An Efficient Method for Mapping Flood Extent in a Coastal Floodplain Using Landsat TM and DEM Data

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Abstract. An efficient and economical method for mapping flooding extent in a coastal floodplain is described. This method was based on the reflectance features of water versus non-water targets on a pair of Landsat 7 Thematic Mapper (TM) images (before and during the flood event), as well as modelling inundation using Digital Elevation Model (DEM) data. Using limited ground observation, most flooded and non-flooded areas derived from this analysis were verified. Utilizing only TM data, the total flooded areas in Pitt County, North Carolina on 30 September 1999 was 237.9 km^2 or 14.0% of the total county area. This number could be low due to the underestimation of the flooded areas beneath dense vegetation canopies. To further investigate this underestimation, a subset of the area covering the four central topographic quadrangles, the Greenville area, in Pitt County was selected. Through addition of the DEM data into the flood mapping analysis of the Greenville area revealed that the total flooded area was 98.6 km^2 (out of a study area of 593.9 km^2) or 16.5%. In the Greenville study area, the three landuse and landcover categories most aVected by the flood were bottomland forest/hardwood swamps (32.7 km^2), southern yellow pine (28.8 km^2), and cultivated land (19.1 km^2). Their total flooded areas were 80.6 km^2 or 81.7% of the total flooded area within this study area. The DEM data helped greatly in identifying the flooding that occurred underneath forest canopies, especially within bottomland forest and hardwood swamps. The method was reliable and could be applied quickly in other coastal floodplain regions using data that are relatively easy to obtain and analyse, and at a reasonable cost. This method should also work well in areas of large spatial extent where topography is relative flat.

1. Introduction

During an extreme flood event it is important to be able to determine quickly the extent of flooding and the landuse and landcover types under water. This information can be used in developing a comprehensive relief eVort (Corbley 1993). During flooding events remotely sensed data can provide significant mapping capabilities. However, obtaining remotely sensed data that represents the ideal combination of fine spatial and temporal sampling, and the ability to see through clouds and/or to discriminate flooding under forest cover is a diYcult task. In addition, accessibility

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to the data in terms of cost, ease of acquisition, and ease in data processing and analysis are significant factors.

On 2 September 1999, Hurricane Dennis visited the Outer Banks of North Carolina. It then returned as a tropical storm on 5 September, spreading significant precipitation across eastern North Carolina and left the ground saturated. On 15 September 1999, Hurricane Floyd made landfall near the South Carolina – North Carolina border and proceeded to churn through eastern North Carolina, dumping

25 – 46 cm of rain in many areas in less than 72 h. On 17 September the Tar, Neuse, Roanoke and Pamlico Rivers were predicted to reach flood stage, and to continue to rise for several days. The devastation due to flooding from these storms and two additional precipitation events in late September was immense. Within a few days floodwaters rose and covered over 50 000 km^2, causing an unprecedented disaster in the eastern region of state as one of the worst floods in history inundated eastern North Carolina. In addition to the loss of over 50 lives, more than 6000 homes were destroyed and some 44 000 were damaged. Estimates indicated that losses could exceed $6 billion (Gares 1999).

In response to the extensive flooding that occurred after Hurricane Floyd in eastern North Carolina, we developed an efficient method for mapping flood extent that used Landsat 7 Thematic Mapper (TM) imagery, as well as Digital Elevation Model (DEM) data. This method provides fine spatial sampling and determines flooding under forest cover within a floodplain, with data that is relatively inexpensive and easy to obtain, process, and analyse.

Studies of mapping flood extent using Landsat TM data (e.g. Dartmouth Flood Observatory 1999) have noted the inability of the imagery to identify flooded areas under forest cover. Jin (1999) developed a flooding index using the Specific Sensor Microwave/Imager (SSM/I) data of the Defense Meteorologic Satellite Program (DMSP). Synthetic Aperture Radar (SAR) data can penetrate cloud cover, and have been applied to mapping flooded areas of the Amazon rainforest (e.g. Hess *et al.* 1995, Melack and Wang 1998, Miranda *et al.* 1998), monsoon flood damage in Bangladesh (ImhoV *et al.* 1987), and river flood waves in the Great Upper Mississippi Valley flood of 1993 (Brakenridge *et al.* 1998). ImhoV *et al.* (1987) also incorporated the use of Landsat Multi-Spectral Scanner (MSS) data and inventoried landcover classes inundated during flooding.

DEMs have been used in various ways to aid in flood mapping and modelling. They have been used as an integral part of a Geographic Information System (GIS) database applied to hydrologic flood modelling eVorts (e.g. Muzik 1996, Correia *et al.* 1998). They can also be applied towards verification of insurance claims after a flood (Barnes 1996). In addition, the delineation of floodplains and the development of flood inundation maps have relied on DEMs (e.g. Jones *et al.* 1998). The recognition of error in DEMs is an important concern. However, it has been investigated (Brown and Bara 1994), and a few examples have been provided in the literature that is applicable to floodplain mapping (e.g. Lee *et al.* 1992, Hunter and Goodchild 1995).

In this paper, we present a method for mapping flood extent in a coastal floodplain through the use of TM data, as well as DEM data. First, we describe the study area, and the extent of damage due to flooding from the hurricane. Then we provide a discussion of the TM, DEM, and landuse/landcover data and initial processing steps, and describe ground observations. Next, the flood mapping eVorts are explained using TM data for Pitt County, and TM and DEM data for a subset of Pitt County.

