State of Delaware
DELAWARE GEOLOGICAL SURVEY
John H. Talley, State Geologist

REPORT OF INVESTIGATIONS NO. 74

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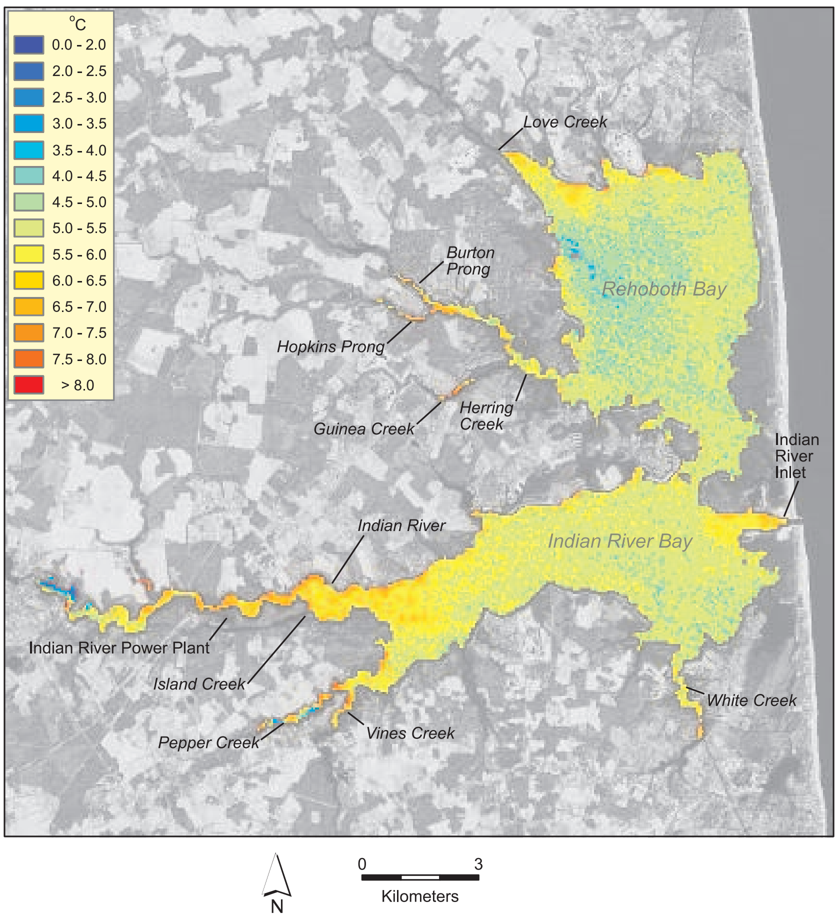

By

Lillian T. Wang[1], Thomas E. McKenna[1], and Tracy L. DeLiberty[2]

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TABLE OF CONTENTS

ILLUSTRATIONS

TABLES

LOCATING GROUND-WATER DISCHARGE AREAS IN REHOBOTH AND INDIAN RIVER BAYS AND INDIAN RIVER, DELAWARE USING LANDSAT 7 IMAGERY

ABSTRACT

Delaware's Inland Bays in southeastern Sussex County are valuable natural resources that have been experiencing environmental degradation since the late 1960s. Stresses on the water resource include land use practices, modifications of surface drainage, ground-water pumping, and wastewater disposal. One of the primary environmental problems in the Inland Bays is nutrient over-enrichment. Nitrogen and phosphorous loads are delivered to the bays by ground water, surface water, and air. Nitrogen loading from ground-water discharge is one of the most difficult to quantify; therefore, locating these discharge areas is a critical step toward mitigating this load to the bays.

Landsat 7 imagery was used to identify ground-water discharge areas in Indian River and Rehoboth and Indian River bays in Sussex County, Delaware. Panchromatic, near-infrared, and thermal bands were used to identify ice patterns and temperature differences in the surface water, which are indicative of ground-water discharge. Defining a shoreline specific to each image was critical in order to eliminate areas of the bays that were not representative of open water. Atmospheric correction was not necessary due to low humidity conditions during image acquisition. Ground-water discharge locations were identified on the north shore of Rehoboth Bay (west of the Lewes and Rehoboth Canal), Herring and Guinea creeks, the north shore of Indian River, and the north shore of Indian River Bay near Oak Orchard.

INTRODUCTION

Delaware's Inland Bays in southeastern Sussex County (Rehoboth Bay, Indian River Bay, and Little Assawoman Bay) are valuable natural resources supporting ecology, tourism, community-based recreation, and fisheries. Environmental degradation of the bays was first investigated in the late 1960s (Peterson, 1969). The significance of the bays was enhanced when they became part of the National Estuary Program in 1987. Evaluations of environmental stresses and their impacts on the Inland Bays have been ongoing since the early investigations mentioned above (Scotto et al., 1983; Andres, 1991, 1992; Weston, 1993; Center for the Inland Bays, 1995; DNREC, 1998a, 2001; Price and Savchuck, 2001; Gutierrez-Magness and Raffensperger, 2003; Entrix and Edinger, 2004; Gutierrez-Magness, 2006; Volk et al., 2006). Sussex County's population is projected to increase by approximately 61 percent from 2000 to 2030 (Delaware Population Consortium, 2006), which will increase and redistribute stresses on the quantity and quality of local water resources. These stresses include land use practices, modifications of surface drainage (dams, ditches, routing of stormwater), ground-water pumping, and wastewater disposal.

One of the primary environmental problems in the Inland Bays is nutrient over-enrichment (U.S. EPA, 2002). The Inland Bays and its tributaries are currently listed as impaired water bodies with respect to nitrogen and phosphorous under the U. S. Clean Water Act (DNREC, 2007a). As a result, the Delaware Department of Natural Resources and Environmental Control (DNREC) established total maximum daily loads (TMDLs) (DNREC, 1998a, 1998b, 2004; Entrix and Edinger, 2004) that require significant reductions (40 to 85 percent) in nitrogen and phosphorous to the bays (DNREC, 2007b). However, even with the most stringent pollution-control strategies requiring elimination of all sources of nutrient loads, the problem of nutrient over-enrichment will likely persist well into the future because of the large quantity of nutrients currently stored in the environment (Andres, 1991; Sims et al., 1996).

Nitrogen and phosphorous are delivered to the bays by ground water, surface water (overland flow, streams, and ocean tides), and air. Nitrogen loading from ground-water discharge to the bays is one of the most difficult to quantify. Difficulties include identifying the ground-water flow paths, locating where ground water discharges to the bays, obtaining discharge measurements, and quantifying biogeochemical reactions occurring in discharge areas.

Purpose and Scope

The purpose of this report is to establish the feasibility of using satellite imagery to identify locations of ground-water discharge to estuaries and determine locations of discharge into Rehoboth Bay, Indian River, and Indian River Bay (referred to as the Inland Bays in this report) (Fig. 1). The temperature of surface water can be determined using satellite imagery. This is useful because ground water discharging into surface water can alter its temperature. In general, this occurs because water heats up more quickly and cools down more slowly than most other materials, and surface water encounters more diverse environmental conditions (e.g. solar heating, air temperature, wind, evaporation) than does water flowing underground. In most environments, ground water between about 5-and-100-meter-depths has a nearly constant temperature of 1 to 2^{o}C higher than the mean annual air temperature (Domenico and Schwartz, 1998; Anderson, 2004). If the discharging ground water is hotter or colder than the surface water that it discharges into, a thermal anomaly may be detectable in the surface water. In this study, we expected to see a signature of warmer ground water discharging into cooler ambient surface water in satellite images collected during the winter.

