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Remote sensing half-century record of environmental changes at Cheyenne Bottoms, Kansas

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Cheyenne Bottoms is an internationally renowned wetland area located in central Kansas. We have compiled a half-century record of changes in land cover and use based on a combination of aerial photography, satellite imagery, and ground observations. Each type of data source has advantages and limitations in terms of spatial and temporal resolution, interpretability, and cost. Together they demonstrate the highly dynamic nature of Cheyenne Bottoms in terms of rapid and frequent changes in water bodies and vegetation cover. Of particular note are climatic events and ecological changes of the past five years. However, the extent of water bodies depicted in imagery does not correspond closely with annual precipitation in many cases. Water levels in the bottoms respond to upstream storm events and runoff as well as antecedent conditions, which may differ considerably for each drainage basin.

Keywords: satellite imagery, aerial photography, Cheyenne Bottoms, Kansas.

INTRODUCTION

Cheyenne Bottoms is an internationally renowned wetland located in Barton County, central Kansas. Because of its central position in the Great Plains, it provides a crucial stopover for some 40% of the migrating birds in North America (Zimmerman 1990). Cheyenne Bottoms Wildlife Area, managed by the Kansas Department of Wildlife and Parks, was designated as a Wetland of International Importance by the Ramsar Convention on Wetlands in 1988, and adjacent land of The Nature Conservancy (TNC) was added in 2002 (Ramsar 2010). The area also has been recognized as a site of hemispheric importance by the Western Hemisphere Shorebird Reserve Network (Kostecke, Smith and Hands 2004).

Cheyenne Bottoms rests within an oval-shaped land sink that is the terminal point of an enclosed drainage basin (Fig. 1). The principal tributaries are Blood Creek and Deception Creek. The geologic record of the area reveals the basin has existed intermittently as a wetland or lake for more than 100,000 years (Zimmerman 1990). Mean annual precipitation for Cheyenne Bottoms is ~65 cm per year (Table 1), but yearly precipitation fluctuates greatly from <40 cm to >1 m, which leads to highly variable water conditions. During times of excessive precipitation, the topography of the area is conducive to flooding. Conversely, due to its relatively shallow topography and large surface area, loss of water to evaporation may exacerbate conditions during times of regional drought, causing the bottoms to dry up nearly completely. Over the long term, the region has a net water deficit, and the bottoms is dry more often than wet.

These extreme fluctuations have made the area subject to water management endeavors since 1899, when the first water diverted from the Arkansas River was channeled into the bottoms. For the state wildlife area, the current water diversion setup was enacted in the 1950s and substantially enhanced in the 1990s. It involves dams, canals, dikes, and high-capacity pumps to regulate water levels in several artificial pools. Water is diverted from Walnut Creek via a dam and inlet canal (see Fig. 1), and then distributed to various pools as needed. This management scheme is effective in theory, but it has fallen short of expectations, as upstream competition for water has increased over the past several decades (Zimmerman 1990). The flow of Walnut Creek exhibits large variations from year to year, which reflect upstream fluctuations in precipitation (Table 2). During dry periods, Walnut Creek has insufficient flow to supply the state wildlife area. The Nature Conservancy, on the other hand, makes no attempt to manipulate water supplies on its land. Since the 1990s, in fact, TNC has removed barriers or artificial controls, where possible, in order to restore and maintain natural wetland habitats.

Among the emergent wetland plants in marshes at Cheyenne Bottoms, three are ecological indicators, namely cattail (*Typha* sp.), bulrush (*Scirpus* sp.) and spike rush (*Eleocharis* sp.). Cheyenne Bottoms has experienced cattail expansion since the 1970s, which was quite dramatic during the 1990s, as documented by multitemporal Landsat imagery (Pavri and Aber 2004). This was a result of relatively cool and wet climate, water management schemes, and general expansion of cattails across the Great Plains (Zimmerman 1990). This invasion led to the decline of open-water and mud-flat habitats, which subsequently caused a reduction in shorebird use (Kostecke, Smith and Hands 2004). A variety of methods for cattail management is practiced; these include disking, mowing, controlled burning, flooding, drying, grazing, and combinations thereof.