We then present the results. We also discuss the potential for applying the flood mapping methods (using TM data alone, and combining TM and DEM data) in coastal floodplains in general, and the limitations and cautions that should be noted when applying these methods to mapping flood extent in areas of large spatial extent, and areas having large topographic variation.

2. Analytical approaches

2.1. *Study area and ground observation*

Most of eastern North Carolina lies within the Atlantic coastal plain. Pitt County lies in the eastern coastal plain of North Carolina, at the approximate centre of the region. The elevation of the area drops only about 60 m as it extends 120 – 160 km from the Piedmont region in the middle of the state towards the coast. Four large elongated river systems drain the coastal plain in a north-west – south-east direction. Flat broad floodplains are usually located on the northern side of the rivers with higher ground on the south (Gares 1999). In Pitt County the land surface has very low relief and many parts of the region have been extensively drained, cleared and ditched for agricultural use. The soils are primarily characterized as poorly drained or extremely poorly drained (63.0%), with the remaining area consisting of moderately well to well-drained soils (Gares 1999). Pitt County has a population of about 126 000 (estimated in 1998). The largest city, Greenville, is centrally located and has a population of approximately 60 000 (estimated in 1998). The additional residents of the county are spread throughout rural towns.

In Pitt County the majority of the 1999 flooding occurred north of the Tar River. The Tar River has been slowly migrating southward towards the drainage divide of the Neuse River so broad primary and secondary floodplains extend northward from the river channel. North and immediately adjacent to the Tar River is a band following the channel that is currently defined as conservation/open space landuse in the City of Greenville (figure 1). This conservation/open space landuse zone grades into low and medium density residential, industrial and mixed land uses. It is clear from the photograph, however, that there is significant activity within this open space landuse. The City of Greenville alone suVered flooding to its airport, water treatment facility, power transmission substation and numerous residential and industrial areas that are within or nearby current open space landuse zones. In Pitt County, some 6000 homes were flooded. Over three-quarters of these homes were largely uninsured. Upwards of 50 000 people were displaced. More than 6000 were housed in emergency shelters, many for over 3 weeks.

Once the floodwaters had completely subsided, but before high water marks faded, ground data information was gathered in the field. Areas both north and south of the Tar River were examined for the extent and depth of flood waters. The aerial photo (figure 1) was taken on 23 September 1999 during the flood event and is centred approximately on the City of Greenville. The flood gauge information used for this study was taken from the gauge on the Green Street Bridge (figure 1). Floodwaters extend into the student housing district seen in the south-eastern section of the photo and throughout the entire area shown north of the river. Areas of extensive tree canopy north of the river in the primary and secondary flood plain were completely flooded. Figure 2 shows the high water marks (reaching the middle of windows) on a house trailer in a trailer park that is located immediately adjacent to the north-eastern most section of the photo. These areas of tree canopy were not

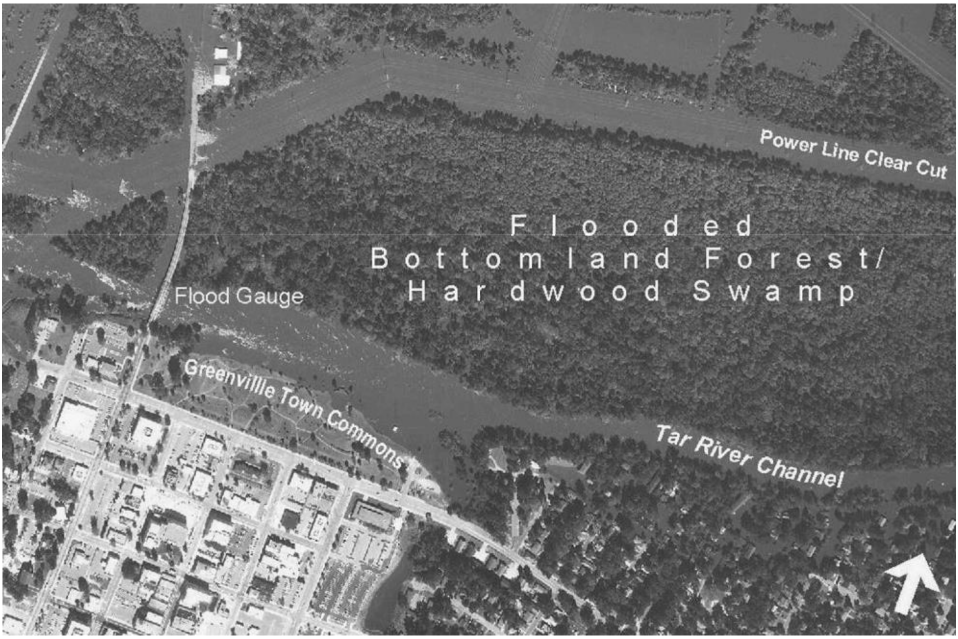

Figure 1. Aerial photo of a portion of the City of Greenville, North Carolina, taken during the September 1999 flood. The major part of the City of Greenville is on the south side of the Tar River.

classified in the TM images as flooded but, clearly, they were flooded to a significant depth.