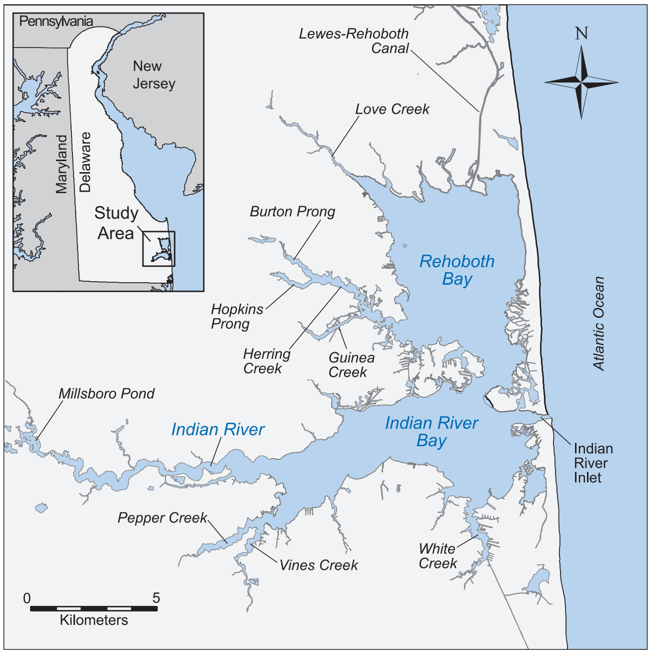

Figure 1. Location of study area in Sussex County, Delaware.

Results from processing and analyzing two sets of multi-spectral imagery from the Landsat 7 satellite are discussed in this report. Identified discharge locations are compared to results from Andres (1992) that estimated ground-water discharge to the bays.

Study Area

The Inland Bays watershed has a total area of 670 km^2 that includes the 80 km^2 of the bays and 20 km^2 of tidal marsh adjacent to the bays (McKenna et al., 2007). Rehoboth Bay is an estuarine lagoon connected to the Delaware Bay through the Lewes-Rehoboth Canal to the north and to the Indian River Bay to the south. The Indian River Bay and Indian River comprise a true estuary with predominant fresh-water input from Millsboro Pond to the west and connection to the Atlantic Ocean through Indian River Inlet to the east. The bays are less than three meters deep and have a tidal range of about one meter (DNREC, 2001). The bays are well-mixed, so stratification with respect to temperature and salinity is rare (Entrix, 2001). The southern portion of Rehoboth Bay and the eastern end of Indian River Bay exchange water with the ocean on a daily basis due to their proximity to Indian River Inlet. Elsewhere, the interaction of bay and ocean waters is much less intense. It is estimated that it takes more than 90 days to replace all of the water in the bays with "new" fresh water and ocean water (DNREC, 2001).

Fresh-water inputs to the Inland Bays include direct precipitation on the bays, surface-water discharge, and ground-water discharge (Ullman et al., 2002). Precipitation is generally evenly distributed throughout the year with a mean annual precipitation of 115 centimeters (Scudlark and Church, 1993). Mean surface-water discharge to the Inland Bays from all tributaries is about nine cubic meters per second (m^3/sec) (Ullman et al., 2001). In addition, some ground water in the surficial Columbia aquifer discharges directly into the Inland Bays (Andres, 1987, 1992).

The Columbia aquifer in the Inland Bays watershed is a shallow, unconfined, sand and gravel aquifer with high hydraulic conductivity (Andres and Klingbeil, 2006). Ground water is recharged by precipitation, surface water, and artificial recharge (e.g. irrigation return, land-based wastewater disposal) infiltrating to the water table (Andres, 2004). Flow in the aquifer is controlled by the geometry of a shallow water table (Andres and Martin, 2005) that is generally a subdued version of surface topography modified by anthropogenic pumping and recharge, and variations in hydraulic conductivity (Andres and Klingbeil, 2006). Flowpaths are constrained by hydraulic divides between ground-water flow systems that may or may not underlie surface-water divides and streams (Andres and Martin, 2005; Volk et al., 2006). These flowpaths range from shallow, local flowpaths several meters long to deeper, regional flowpaths approximately 13 kilometers in length. Discharge occurs as seepage to streams, ponds, bays, and the land surface (Johnston, 1977; Denver, 1986; Andres, 1987, 1992; McKenna, 2000; Ullman et al., 2001; Volk et al., 2006), evapotranspiration (Johnston, 1977), and flow to pumping wells. The ground-water discharge directly to the Inland Bays from the surficial Columbia aquifer is estimated at 0.9 to 1.7 m^3/sec (Andres, 1992), which is about 10 to 20 percent of total surface-water discharge.

Ground-water temperatures in the Columbia aquifer in the watershed are consistently 14 to 16°C (Andres, 1991). This is 1 to 3°C higher than the mean annual surface temperature at Georgetown of 13°C (Fig. 2; University of

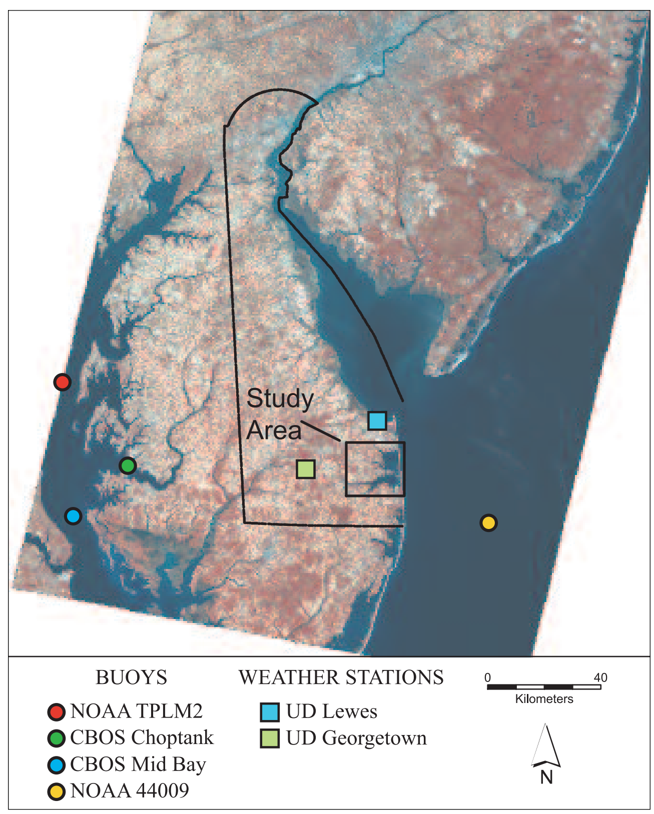

Figure 2. Location of buoys and weather stations maintained by the National Oceanic and Atmospheric Administration, Chesapeake Bay Observing System, and the University of Delaware.

