded intensities are also directly affected by the sun angle and the condition of the sky (whether it is hazy, cloudy or clear) when the image is captured. All these radiometric effects must be considered before videography can be used to make quantitative measurements for scientific purposes.

The video mosaic image was created by "cutting and pasting" of adjacent image frames together. The individual frames were not ortho-rectified. Therefore, there are residual spatial distortions due to the viewing geometry of the instrument. The spatial displacement between two adjacent frames might be noticeable as tall, vertical objects on one frame (such as trees) are apparently tilted in one direction, and similar objects are tilted in another direction on the other frame. Depending on the linearity of the optical transfer function of lenses, higher geometric distortion is expected if picture areas near edges of the image frames are used in the mosaic (this was deliberately avoided in the mosaicking of Saguenay flood videograph). This kind of geometric distortion depends also on the setup of the optical instrument. In the Saguenay data acquisition, the video camera was mounted for nadir viewing, thus minimizing the spatial displacement due to viewing direction.

The airborne videography described here is still an emerging technology. It is a suitable method for acquiring digital imagery during the course of a disaster, but the imagery may be negatively affected by the actual environmental conditions being studied, for instance, in the case of heavy rains, fog or fire. The acquisition of the data for scientific analysis requires considerable rigor and planning. In this study, it was determined that the video camera coverage of the unconsolidated sediments deposited and eroded by the floodwaters and many man-made features, such as roads, parking lots and tops of buildings, were saturated (reflectance values couldn’t be obtained from them) because the video camera had not been calibrated in an optimal way.

In order to effectively apply remote sensing techniques to manage disaster-related situations, the acquisition, processing and delivery of relevant image products must become more efficient. In the case of the Saguenay flood, data acquisition and delivery of “raw” satellite image products occurred within two to four weeks. Production of airborne image mosaics required more than a month, while black and white photographs required a few days. This shows that the remote sensing industry must speed up the acquisition, processing and delivery of multispectral products to the level that image products can be delivered to the concerned organization in almost near-real time.

Conclusions:

We have demonstrated how remote sensing images can be used at a wide range of scales during a major flood event as a pictorial means to record and evaluate the extent and nature of flood damage at a wide range of scales, including property damage, and disruption of transportation and communication infrastructure. It has also been shown that remote sensing can assist in flood prediction, disaster planning, emergency relief and reconstruction. It is possible to make some quantitative measurements relating to geomorphic features and flood damage at a large scale.

However, for the effective application of remote sensing techniques for disaster management, the acquisition, processing and delivery of image products must be well-timed, particularly in the case of high-resolution airborne image mosaics, which required a month for delivery following acquisition. In the case of disasters such as floods, the image products must be delivered to the concerned organization in as close to real time as possible.

The flood was documented in a data set recorded on an interactive compact disk which is available to the public. This data set consists of ground and oblique aerial photographs, satellite images and airborne multispectral images. The photographs were taken during the flood by a team from the GSC and about two weeks after the flood by CCRS staff. The satellite and airborne images on the compact disk are accompanied by geomorphological interpretations based on field analysis by the GSC and CCRS teams.

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