2.2. *Remotely sensed data*

For flood mapping, two sets of the remotely sensed data are required; one set consisting of data acquired before (and as close as possible to) the flood event, and the other acquired during the occurrence of the flood. In reality, data availability may cause some compromise. In this study, the Tar River reached peak flood stage in the area of Pitt County on 21 September 1999. The Landsat 7 TM data that were available closest to this date were acquired on 30 September 1999. Due to the 16-day repeat orbiting of the Landsat 7 satellite, the availability dates for images of pre-flood data were 14 September, 29 August, 13 August and 28 July. Due to the severe cloud coverage in the 14 September and August images, we used the image acquired on 28 July for pre-flood analysis. (There were some thin clouds and patches of cloud in the 28 July image that did aVect our analysis.) In summary, we ordered two TM images, one acquired on 28 July 1999, and the other on 30 September 1999. We geo-referenced both images and were able to determine the extent of flooding in Pitt County using the non-flooded 28 July image as a reference.

2.3. *DEM data of Greenville area and river gauge readings at Greenville*

DEM data were available from the United States Geological Survey' s (USGS) web site in the Spatial Data Transfer Standard (SDTS) format. The DEM has a 30 m×30 m resolution, and in this area the elevation interval (z=height) is 0.30 m. The accuracy of the DEM data (i.e. the uncertainty, or root mean square error,

Figure 2. Flooded mobile home in a densely vegetated trailer park on the floodplain, just north of the Tar River, Greenville, North Carolina. The high-water mark reaching the middle of windows is clearly shown on the side of the mobile home.

RMSE) in this area is 1 m. Four 7.5 min USGS topographic quadrangles, Greenville NW, NE, SE and SW were downloaded, imported, and mosaiced. The four mosaiced quads covered an area of about 600 km^2. Descriptive statistics for the four-quadrangle DEM area included min.=0 m, mode=11.9 m, median=14.0 m, mean=14.6 m, max.=26.2 m, and standard deviation=6.4 m. This study area is primarily flat, especially on the north side of the Tar River where most of the flooding occurred (e.g. figures 1 and 2). We then co-registered the TM and DEM data so that the same area of interest can be easily extracted.

Flood stage on the Tar River is measured from a point 0.7 m below sea level (based on the North American Vertical Datum, NAD88). The bottom of the river is about 2 m below sea level. The Tar River leaves its banks 4 m above this measuring point. The Tar River crested at 9.2 m on 21 September. On the date the imagery was taken, 30 September, data from the USGS showed that the mean stage level for the Tar River at the Greenville station was 6.1 m. The non-flood stage surface height of the water in the Tar River according to the river gauge reading on 28 July 1999 was

1.1 m. Therefore, the elevations that represented flooded areas on 30 September ranged from 1.1 to 6.1 m. These elevations were used as a basis for classifying the area on the Greenville topographic quadrangles into water bodies/rivers, flooded areas, and non-flooded areas, which will be discussed in detail in a later section (see tables 5 and 6).

2.4. *North Carolina landuse and landcover data*

Between 1995 and 1997, the North Carolina Center for Geographic Information and Analysis (NCCGIA), in cooperation with the NC Department of Transportation and United States Environmental Protection Agency Region IV Wetlands Division, contracted Earth Satellite Corporation (EarthSat) of Rockville, Maryland to generate comprehensive landcover data for the entire state of North Carolina (Earth Satellite Corporation 1997). There are 21 landuse and landcover type categories in the entire state data layer. For Pitt County, only 17 categories exist ranging from highly developed areas to unconsolidated sediment areas. To facilitate the presentation of this paper and to provide the reader with a better understanding of the landcover classes, we provide brief definitions of some categories (in table 3). The three landuse/landcover categories that were aVected the most by the flood were bottomland forest/hardwood swamps, southern yellow pine, and cultivated land. Bottomland forests/hardwood swamps are areas where deciduous, dominant, woody vegetation is above 3 m in height, as well as occurring in lowland and wet areas. Crown density is at least 25%. Southern yellow pine are areas where stocking of trees is 75% evergreen needleleaf or broad-leaf species, including the following forest types: longleaf pine, loblolly-slash pine, other yellow pine, and pond pine. Cultivated lands are areas of land that are occupied by row and root crops that are cultivated in distinguishable rows and patterns. Two other important categories aVected by the floods were high and low intensity developed areas, which contains the housing and infrastructure for the majority of the human population in the area. High intensity developed areas are covered by more than 80% synthetic (man-made) landcover. Low intensity developed areas have between 50 and 80% coverage by synthetic landcover. (See table 3 for the flooded areas for other landuse and landcover types.)

2.5. *Flood mapping using TM images*

The initial goal in flood mapping was to investigate the utility of the TM images for identifying areas that were flooded or not flooded. There were two steps: (1) identify water versus non-water areas on the TM images before and during the flood event, respectively, and (2) compare the areas classified as water or non-water on both TM images to determine which areas represented flooding.

2.5.1. *Identifying water areas versus non-water areas*

There are many possible methods for identifying water versus non-water areas using TM data (e.g. Jensen 1996). After unsuccessful trials of using supervised and unsupervised classification, and other methods, we used the addition of two TM bands (TM4+TM7) of 28 July, and of 30 September, respectively. TM4 (0.76 – 0.90 *m*m, reflective infrared) is responsive to the amount of vegetation biomass, and is useful in identifying land and water boundaries. However, it is possible to confuse water and asphalt areas (road pavements and rooftops of buildings) in the developed areas such as downtown, commercial/industrial areas, etc., as they appear black on the TM4 image or they reflect little back to the sensor. On the TM7

(2.08 – 2.35 *m*m, mid-infrared) image, the reflectance from water, paved road surfaces, and rooftops diVers. Thus, one can identify the water (flooded) and non-water (non-flooded) area in the developed areas, by incorporating of TM4 and TM7 into the analysis, as detailed in table 1. This addition is done separately for the July and September TM data. Therefore, the classification rule was:

> If the reflectance of pixels or areas is low in the TM4 plus TM7 image, the pixels represented water, otherwise the pixels represented non-water or dry areas.