Table 1. Water temperature by season for Indian River Bay (IRB), Rehoboth Bay (RB), and the coastal ocean. Bay statistics are given for open areas of the bays (open) and restricted (rest.) parts of the bays where flushing with ocean water is limited (Pepper Creek for IRB; Love, Herring, Guinea creeks for RB). The first four temperature columns are based on two years of water-temperature data collected by Andres et al. (2002). The last column is for a 17-year period at Buoy 44009 in the Atlantic Ocean, 30 km east of the study area (NOAA, 2007).

Season*	Water Temperature (°C) Mean and (Standard Deviation)				
	IRB open	RB open	IRB rest.	RB rest.	coastal ocean
Winter	7 (2)	8 (2)	8 (2)	10 (3)	6 (2)
Spring	17 (4)	16 (4)	17 (3)	19 (5)	18 (4)
Summer	25 (3)	25 (3)	26 (3)	27 (2)	21 (3)
Fall	18 (5)	18 (5)	18 (5)	19 (6)	13 (2)

*Season: Winter: January, February, March
Spring: March, April, May
Summer: June, July, August
Fall: September, October, November

Delaware, 2007). Bay temperatures away from Indian River Inlet are typically between about 25 and 27°C in the summer and about 7 and 10°C in the winter (Table 1; Ullman et al., 1993; Entrix, 2001; Andres et al., 2002).

Previous Work

Rapid advances in technology in the late 20th century have resulted in wider availability of thermal-infrared radiometers and technology to calibrate and correctly interpret thermal-infrared imagery. As a result, several studies have used aerial thermal-infrared imagery to map temperature differences in surface water and to determine locations of ground-water discharge in surface water. Using airborne thermal-infrared imagery, Rundquist et al. (1985) documented the flow-through lake concept in the Sandhills region of Nebraska, and Nelson et al. (1991) located ground water and small surface inflows to Red Eagle Lake in Montana. Banks et al. (1996), McKenna (2000), Roseen et al. (2001), and Ullman and Miller (2004) used airborne thermal-infrared imagery to identify ground-water discharge into the Chesapeake Bay (Maryland), Delaware's Inland Bays, the Great Bay Estuary (New Hampshire), and Delaware Bay (Lewes, Delaware), respectively. Torgersen et al. (2001) assessed stream temperatures in the Pacific Northwest region of the United States in an aerial survey noting a few areas of possible ground-water discharge.

While widely used for estimating regional-scale sea-surface (SST) and land-surface temperatures (LST), satellite-based thermal studies of nearshore and estuarine environments are rare due to the poor spatial resolution of the thermal-infrared band on most satellite platforms. In fact, most of these studies used satellite imagery where one pixel represents a ground area of 10^6 m^2 (1 km x 1 km) or more. Currently, the Landsat satellite provides the best spatial resolution for publicly available thermal imagery. Gibbons et al. (1989) and Mustard et al. (1999) used Landsat 5 imagery to derive temperatures of thermal effluent from power plants in California and Massachusetts, respectively. The pixel-size of the thermal-infrared band decreased from 14,400 m^2 (120 m x 120 m) on the Landsat 5 satellite to 3,600 m^2 (60 m x 60 m) on Landsat 7; as a result, studies are now emerging using Landsat thermal band for terrestrial water-resource studies (Schott et al., 2001).

Acknowledgments

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METHODS

Methods included image selection and processing, temperature validation, and identification of discharge locations. Image selection included choice of a satellite platform and preferred date of image acquisition. Image processing consisted of shoreline delineation, evaluation of atmospheric conditions, and conversion of at-sensor radiance to kinetic temperature (Wang, 2005). Temperatures were validated using in-situ measurements from buoys. Potential discharge locations were identified by analyzing processed thermal images along with the panchromatic and near-infrared spectral bands.

Image Selection

High spatial-resolution thermal-infrared imagery is preferred to determine surface-water temperatures. Multi-spectral imagery is useful for processing the thermal band, putting it into a visual context, and evaluating the state of the water in the bay (e.g. ice-cover). The following additional criteria for image selection were assessed to maximize the potential of recognizing a ground-water discharge signal in the thermal-infrared imagery: (1) a time frame that maximizes the temperature difference between surface and ground waters; (2) zero percent cloud cover (maximum visibility of surface water); (3) low tide (minimize volume of overlying surface water in discharge areas and maximize hydraulic gradient driving discharge); (4) highest water-table elevations (maximize hydraulic gradient driving discharge); and (5) no heavy precipitation prior to the image date (minimize storm-flow effects and reduce disturbance of the surface water).

Shoreline Delineation

Defining a shoreline specific to each image is critical in order to eliminate areas of the bays that are not representative of open water because these areas could result in inaccurate surface-water temperatures near the shoreline (Wang, 2005). A single multi-band file was created (visible, near-infrared and mid-infrared bands) and used for the tasseled-cap transformation, a spectral enhancement method typically used for vegetation studies but that also can yield separation between water and other classes (Jensen, 2007). The classified image was converted from raster to vector format and a 45-meter-wide buffer was applied to the Inland Bays polygon boundary to exclude land areas in the imagery from further processing.

Atmospheric Correction

Atmospheric correction was evaluated to remove potential influence of the atmosphere. Atmospheric-correction modules in image-processing software can correct for numerous atmospheric conditions. Atmospheric data (NOAA, 2001) from three rawinsonde stations were evaluated (Aberdeen, Md., Sterling, Va., and Wallops Island, Va.).

Temperature Calculation

Image-processing software (ENVI, 2007) was used to derive surface-water temperatures from the thermal-infrared band in a multi-step process. Digital numbers (DN; ranging from zero to 255) were converted to spectral radiances, then into temperatures. Spectral radiance (L_λ) was calculated using the satellite-sensor gain and offset given in Irish (2006) and

$$L_\lambda = \text{gain} * \text{DN} + \text{offset} \tag{1}$$

where L_λ is in watts per meter squared per steradian per micrometer ($Wm^{-2}\ sr^{-1}\ \mu m^{-1}$).

Radiances were converted to temperatures using a raster calculator and a temperature image was created using emissivity normalization. This technique uses Planck's radiation law and emissivity to calculate temperature. Planck's Radiation Law gives the radiance (B_λ) emitted by a blackbody as a function of its temperature and wavelength:

$$B_\lambda = \frac{2\eta\chi^2}{\lambda^5}\left(e^{\eta\chi/(\lambda KT)} - 1\right)^{-1} \tag{2}$$

where h is Planck's constant (6.6256 x 10^{-34} Joule-seconds), c is the speed of light (3 x 10^8 meters per second), λ is wavelength in meters, K is Boltzmann's constant (1.3805 x 10^{-23} Joules per Kelvin), and T is temperature in Kelvin. A blackbody is a perfect absorber and emitter of radiation. All radiation incident on a blackbody is re-emitted, and emittance is a function of its temperature. While true blackbodies do not exist in nature, natural objects can approximate blackbodies.

Spectral emissivity (ε_λ) relates the thermal emission from real objects to blackbodies, and is defined (Equation 3) as the ratio between the spectral radiance exiting a selective radiator (L_λ) and the spectral radiance exiting a blackbody (B_λ) at the same temperature (Jensen, 2007).

$$\varepsilon_\lambda = \frac{L_\lambda}{B_\lambda} \tag{3}$$

All radiating bodies have emissivies between zero and one that are functions of wavelength and viewing geometry. The emissivity of water in the Landsat 7 thermal band (10.45 to 12.5 μm) ranges from 0.98 to 0.99 (NASA, 1999). In this study, a constant emissivity of 0.98 was used, and the radiance from water was determined by solving for L_λ in equation 3. Radiant temperature from Landsat 7 imagery was calculated using an approximation of Planck's Radiation Law specific to the Landsat instrument:

$$T = \frac{K2}{\ell n\left(\frac{K1}{L_\lambda + 1}\right)} \tag{4}$$

where $K2$ = 1282.71 K and $K1$ = 666.09 $Wm^{-2}\ sr^{-1}\ \mu m^{-1}$ (Irish, 2006).

Heat is the kinetic energy of molecules in random motion and is referred to as internal, real, or true heat measured in calories. The intensity of this heat as we sense it in-situ is its kinetic temperature. The remote measurement of radiant temperature is always somewhat less than the true kinetic temperature of an object (Jensen, 2007). Radiant temperatures ($T_{\rho\alpha\delta}$) were converted to kinetic temperatures ($T_{\kappa\iota\nu}$), assuming that the bulk emissivity (ε) is equivalent to the spectral emissivity using (Sabins, 1997):

$$T_{\kappa\iota\nu} = T_{\rho\alpha\delta}/\varepsilon^{1/4} \tag{5}$$

Temperature Validation

Image-derived temperatures were compared to in-situ water temperature data (NOAA, 2007; CBOS, 2007) from four buoys (Fig. 2) to verify accuracy. Temperatures from the buoys were retrieved for times closest to the time of image acquisition.

Image Evaluation

The thermal, panchromatic (visual), and near-infrared bands were used for identifying potential ground-water discharge areas. The thermal band was used to identify areas of relatively warmer surface water that may be caused by ground-water discharge. The panchromatic and near-infrared bands were used to visually locate ice on the bays. Ice-free areas or areas with thin ice surrounded by thick ice may result from warm ground-water discharge. In this report, ice cover in the panchromatic image is displayed as lighter areas in the water. Black, dark gray, and light gray areas represent areas of open water, thin ice, and thick ice, respectively. The analysis of ice cover was compared to water temperatures in the February 2002 image and previous discharge estimates.

RESULTS AND DISCUSSION

Image Selection and Processing

After evaluating criteria for optimizing the identification of thermal signals of ground-water discharge, two winter images from the Landsat 7 satellite were selected for analysis (January 29, 2000 and February 19, 2002). Both images were acquired at 10:30 AM Eastern standard time.

Table 2. Tidal stage, depth to water table, daily mean discharge, and precipitation data used in the image selection process[1].

Image date	Tidal stage[2] (m)	Depth to water table[3] (mbls) and date	Daily mean discharge[4] (m^3/s)	Date of last precipitation
1/29/2000	8:00 AM (low) -0.26 3:00 PM (high) 0.24	2.41 on 1/20/2000	1.7	1/26/2000 (snow)
2/19/2002	6:00 PM (low) 0.20 2:00 PM (high) 0.70	3.10 on 2/21/2002	0.88	2/11/2002

[1] Source: Tide and discharge (USGS, 2007); depth to water table (DGS, 2007), and precipitation (University of Delaware, 2007).

[2] Indian River Inlet (USGS Station # 01484683) in meters relative to NGVD 29 datum; 14-year period of record with mean of 0.82 and a typical tidal range of 0.91 m.

[3] Depth to water table in well Qe44-01 (USGS 383138075260201) in meters below land surface; 46 year period of record with minimum and maximum depth to water of 1.12 to 4.0 m bls, respectively.

[4] Indian River at Millsboro Pond Outlet (USGS Station # 01484525); 26-year period of record; mean annual discharge of 2.4 m^3/s; discharge exceeded 0.79 and 1.96 m^3/s for 90% and 50% of the time, respectively.

In winter, the Inland Bays have a mean water temperature of 7 to 10°C (Andres et al., 2002) and ground-water temperatures are consistently 14 to 16°C (Andres, 1991) in the Columbia aquifer. There was no cloud cover in the study area on these dates, and low tide occurred during or shortly after the image-acquisition times (USGS, 2007). Ground-water levels in the Columbia aquifer, as measured in an observation well in south-central Sussex County, were generally within the lower end of the normal range during January 2000, and the lowest level on record occurred during August 2002 (Table 2; DGS, 2007). Precipitation events did not occur within three days prior to image acquisitions (University of Delaware, 2007). Air temperatures during the last two weeks of January 2000 were at or below freezing (University of Delaware, 2007), so ice formed on parts of the Inland Bays. Though ground-water level conditions did not meet the established criteria and the January image contained ice cover (that precludes calculating accurate water temperatures in some areas), the images were considered useful since all other conditions were met and ice cover can be used as a proxy for temperature.

Shorelines were delineated for both images. Processing the February 19, 2002 image resulted in a very accurate classification between land and water areas. The processing of the January 29, 2000 image misclassified many areas of water due to the presence of ice on the Inland Bays. An additional step of manual editing was necessary to create a shoreline for the January 29, 2000 image (Wang, 2005).

Atmospheric conditions were evaluated to determine their contribution to the radiance recorded at the satellite sensor. Air temperatures of -8°C and 7°C were recorded on January 29, 2000 and February 19, 2002, respectively, at the Georgetown, Delaware, weather station (Fig. 2). The amount of water vapor in the atmospheric column was low for all rawinsonde stations on both dates. Because of these low humidity conditions, Wang (2005) determined that atmospheric correction was not necessary to obtain accurate surface-water temperatures.

Temperatures were calculated for all parts of the bays except those areas in the January 29, 2000 image that were ice-covered. No attempt was made to estimate temperatures of ice as it is difficult to reliably estimate the emissivity of the heterogeneous ice surface and the temperature of the ice surface does not necessarily represent the temperature of the underlying water.

Temperature Validation

Two science teams have monitored and evaluated the thermal calibration of Landsat 7 since its launch (Irish, 2006; Barsi et al., 2003). Results indicate that the absolute radiometric-calibration for the thermal bands is stable to better than 0.1 percent per year and derived temperatures have ±0.6 K uncertainty (one standard deviation).

Wang (2005) verified accuracy of calculated temperatures via comparison to in-situ data and performed an independent assessment of uncertainty in derived temperatures. Calculated water temperatures were within 1°C of in-situ water temperatures (Table 3). Relative differences in surface-water temperatures greater than 1°C were reported as representing a signal above the noise level caused by uncertainty in the data and processing. This criteria is followed in this report.

Image Synopsis

The February 19, 2002 thermal-infrared image represents the temperature of the bays during winter with ice-free conditions (Fig. 3; Plate 1). Surface-water temperatures in the offshore portions of Rehoboth Bay generally ranged from 4.5 to 5.5°C with warmer temperatures in the eastern and northern parts of the bay and cooler temperatures in the western bay. Temperatures for much of the Indian River Bay ranged from 4.5 to 6°C with temperatures near the Indian River Inlet up to 7°C. Warmer temperatures occurred along the northern shore of Indian River Bay and most of Indian River. There was no evidence of discharge from the Indian River Power Plant into Indian River as water temperatures at the mouth of Island Creek were similar to surrounding water temperatures (Fig. 3; Plate 1).