In the analysis, we noted that the reflectance from water, paved road surfaces, and asphalt rooftops of buildings in the developed areas may be also distinguished on TM5. Thus, TM5 could have been used to detect water versus non-water areas. However, the diVerences on TM5 were slightly smaller than those on TM7 image. Also, Banumann (1996) added two (before and during flood event) TM4 images in his 1993 Mississippi flood analysis. He then sliced the added image into water, flooded areas, and non-flooded areas. He further added TM7 data to the combined TM4 image to separate some confusion between the water and industrial area.

Once the representation of the reflectance values for water and non-water features was understood, a cut-oV value could be determined to separate the two categories. For the July TM image, the cut-oV value was 141. If a pixel' s DN value was less than 141, that pixel was assigned as a water category, otherwise it would assigned as a non-water category. For the September TM image, the cut-oV value was 109, i.e. if a pixel' s DN was less than 109, that pixel was classified as water, otherwise it was classified as non-water. Even though the selection of the cut-oV values may seem to be somewhat arbitrary, we used two diVerent methods to check the cut-oV values. One was ground truthing, and the other was the analysis of the histograms of the TM4 plus TM7 images. In the former, ground observations along the Tar River were used to pick the cut-oV values. These observations were made in the field in early October of 1999 (e.g. figure 2), and through the analysis of aerial photos taken during the flood event. In the latter, the histogram of the TM4 plus TM7 image was examined to see whether the histogram indicated the cut-oV values. This was the case for the histogram of the July TM4 plus TM7 image; two distinct distributions were observed from the histogram plot. There were also two identifiable distributions in the histogram of the September TM4 plus TM7 image. However, a distinct separation between the two distributions, was not as easily identified (i.e. any DN value ranging from 107 to 111 may be selected).

2.5.2. *Determine flooded areas during the flood event*

After identifying water versus non-water areas on both images (one acquired before the flood event and the other during the flood) using the above criteria, determination of areas that were flooded could be made. On a pixel by pixel basis,

Table 1. Reflectance of water, asphalt pavement (road surface, root of buildings, etc.), and other non-water dry areas on TM4 and TM7 images.

	Reflectance on TM4	Reflectance on TM7	Reflectance on TM4+TM7
Water	low	low	low
Asphalt pavement	low	intermediate	intermediate
Other dry area	high	high	high

there were four possible results, and the following rules were used to determine the flooded areas:

1. If an area was classified as water before and during the flood event, it was not considered to be flooded. Water areas in the study areas are the regular river channels, ponds, etc.
2. If an area was classified as dry or non-water on the July (pre-flood) image, and the area was classified as water on the September (flood) image, the area was considered to be flooded.
3. If an area was dry on both the July and September images, the area was not flooded.
4. It is possible to have an area that was classified as water in the July image, classified as non-water in the September image. Possible explanations include (a) landuse change between the dates that the imagery was acquired, and (b) cloud eVects on the classification. In our analysis, we have noticed the shadows of some small patches of clouds in the July image. The locations shadowed by the cloud were dry in July and September 1999.

3. Results and discussions

3.1. *Flood mapping derived by TM images*

Using the TM data and the method described above, a map representing flooded areas in Pitt County on 30 September 1999, was created (figure 3). The flooded areas are shown in red and water (regular river channels, ponds, etc.) in blue. The small areas shown as yellow were classified as water on the July image, and non-water category on the September image. These areas actually represent the shadows of clouds on the July image. After ground truthing these areas that were non-flooded in September, we recoded this category as non-flooded areas for further analysis (in figure 3). The non-flooded areas are represented by the black/white image of TM band 7 from 30 September. Table 2 summarizes the derived map by the four categories described in §2.5.2. The major flooded areas were along the Tar River flowing into Pitt County from the north-west corner of the image and exiting the County to the east. There were large patches of flooded areas in the north. There were flooded areas along the tributary of the Neuse River as well (south-west side of the image, figure 3).

3.2. *Areas flooded by each landuse and landcover type*

Using the landuse and landcover data layer obtained from the NCCGIA, we provide the following description for the derived flood map. The flooded areas along the Tar River and along the tributary of the Neuse River were primarily bottomland forests/hardwood swamps (e.g. figure 1). The patches of flooded areas in the north, north-east, and south-east of the image were mainly southern yellow pines and cultivated lands. The three categories most aVected by the flood, in terms of size and percentage of the total flooded area in Pitt County, were southern yellow pine (91.7 km^2 or 5.4% out of the total areas in the County), bottomland forest/hardwood swamps (73.6 km^2 or 4.3%), and cultivated lands (40.0 km^2 or 2.4%). It should be noted that most of the high and low intensity developed areas were not flooded on 30 September 1999. (The floodwater from the Tar River had receded about 3 m from its crest on 21 September. The main developed areas are near the banks of the Tar River.) It should be also noted that there was a slight diVerence of the sizes of the