Table 3. In-situ temperatures recorded at buoys (Fig. 2) compared to image-derived temperatures.

Station ID	Time[1]	Date	Water Temperature (°C) in-situ	image	difference
44009 (NOAA)	1100	1/29/2000	3.5	4.1	0.6
		2/19/2002	7.8	8	0.2
TPLM2 (NOAA)	1100	1/29/2000	-0.7	0.2	0.9
		2/19/2002	4.9	*	*
Mid Bay (CBOS)	1030	1/29/2000	0.4	0.9	0.5
		2/19/2002	5.2	5.6	0.4
Choptank River (CBOS)	1040	1/29/2000	*	-2.2	*
		2/19/2002	5.4	5.4	0.0

[1] Time of in-situ measurement (Eastern standard time)
* data not available

Large areas of the Inland Bays were covered with ice in January 29, 2000 (Fig. 4; Plate 1) resulting from below-freezing air temperatures during the previous two weeks (University of Delaware, 2007). Rehoboth Bay was covered with fractured ice with an area of open water in the southern part of the bay, while Indian River and the southwestern and southeastern parts of Indian River Bay were covered with ice of varying thicknesses. A large area of open water occurred in the middle of Indian River Bay (Fig. 4; Plate 1). Surface-water temperatures in open-water parts of Indian River and Rehoboth bays were 0.0°C or lower (not shown) (Wang, 2005), significantly below the mean water temperature in winter (7 to 10°C) (Andres et al., 2002).

Identification of Ground-Water Discharge Signals

Warm bay temperatures in February 2002 (Fig. 3; Plate 1) and open water or thin ice in January 2000 (Fig. 4; Plate 1) were used as indicators of potential locations of ground-water discharge. A temperature anomaly in this study is defined as an area having a maximum temperature exceeding local ambient temperatures by more than 1°C and an area of at least 18,000 m^2 (5 pixels). A water temperature between 5 and 6°C in February 2002 is generally considered as ambient temperature. High temperatures near the Indian River Inlet in February 2002 and the open water in Indian River Bay and southern Rehoboth Bay in January 2000 were likely due to relatively warm ocean water circulating through the inlet so were not considered as anomalous temperatures in this study. In-situ temperatures at Buoy 44009 in the Atlantic Ocean (Fig. 2) were 7.8°C and 3.5°C on February 19, 2002 and January 29, 2000, respectively.

Areas of the bays can be classified into three categories based on water temperatures in February 2002 and ice characteristics in January 2000:

1. Thermal anomaly in February 2002 and open water or thin ice in January 2000 (Table 4)

   Areas B and C (Fig. 5; Plate 1)
   Areas D and I (Figs. 6 and 7; Plate 2)
   Areas J, K, and K′ (Figs. 8 and 9; Plate 2)
   Areas L and M (Fig. 10; Plate 3)
   Areas O, P, and Q (Figs. 11 and 12; Plate 3)

2. Thermal anomaly in February 2002, and thick ice having a sharp contact with open-water/thin-ice in January 2000 (Table 4)

   Areas A and B′ (Fig. 5; Plate 1)
   Areas E, F, G, H , and I′ (Figs. 6 and 7; Plate 2)
   Area N (Fig. 10; Plate 3)

3. Ambient water temperature in February 2002 and thick ice in January 2000.

Categories one and two represent areas of potential ground-water discharge. Category one has the characteristics clearly expected for warm ground-water discharge. Category two has the warm temperatures expected for ground-water discharge but the presence of thick ice is not what would be expected. We propose that the presence of the sharp contact between thick ice and thin-ice/open-water is indicative of a more complex interplay of ground-water discharge, salinity, water and air temperatures, ice cover, and water-body geometry. Upstream areas will be less saline than downstream areas due to discharge from upland streams. Abundant ground-water discharge further decreases salinity. This fresher water freezes before more saline waters even though it may have a slightly higher temperature. As the ice thickens, it insulates water under the ice from the cold air (< 0°C in January 2000). This warmer water emerges downstream or offshore at the sharp contact between thick ice and open-water/thin ice. The location of the sharp contact may depend on mixing with more saline waters of Rehoboth Bay and the increased water velocity caused by a decrease in channel width (A, B′, E-H, I′). Category three includes areas with

Table 4. Identified ground-water discharge areas and supporting information.

CATEGORY 1 *(thermal anomaly in February 2002 and open water or thin ice in January 2000)*			THERMAL ANOMALY			ANDRES (1992)		CORROBORATIVE EVIDENCE	
			MAGNITUDE		AREA		Linear Discharge Density (Q*)		
Area ID	Location	Figure	°C	Category	Category	Watershed	Category	Data	Observations
B	Rehoboth Bay north shore	5	1.9	intermediate	large	Rehoboth Bay North Shore Left	intermediate		
C	Rehoboth Bay north shore	5	3.1	large	intermediate	Rehoboth Bay North Shore Middle	high		
D	Rehoboth Bay west shore	6 & 7	2.4	large	small	Angola Neck East	low		
I	Herring Creek along Massey Marsh	6 & 7	1.3	small	intermediate	Long Neck North Angola Neck West	intermediate low		
J	Indian River near confluence with Swan Creek	8 & 9	1.9	intermediate	large	Indian River North Piney Neck	intermediate high	stream gage[1] thermal-infrared survey[2]	
K	Indian River downstream of Area J	8 & 9	1.8	intermediate	large	Indian River North Piney Neck	intermediate high	seepage meter	visual ice/no ice
K'	Indian River between Warwick Cove and Oak Orchard	8 & 9	1.8	intermediate	large	Long Neck South	high	seepage meter	visual ice/no ice
L	Pepper Creek	10	2.5	large	small	Piney Neck Dumpling Neck	high high		
M	Vines Creek	10	2.5	large	small	Dumpling Neck Champlin Neck	high low		
O	Indian River Bay between White House Point and Steels Cove	11 & 12	2.5	large	small	Long Neck South	high		
P	White Creek near Rogers Haven	11 & 12	2.5	large	small	White Neck Cedar Neck	low intermediate	resistivity survey[3]	
Q	White Creek downstream of Area P and Spring Gut	11 & 12	3.1	large	small	White Neck	low	resistivity survey[3]	

[1] Ullman et al., 2002 [2] Ullman et al., 2003 [3] Manheim, 2004

CATEGORY 2 *(thermal anomaly in February 2002 and thick ice having a sharp contact with open water in January 2000)*			THERMAL ANOMALY			ANDRES (1992)		CORROBORATIVE EVIDENCE	
			MAGNITUDE		AREA		Linear Discharge Density (Q*)		
Area ID	Location	Figure	°C	Category	Category	Watershed	Category	Data	Observations
A	mouth of Love Creek	5	1.9	intermediate	large	Rehoboth Bay North Shore Left	intermediate		
B'	Rehoboth Bay north shore	5	1.9	intermediate	small	Rehoboth Bay North Shore Left	intermediate		
E	Burton Prong	6 & 7	1.3	small	large	Long Neck North Angola Neck West	intermediate low		visual ice/no ice
F	Hopkins Prong	6 & 7	1.9	intermediate	large	Long Neck North	intermediate		visual ice/no ice
G	confluence of Hopkins and Burton prongs	6 & 7	1.3	small	large	Long Neck North Angola Neck West	intermediate low		visual thin ice
H	Herring Creek downstream of Area G	6 & 7	1.2	small	small	Long Neck North	intermediate	seepage meter, water temperature & salinity	visual ice/no ice
I'	Guinea Creek	6 & 7	3.1	large	intermediate	Long Neck North	intermediate		visual ice/no ice
N	Indian River Bay near confluene of Pepper and Vines creeks	10	1.9	intermediate	small	Piney Neck	high		

Table 5. Categorization of linear discharge density from Andres (1992).

Watershed	LINEAR DISCHARGE DENSITY[1] liters/m/min	Category	Waterbody Receiving Ground-Water Discharge
Piney Neck	2.46	high	Indian River Pepper Creek
Long Neck South	1.78	high	Indian River Bay Indian River
Dumpling Neck	1.77	high	Pepper Creek
Rehoboth Bay North Shore Middle	1.64	high	Rehoboth Bay
White Creek	1.51	intermediate	Indian River Bay White Creek
Cedar Neck	1.30	intermediate	Indian River Bay White Creek
Rehoboth Bay North Shore Left	1.27	intermediate	Rehoboth Bay Love Creek
Indian River North	1.08	intermediate	Indian River
Long Neck North	1.07	intermediate	Rehoboth Bay Herring Creek Guinea Creek
Indian River South	0.99	low	Indian River
Champlin Neck	0.99	low	Indian River Bay Vines Creek
Angola Neck East	0.88	low	Rehoboth Bay Love Creek
White Neck	0.86	low	Indian River Bay White Creek
Angola Neck West	0.70	low	Rehoboth Bay Herring Creek
Rehoboth Bay North Shore Right	0.36	low	Rehoboth Bay
Long Neck East	0.13	low	Rehoboth Bay Indian River Bay

[1] 1991 Unit G-W Flux in Andres (1992)

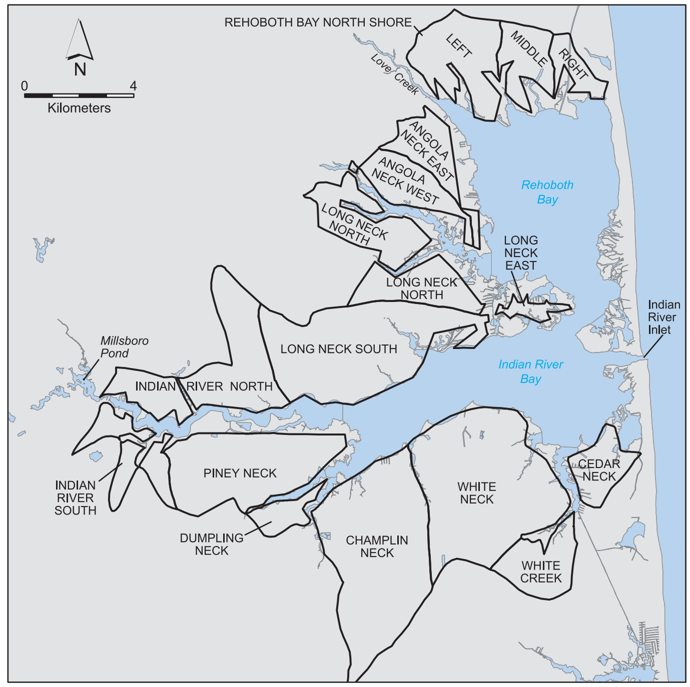

Figure 13. Andres (1992) watershed boundaries.

ambient water temperatures in February 2002 and thick ice in January 2000 and these are consistent with an interpretation of relatively little ground-water discharge. These areas include the northeastern and eastern shores of Rehoboth Bay, most of the western shore of Rehoboth Bay (except Area D), the south and southeastern shores of Indian River Bay and the open waters of Rehoboth Bay and western Indian River Bay.

Comparison to Previous Discharge Estimates

Andres (1992) estimated ground-water discharge to the Inland Bays from sixteen watersheds (Fig. 13) using both a calculated water budget and calculations based on Darcy's Law. The most direct comparison that can be made between results of the present study and those of Andres (1992) are those using Darcy's Law as presented in Table 3 of Andres (1992) as the column labeled "unit G-W Flux (1991)." This value represents the discharge per unit of shoreline length for a watershed and is referred to here as the "linear discharge density" (Q*) to avoid confusion with other terminology in the literature. The linear discharge density is a single average value that represents conditions over a watershed's entire shoreline. The term "focusing of discharge" is used to describe areas where discharge appears to occur only across a fraction of a watershed's shoreline. The Q* of Andres (1992) was categorized into low, intermediate, and high values (Table 5) to facilitate comparison with results from this study (Table 4). Discharge to the bays adjacent to watersheds that have a relatively high Q* should be the most easily detected via remote sensing of water temperature and ice-cover. The White Creek watershed (Fig. 13) was not considered in the comparison since February 2002 water temperatures were not available in this area. All of Andres (1992) watersheds with low Q* (Table 5) correspond to one of two cases. They are either (1) adjacent to a waterbody without evidence of discharge in Landsat imagery, or (2) adjacent to a waterbody with evidence of discharge, but the waterbody is also adjacent to another Andres (1992) watershed (Fig. 13) having intermediate or high Q*. Most of the areas in category one of this study are adjacent to at least one watershed having a high Q*. Exceptions in category one are areas adjacent to watersheds with either low Q* (Areas D, P, and Q) or low and intermediate Q* (Area I). These four areas, having relatively small surface areas, are interpreted as being areas of focused discharge. Areas in category two of this study (Table 4) are all adjacent to at least one watershed classified with intermediate Q*. Therefore, the interpretation of areas in categories one and two (Table 4) being preferred locations of ground-water discharge is consistent with the results presented in Andres (1992). In absolute terms, a Q* of greater than one liter per meter of shoreline per minute (l/m/min) creates a thermal signal detectable in Landsat 7 imagery.