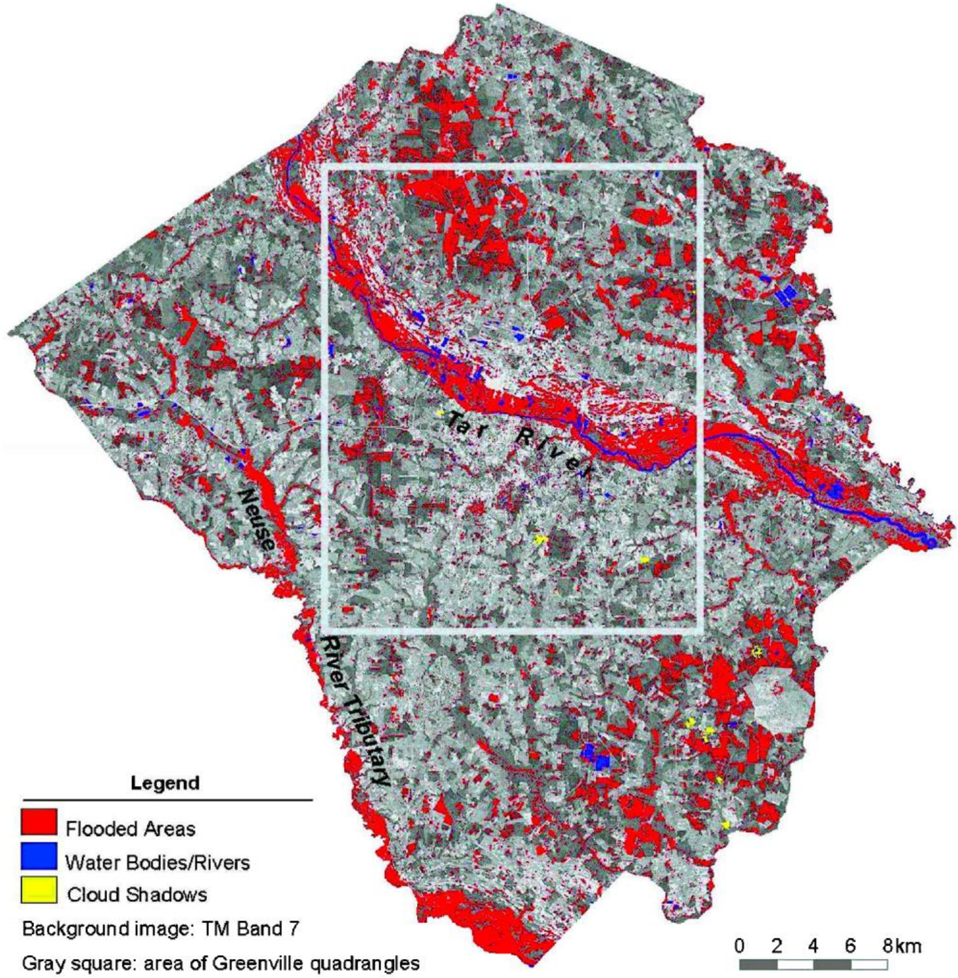

Figure 3. The flood extent in Pitt County, North Carolina on 30 September 1999, derived from a pair of Landsat TM images of 28 July and 30 September 1999. The grey rectangle indicates the Greenville study area.

Table 2. Flood mapping of Pitt County, North Carolina, as of 30 September 1999.

	Area (km^2)	Area (%)
Water bodies/Rivers	13.3	0.8
Flooded areas	237.9	14.0
Cloud shadows	1.2	0.1
Non-flooded areas	1444.8	85.1
Total	1697.2	100

water bodies/river channels derived from the TM image pair of 1999 and NCCGIA landuse data layer (13.3 km^2 vs 12.2 km^2, cf. Tables 2 and 3). This difference could be due to different ways to identify water, due to the errors in our analysis and/or

Table 3. Total areas from the landuse and landcover type data layer and flooded areas of each landuse and landcover type in Pitt County (NC) derived from TM data.

	Total areas from the landuse data layer (km^2)	Flooded areas on 30 Sept. 1999 (km^2)	Overall (%)
High intensity developed	12.6	1.1	0.1
Low intensity developed	22.8	0.9	0.1
Cultivated	612.8	40.0	2.4
Managed herbaceous cover	40.6	3.1	0.2
Unmanaged herbaceous cover—upland	13.4	0.5	0.0
Unmanaged herbaceous cover—wetland	0.1	0.0	0.0
Evergreen shrubland	177.1	16.0	0.9
Deciduous shrubland	19.5	1.9	0.1
Mixed shrubland	26.0	2.3	0.1
Mixed upland hardwoods	0.1	0.0	0.0
Bottomland forest/hardwood swamps	369.3	73.6	4.3
Needleaf deciduous	0.1	0.0	0.0
Southern yellow pine	350.5	91.7	5.4
Mixed hardwoods/conifers	39.1	3.4	0.2
Oak/gum/cypress	0.3	0.1	0.0
Water bodies/rivers	12.2	3.1	0.2
Unconsolidated sediment	0.7	0.1	0.0
Total	1697.2	237.8	14.0

in the landuse data layer, due simply to landuse change since the creation of the landuse data layer in 1996, or all three.