Corroborative evidence of ground-water discharge to some of the areas in categories one and two is listed in Table 4. Evidence includes aerial remote sensing with a thermal-infrared imager (McKenna, 2000; Ullman et al., 2003) electri-

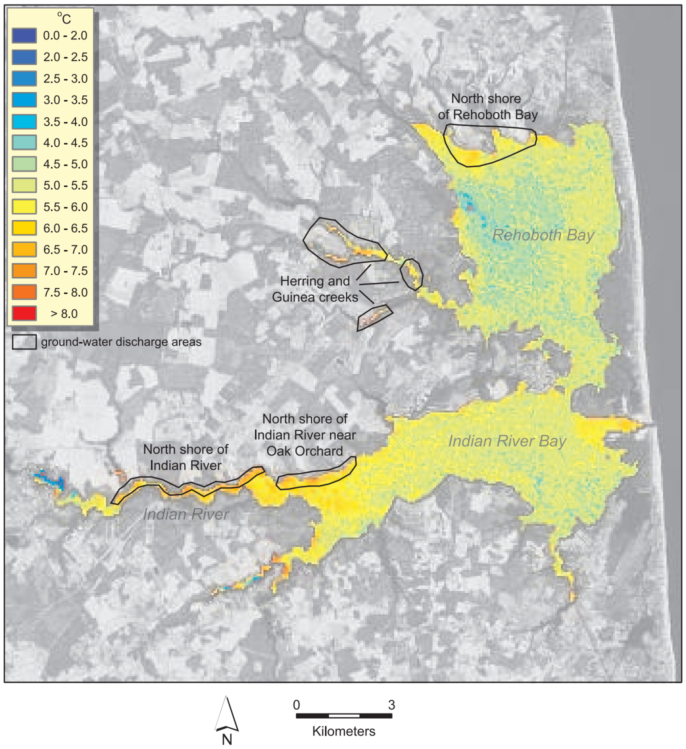

Figure 14. Ground-water discharge areas in the Inland Bays identified using Landsat 7 imagery acquired on February 19, 2002.

cal-resistivity surveying (Manheim et al., 2004), stream-gaging (Ullman et al., 2002), observations of ice-cover, and measurements of seepage, water temperature, and salinity by one of the authors (on file at the Delaware Geological Survey).

CONCLUSIONS

Ground-water discharge areas were successfully located in estuarine environments using Landsat 7 imagery. Shoreline delineation and evaluation of atmospheric effects are essential image processing steps. The thermal, near-infrared, and panchromatic bands can be used to identify temperature differences and ice patterns resulting from ground-water discharge.

Ground-water discharge locations (Fig. 14) were identified on the north shore of Rehoboth Bay west of the Lewes and Rehoboth Canal, on Herring and Guinea creeks, on the north shore of Indian River and on the north shore of Indian River Bay near Oak Orchard. The identified locations are consistent with Andres (1992) and other indicators of ground-water discharge.

REFERENCES

Anderson, M. P., 2004, Heat as a ground water tracer: Ground Water, v. 43, n. 6, p. 951-968.

Andres, A. S., 1987, Estimate of direct discharge of fresh ground water to Rehoboth and Indian River bays: Delaware Geological Survey Report of Investigations No. 43, 37 p.

_____1991, Results of the coastal Sussex County, Delaware, ground-water quality survey: Delaware Geological Survey Report of Investigations No. 49, 28 p.

_____1992, Estimate of nitrate flux to Rehoboth and Indian River bays, Delaware, through direct discharge of ground water: Delaware Geological Survey Open File Report No. 35, 36 p.

_____2004, Ground-water recharge potential mapping in Kent and Sussex counties, Delaware: Delaware Geological Survey Report of Investigations No. 66, 20 p.

Andres, A. S. and Klingbeil, A. D., 2006, Thickness and transmissivity of the unconfined aquifer of eastern Sussex County, Delaware: Delaware Geological Survey Report of Investigations No. 70, 19 p.

Andres, A. S. and Martin, M. J., 2005, Estimation of the water table for the Inland Bays watershed, Delaware: Delaware Geological Survey Report of Investigations No. 68, 20 p.

Andres, A. S., Savidge, K. S., Scudlark, J. R. and Ullman, W. J., 2002, Delaware Inland Bays tributary total maximum daily load water-quality database: Delaware Geological Survey Digital Product 02-02, v. 7.02, MS Access 2000 format.

Banks, W. S. L., Paylor, R. L., and Hughes, W. B., 1996, Using thermal-infrared imagery to delineate ground-water discharge: Ground Water, v. 34, n. 3, p. 434-443.

Barsi, J. A., Schott, J. R., Palluconi, F. D., Helder, D. L., Hook, S. J., Markham, B. L., Chander, G., and O'Donnell, E. M., 2003, Landsat TM and ETM+ thermal band calibration: Canadian Journal of Remote Sensing, v. 29, n. 2, p. 141-153.

Center for the Inland Bays (CIB), 1995, Delaware Inland Bays comprehensive conservation and management plan: CIB, Lewes, DE, 102 p.

Chesapeake Bay Observing System (CBOS), 2007, Chesapeake Bay Observing System: http://www.cbos.org

Delaware Department of Natural Resources and Environmental Control (DNREC), 1998a, Total maximum daily load (TMDL) analysis for Indian River, Indian River Bay, and Rehoboth Bay, Delaware: DNREC, Dover, DE, 59 p.

_____1998b, Total maximum daily loads (TMDLs) for Indian River, Indian River Bay, and Rehoboth Bay, Delaware: DNREC Secretary Order No. 98-W-0044 (November 6, 1998) under Statutory Authority of 7 Delaware Code, Chapter 60, DNREC, Dover, DE.

_____2001, Inland Bays/Atlantic Ocean Basin assessment report: DNREC, Dover, DE, 180 p.

_____2004, Total maximum daily loads (TMDLs) for the Little Assawoman Bay watershed: DNREC Secretary Order No. 2004-W-0059 (December 9, 2004) under Statutory Authority of 7 Delaware Code, Chapter 60, DNREC, Dover, DE.

_____2007a, State of Delaware 2006 combined watershed assessment report (305(b)) and determination for the Clean Water Act section 303(d) list of waters needing TMDLs, February 13, 2007.

_____2007b, Inland Bays pollution control strategy (April 2007): DNREC, Dover, DE, 66 p.

Delaware Geological Survey, 2007, Recent and historical ground-water level data: http://www.udel.edu/dgs/Hydrology/histgw.html.

Delaware Population Consortium, 2006, Delaware Population Projections, October 26, 2006, Version 2006.0: Office of State Planning Coordination, 57 p.

Denver, J. M., 1986, Hydrogeology and geochemistry of the unconfined aquifer, west-central and southwestern Delaware: Delaware Geological Survey Report of Investigations No. 41, 100 p.

Domenico, P. A. and Schwartz, F. W., 1998, Physical and Chemical Hydrogeology: 2nd ed., New York, NY, John Wiley & Sons, Inc., 506 p.

Entrix, Inc., 2001, An ecological risk-based 316(a) demonstration for the Indian River power plant: report prepared for Conectiv Energy.

Entrix, Inc. and J. E. Edinger Associates, Inc. (Entrix and Edinger), 2004, Total maximum daily loads (TMDLs) for the Little Assawoman Bay and tributaries and ponds of the Indian River, Indian River Bay, and Rehoboth Bay (December, 2004): Report prepared for DNREC, Dover, DE, 74 p.

Environment for Visualizing Images (ENVI), 2007, ENVI – The remote sensing exploitation platform – ITT Visual Information Solutions: http://www.ittvis.com/envi.

Gibbons, D. E., Wukelic, G. E., Leighton, J. P., and Doyle, M. J., 1989, Application of Landsat thematic mapper data for coastal thermal plume analysis at Diablo Canyon: Photogrammetric Engineering and Remote Sensing, v. 55, n. 6, p.903-909.

Gutierrez-Magness, A. L., 2006, Simulation of nutrients and sediment concentrations and loads in the Delaware Inland Bays watershed: Extension of the hydrologic and water-quality model to ungaged segments, USGS SIR2006-5038, 26 p.