3.3. *Addition of the DEM data into the flood mapping analysis*

Due to the dense or continuous canopy coverage in bottomland forest/hardwood swamps and in some dense southern yellow pine stands, and due to the lack of canopy penetration of the TM data, flooded areas under the canopies were not detected by classification of the TM data. This underestimation of flooded areas was verified through ground truthing and visual interpretation of low-altitude oblique aerial photos taken during the 1999 flood. On the flood map, these undetected flooded areas show up as 'patches or holes' along the primary floodplain near the riverbanks. It is important to point out this underestimation, because floods in the coastal floodplains of North Carolina, as well as the entire East Coast and the coast of the Gulf of Mexico often occur from the mid-summer to fall, and trees in the floodplain are almost fully leaf-on during this period of time. Radar data (especially radar data from a long wavelength system) can penetrate the (dense) canopies and identify whether the areas underneath the canopies were flooded or not. However, due to the cost of the radar (such as ERS SAR or Radarsat SAR) data we did not incorporate them in the flood mapping analysis. One alternative is to integrate DEM data into the analysis. There are several advantages to this integration. In the USA, the DEM data are widely available and can be directly download from USGS/EROS web site. (It should be noted that the availability of DEM data in other countries might be limited.) Also, most of the bottomland forest and hardwood swamps in the floodplain are located in places of low elevation or along the banks of rivers. By

using river gauge reading to inundate the DEM, one can map the flood underneath tree canopies in the bottomland forest, and hardwood swamps, as well as in some southern yellow pine stands in low elevation areas. Additionally, high-quality DEM data work well for flood mapping in areas of relatively flat terrain, as exists in this study area and other coastal floodplains along the East Coast and the Gulf of Mexico. The following discussion describes the integration of the DEM and TM data for the flood mapping study.

We used four 7.5 min quadrangles of USGS DEM data for the Greenville areas. A grey box shown in figure 3 indicates the coverage of the four quads, which includes most of the Tar River in Pitt County. We then extracted the area (of the block, figure 4(*a*)) from the flood map of Pitt County (figure 3) derived from the TM data. Black areas on the image represent water bodies/rivers, grey represents flooded areas, and white represents non-flooded areas. A detailed statistical summary of flooded areas for each landuse and landcover type is provided in table 4. The three categories having the largest areas and highest percentage of flooding were southern yellow pine, bottomland forest/hardwood swamps, and cultivated land.

We then inundated the DEM based on the river gauge readings before the flood event and on 30 September 1999. The river gauge station is near the centre of the four quads (figure 1). These readings were 1.1 m preceding the flood event, and 6.1 m on 30 September. Using the rules found in table 5, we reclassified the DEM into water bodies/rivers, flooded areas, and non-flooded areas (figure 4(*b*)). The simple threshold used for inundating the DEM was possible due to the relatively flat terrain (no sinks) away from the river channel within our study area. The flooded areas were located in the floodplain of the Tar River, and flooded areas did not exhibit the canopy 'holes' found on the TM images. By inundating the DEM data, flooded areas under the canopies of the bottomland forest and hardwood swamps could be identified. At higher elevations and away from the river, the DEM suggested that those areas were dry or there was no flooding. The DEM does not identify water bodies and/or flooded areas at higher elevations. The flooded areas of each landuse and landcover type derived from the DEM data were also tabulated (table 4), and the largest area (22.6 km^2) and highest percentage (3.8%) of flooded landcover type was bottomland forest/hardwood swamps.

The final flood map for the Greenville areas was derived by using the logical 'OR' operator to combine the flooded areas from either the TM data or the DEM data (figure 4(*c*)). Flooded areas located away from the river and at high elevation were identified by the TM data. Flooded areas near the river and its tributaries were determined primarily by the DEM and partially by the TM data. No patches or 'holes' were visible on the combined flood map. This 'OR' logic allows us to extract the best of the TM and DEM data in the flood mapping analysis, and overcame some of the deficiencies of using the TM data or the DEM data alone. The use of both TM and DEM data in flood mapping was straightforward and efficient. Furthermore, based on our limited ground observation and analysis of aerial photos taken in the study area during the flood, the results were fairly accurate and reliable.

3.4. *Limitation of the integration of the DEM data into the flood mapping analysis*

Although the results derived from the integrated TM and DEM data were very promising, we would like to offer two cautions regarding the accuracy of the DEM data and inundation of the DEM data using the river stage data.

The DEM data, created by USGS, have an estimated accuracy of 1 m (RMSE).