Gutierrez-Magness, A. L. and Raffensperger, J. P., 2003, Development, calibration, and analysis of a hydrologic and water-quality model of the Delaware Inland Bays watershed: USGS WRI03-4124, 42 p.

Irish, R. R., 2006, Landsat 7 science data users handbook, National Aeronautics and Space Administration Report 430-15-01-003-0: http://ltpwww.gsfc.nasa.gov/IAS/handbook/handbook_toc.html.

Jensen, J. R., 2007, Remote sensing of the environment: an earth resource perspective: Upper Saddle River, NJ, Prentice Hall, 592 p.

Johnston, R. H., 1977, Digital model of the unconfined aquifer in central and southeastern Delaware: Delaware Geological Survey Bulletin No. 15, 47 p.

Manheim, F. T., Krantz, D. E., and Bratton, J. F., 2004, Studying ground water under Delmarva coastal bays using electrical resistivity: Ground Water, v. 42, n. 7, p. 1052-1068.

McKenna, T. E., 2000, 'Low-budget - do it yourself' thermal-infrared imaging of ground-water discharge to surface waters: in Abstracts with Programs, v. 32, n. 7, p. A60, Boulder, Geological Society of America.

McKenna, T. E., Andres, A. S., and Lepp, K. P., 2007, Digital watershed and bay boundaries for Rehoboth Bay, Indian River Bay and Indian River: Delaware Geological Survey Open File Report No. 47, 8 p.

Mustard, J. F., Carney, M. A., and Sen, A., 1999, The use of satellite data to quantify thermal effluent impacts: Estuarine, Coastal and Shelf Science, v. 49, p.509-524.

National Aeronautics and Space Administration (NASA), 1999, MODIS UCSB emissivity library: http://www.icess.ucsb.edu/modis/EMIS/html/em.html.

National Oceanic and Atmospheric Administration (NOAA), 2001, FSL radiosonde database information: http://raob.fsl.noaa.gov/Raob_Software.html.

_____2007, National Oceanographic Data Center buoy locations – mid-Atlantic: http://www.nodc.noaa.gov/BUOY/bam.html.

Nelson, J. E., Silliman, S. E., and Wasowski, R. J., 1991, Analysis of thermal scanning imagery to investigate point inflows into surface water bodies: Civil Engineering Applications of Remote Sensing and Geographic Information Systems, ed. D. B. Stafford, American Society of Civil Engineers, p. 179-188.

Peterson, R. W., 1969, Environmental study of the Rehoboth, Indian River and Little Assawoman bays: report to the Governor by various state agencies.

Price, K. S. and Savchuck, S. D., 2001, A characterization of the water quality stressors and their impacts in the Delaware Inland Bays and their watershed based on research conducted during the decade of the nineties: Technical report prepared for the Center for the Inland Bays, 72 p.

Roseen, R. M., Brannaka, L. K., and Ballestero, T. P., 2001, Determination of nutrient loading from groundwater discharge into an inland estuary using airborne thermal imagery: Proceedings of the 12th Biennial Coastal Zone Conference, Cleveland, OH.

Rundquist, D., Murray, G., and Queen, L., 1985, Airborne thermal mapping of a flow-through lake in the Nebraska Sandhills: Water Resources Bulletin, v. 21, n. 6, p. 989-994.

Sabins, F. F., Jr., 1997, Remote sensing principles and interpretation: New York, W.H. Freeman and Co., 494 p.

Schott, J. R., Barsi, J. A., Nordgren, B. L., Raqueno, N. G., and de Alwis, D., 2001, Calibration of Landsat thermal data and application to water resource studies: Remote Sensing of Environment, v. 78, p. 108-117.

Scotto, S. L., Biggs, R. B., Brown, B., Manus, A. T., and Lyman, J. M., 1983, Decisions for Delaware: Sea Grant looks at the Inland Bays: DEL-SG-01-83, University of Delaware Marine Advisory Service, Newark, DE.

Scudlark, J. R. and Church, T. M., 1993, The atmospheric input of inorganic nitrogen to Delaware Bay: Estuaries, v. 16, p. 747-759.

Sims, J. T., Andres, A. S., Denver, J. M., Gangloff, W. J., Vadas, P. A., and Ware, D. R., 1996, Assessing the impact of agricultural drainage on ground and surface water quality in Delaware: University of Delaware Department of Plant and Soil Science, Newark, DE.

Torgersen, C. E., Faux, R. N., McIntosh, B. A., Poage, N. J., and Norton, D. J., 2001, Airborne thermal remote sensing for water temperature assessment in rivers and streams: Remote Sensing of the Environment, v. 76, p. 386-398.

U.S. Environmental Protection Agency (U.S. EPA), 2002, Environmental conditions in the mid-Atlantic estuaries, summary report for the mid-Atlantic integrated assessment (MAIA) estuaries 1997-98: EPA/620/R-02/003, 115 p.

U.S. Geological Survey (USGS), 2007, NWIS water data for the nation: http://waterdata.usgs.gov/nwis

Ullman, W. J., Andres, A. S., Scudlark, J. R. and Savidge, K. B., 2002, Storm-water and base-flow sampling and analysis in the Delaware Inland Bays, preliminary report of findings 1998-2000: Delaware Geological Survey Open File Report No. 44, 40 p.

Ullman, W. J., Geider, R. J., Welch, S. A., Graziano, L. M., and Overman, B., 1993, Nutrient fluxes and utilization in Rehoboth and Indian River bays: Report prepared for DNREC.

Ullman, W. J. and Miller, D. C., 2004, Ecological consequences of ground water discharge to Delaware Bay, United States: Ground Water, v. 42, n. 7, p. 959-970.

Ullman, W. J., Wong, K. C. , Madsen, J. A., Scudlark, J. R., Krantz, D. E., Andres, A. S., and McKenna, T. E., 2001, Nutrient transport and cycling in an agriculturally impacted coastal watershed: multidisciplinary approaches to interdisciplinary environmental problems: Proceedings of the 5th annual Environmental Engineering Research Event (20–23 November 2001, Noosa, Queensland), 10 p.

Ullman, W. J., Wong, K. C., Scudlark, J. R. , Madsen, J. A., Krantz, D. E., Andres, A. S., and McKenna, T. E., 2003,. CISNet Final Technical Report. Final technical report to the U.S. EPA, STAR Grant 826945.

University of Delaware, 2007, Current weather at REC: http://www.rec.udel.edu/TopLevel/Weather.htm.

Volk, J. A., Savidge, K. B., Scudlark, J. R., Andres, A. S., and Ullman, W. J., 2006, Nitrogen loads through baseflow, stormflow and underflow to Rehoboth Bay, Delaware: Journal of Environmental Quality, v. 35, p. 1742-1755.

Wang, L. T., 2005, Locating ground water discharge areas in Rehoboth and Indian River bays, Delaware using Landsat 7 imagery: unpublished M.S. thesis, University of Delaware, Department of Geography, 128 p.

Weston, R. F., Inc., 1993, Report to the Delaware Inland Bays National Estuary Program: Delaware Department of Natural Resources and Environmental Control, Dover, DE.

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