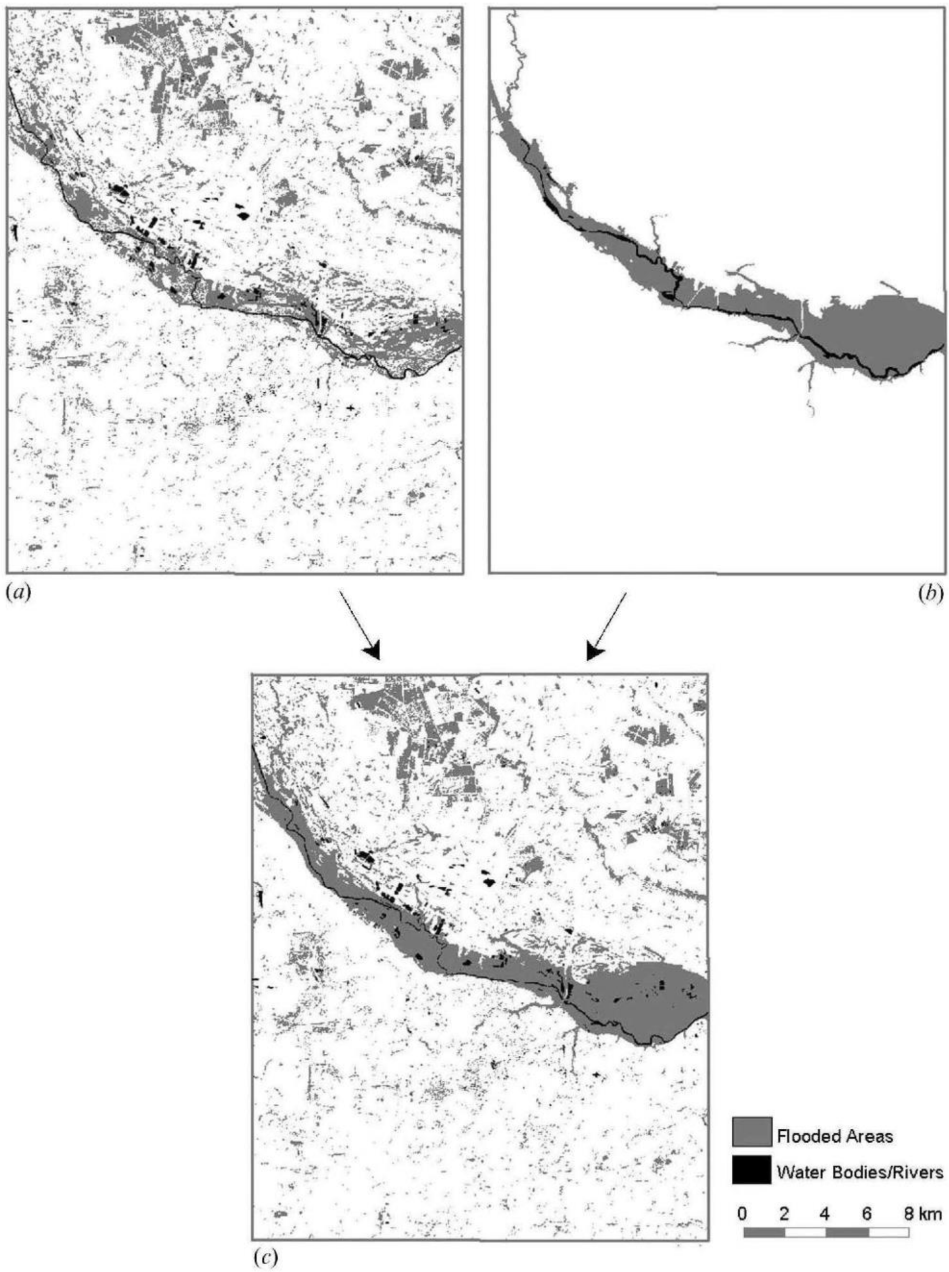

Figure 4. Integration of the TM and DEM data in the 1999 flood mapping study for areas of four Greenville quadrangles. (*a*) Extracted flood map (from figure 3) derived from TM data alone, (*b*) inundated DEM data based on the river gauge reading on 30 September 1999, and (*c*) final flood map by combining the TM and DEM data through a logical 'OR' for flooded areas.

Table 4. Total and flooded areas of each landuse and landcover type in Greenville (NC) derived from TM data alone, DEM data alone, and TM and DEM data combined.

	Total areas from the landuse data layer (km^2)	Flooded areas derived from TM data (km^2)	Overall (%)	Flooded areas derived from DEM data (km^2)	Overall (%)	Flooded areas derived from TM and DEM data (km^2)	Overall (%)
High intensity developed	9.2	0.7	0.1	0.2	0.0	0.8	0.1
Low intensity developed	11.9	0.3	0.1	0.1	0.0	0.4	0.1
Cultivated	208.8	15.1	2.6	8.5	1.4	19.1	3.2
Managed herbaceous cover	18.9	2.1	0.4	1.3	0.2	2.5	0.4
Unmanaged herbaceous cover—upland	0.5	0.0	0.0	0.0	0.0	0.0	0.0
Unmanaged herbaceous cover—wetland	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Evergreen shrubland	74.3	7.0	1.2	2.9	0.5	8.0	1.3
Deciduous shrubland	7.8	1.1	0.2	0.7	0.1	1.3	0.2
Mixed shrubland	9.6	1.0	0.2	0.4	0.1	1.1	0.2
Mixed upland hardwoods	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Bottomland forest/hardwood swamps	112.7	23.2	3.9	22.6	3.8	32.7	5.5
Southern yellow pine	123.9	28.2	4.8	2.0	0.3	28.8	4.9
Mixed hardwoods/conifers	11.4	1.2	0.2	2.0	0.3	2.6	0.4
Oak/gum/cypress	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Water bodies/rivers	4.7	1.3	0.2	2.0	0.3	1.3	0.2
Unconsolidated sediment	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Total	593.9	81.2	13.9	42.7	7.0	98.6	16.5

Table 5. Classification rules based on the gauge readings before the flood event and on 30 September 1999. (The interval of the DEM data is 0.3 m.)

	Min.	Max.
Water bodies/rivers		å1
Flooded areas	>1	å6
Non-flooded areas	>6	

In some areas the RMSE may be higher, for example, under canopies due to the DEM generation procedure used by the USGS. We re-ran the analysis with the DEM dataset at ±1 m of the river gauge reading (with the integration of TM data). Recoding the elevation to represent flooding at 1 m less than the river gauge reading did not significantly change the pattern of the flood (i.e. 95.3 km^2 vs 98.6 km^2 total flooded areas and 16.5% vs 16.1%, tables 6 and 4). The elevation data recoded at 1 m above the gauge reading did expand the flood to the north of the river considerably, as this is an area of very low relief (110.4 km^2 vs 98.6 km^2, tables 6 and 4). Due to the estimated accuracy of the DEM data, the total flooded areas derived from the combination of TM and DEM data in the Greenville areas could vary from 95.3 km^2 to 110.4 km^2, and the flooded areas from 16.1% to 18.6% of the total study area (table 6).

Flooding of the DEM data only works for a reasonable distance from the river gauge from which you measure stage height. This can be a significant distance in

Table 6. Flooded areas of each landuse and landcover type in Greenville derived from TM and DEM data. The DEM data were set at ±1 m of the river gauge reading of Tar River on 30 September 1999.

	At 1 m less than the river gauge data		At 1 m above the river gauge data	
	Flooded areas (km^2)	Overall (%)	Flooded areas (km^2)	Overall (%)
High intensity developed	0.7	0.1	1.4	0.2
Low intensity developed	0.3	0.1	1.0	0.2
Cultivated	17.7	3.0	23.6	4.0
Managed herbaceous cover	2.4	0.4	4.0	0.7
Unmanaged herbaceous cover—upland	0.0	0.0	0.0	0.0
Unmanaged herbaceous cover—wetland	0.0	0.0	0.0	0.0
Evergreen shrubland	7.6	1.3	9.3	1.6
Deciduous shrubland	1.3	0.2	1.4	0.2
Mixed shrubland	1.1	0.2	1.2	0.2
Mixed upland hardwoods	0.0	0.0	0.0	0.0
Bottomland forest/hardwood swamps	31.8	5.4	35.1	5.9
Southern yellow pine	28.6	4.8	29.3	4.9
Mixed hardwoods/conifers	2.5	0.4	2.8	0.5
Oak/gum/cypress	0.0	0.0	0.0	0.0
Water bodies/rivers	1.3	0.2	1.3	0.2
Unconsolidated sediment	0.0	0.0	0.0	0.0
Total	95.3	16.1	110.4	18.6

areas of low relief such as the coastal plain of eastern North Carolina. This is a relatively flat region, as shown above by the summary of the statistics of the four-quad DEM data of Greenville. To work in an area of larger spatial extent or large variation of topography (even in a relatively small spatial extent), stage height from other river gauges should be incorporated and an interpolation method developed to adequately represent flood elevation upstream and downstream. This was one reason that we limited the use of the river gauge data collected in Greenville to leave out inundation in the north-west corner and eastern portion of the Tar River in our DEM data (figure 3). However, in areas where few river gauges exist estimates have to be made.

4. Conclusions

A simple and efficient method for mapping flood extent in a coastal floodplain has been presented. With limited ground observation, most flooded and non-flooded areas derived from the analysis were verified. This method was based on a comparison of the reflectance feature of the water versus non-water targets on a pair of TM images (one acquired before and the other during the flood event), as well as by incorporating DEM data into the analysis. The objective of incorporating the DEM data into the analysis was to overcome the limitation of the TM data in distinguishing between flooded areas and forest canopies. Due to the lack of penetration through the vegetation canopies in the forested areas such as in bottomland forest and hardwood swamps, TM data alone could not identify those flooded areas and led to an underestimation of the flooding. This method was reliable and could be used in the other coastal floodplains (such as the East Coast, and the coast of the Gulf of Mexico of the USA), using similar TM images, DEM data, and river stage data. This method should work well for areas of large spatial extent if the (local) topography is relatively flat, as demonstrated in this study.

The total flooded areas derived from the TM data alone, on 30 September 1999 for Pitt County, North Carolina were 237.9 km^2 or 14.0% of the total county area. This number may be low due to the underestimation of the flooded areas beneath dense vegetation canopies. The landuse/landcover categories most aVected by the flood were the southern yellow pine (91.7 km^2), bottomland forest/hardwood swamps (73.6 km^2), and cultivated land (40.0 km^2). Their total flooded areas were 205.3 km^2 or 86.3% of the total flooded areas in the County.

Through integrating the classification of flooded areas from TM imagery and from inundating a DEM to represent flooding, the following results were obtained for the Greenville area on 30 September 1999. The total flooded area was 98.6 km^2 (out of the total study area of 593.9 km^2) or 16.5%. The landuse/landcover categories most aVected by flooding were bottomland forest/hardwood swamps (32.7 km^2), southern yellow pine (28.8 km^2), and cultivated land (19.1 km^2). Their total flooded areas were 80.6 km^2 or 81.7% of the total flooded area in the studied area. Incorporating the DEM data assisted greatly in identifying the flooding that occurred underneath the forest canopies, especially under the canopies of bottomland forest and hardwood swamps. However, it should be noted that there were two main limitations regarding the integration of DEM data with TM data for flood mapping. One was the use of river gauge readings to inundate the DEM, and the other was the handling of error in the DEM. The authors intend to investigate methods of error representation (e.g. Hunter and Goodchild 1995) in the future. In addition, the US Army Corp of Engineers is currently surveying high-water marks from the flooding in this area, and this data will be used to assess the accuracy of the DEM in modelling flood extent.

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