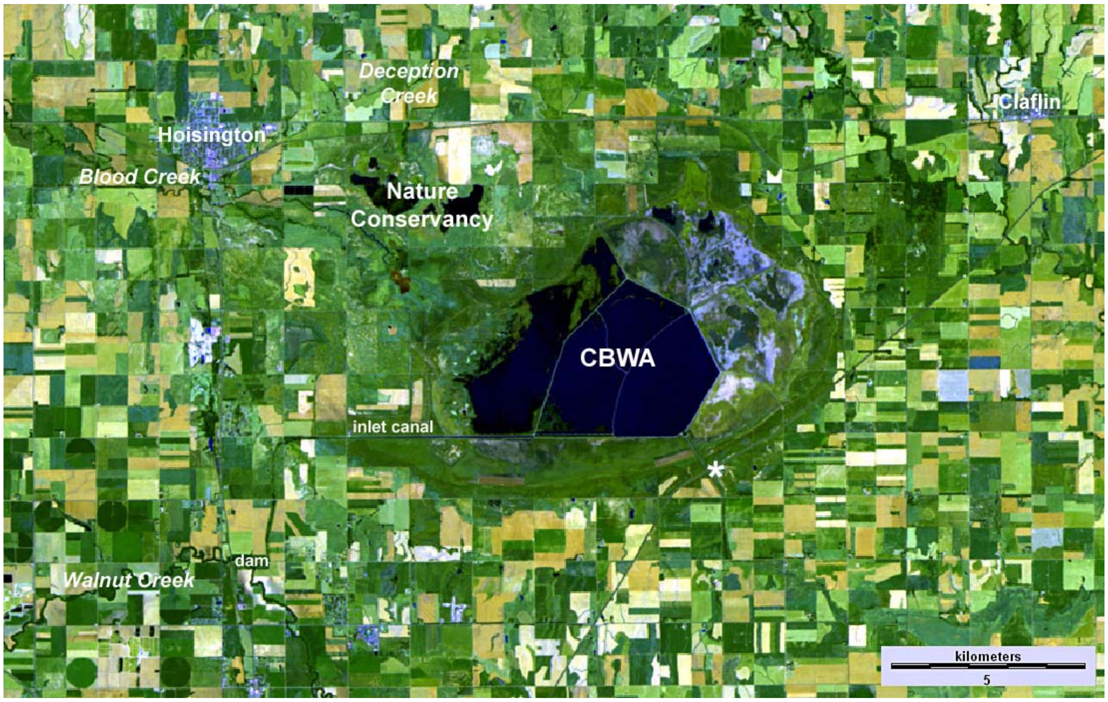

Figure 1. General locality map for Cheyenne Bottoms, Barton County, central Kansas. Cheyenne Bottoms Wildlife Area (CBWA) occupies the downstream or sump portion of the bottoms; its water supply is diverted from Walnut Creek and delivered via an inlet canal. Nature Conservancy land is located in the upstream deltaic portion of the bottoms; its water is derived from natural overflows of Blood and Deception creeks. Location of the Kansas Wetland Education Center is indicated by the asterisk (*). Based on Landsat TM false-color composite; bands 2, 5 and 7 color coded as blue, green and red; active vegetation appears green and water bodies are dark blue. Landsat TM dataset acquired September 3, 2009.

We have monitored TNC portions of Cheyenne Bottoms during the growing season for the past several years using a variety of remote sensing methods and ground observations (Aber et al. 2006, 2009, 2010), and we have utilized satellite imagery to evaluate changes in land use and cover (Pavri and Aber 2004). Our goal in pursuing this project is to compile a long-term record for land use and cover at Cheyenne Bottoms based on remote sensing and to compare changes in land use and cover with climatic conditions and human management of the bottoms. Of particular note are climatic events and ecological changes of the past five years.

Methods

Aerial photography and satellite imagery are the primary sources of information for this study. Our time frame covers more than a half century, from 1957 to 2010, based on historical airphotos, digital orthophoto quadrangles (DOQs), small-format aerial photography (SFAP), and satellite imagery (Landsat and Ikonos). Historical aerial photographs were obtained from the Kansas State University Library and Kansas Applied Remote Sensing, University of Kansas. DOQs and Landsat datasets were supplied by the U.S. Geological Survey, and Ikonos datasets were purchased commercially. Remotely sensed datasets acquired with different platforms and instruments at multiple heights and spatial resolutions ideally should be obtained at the same time under uniform lighting conditions with similar ground cover (e.g. Lillesand, Kiefer and Chipman 2008). This is rarely possible in practice, however, particularly when dealing with archival datasets. We selected available imagery based on best quality for interpretation of land cover. We did achieve seasonal correspondence for SFAP and satellite imagery during the interval 2002-2010.

Table 1. Long-term yearly precipitation data (cm) for sites near Cheyenne Bottoms, central Kansas. Years of highest precipitation represent floods in 1973 and 2007; lowest precipitation years are drought periods in the 1930s, 1950s, and 1980s. Data adapted from HPRCC (2011).

Site	Period of record	Location	Mean annual	Highest (year)	Lowest (year)
Great Bend	1909-2010	12 km to SW	64	110 (1973)	36 (1956)
Claflin	1930-2010	12 km to NE	65	132 (2007)	31 (1988)
Hudson	1922-2010	40 km to south	64	108 (2007)	36 (1936)
Geneseo	1939-2010	44 km to east	67	146 (1973)	34 (1956)
Bison	1923-2010	48 km to west	59	97 (1973)	32 (1956)

Table 2. Half-century of mean and peak annual flows on Walnut Creek at Albert, ~25 km west of Cheyenne Bottoms. Years with exceptionally high flows are indicated in blue; years with unusually low flows are highlighted in magenta. Total average values given at bottom. Discharge in cubic feet per second; data obtained from USGS (2011).

Year	Mean annual discharge	Peak annual discharge		Year	Mean annual discharge	Peak annual discharge
1960	156.1	4320		1986	8.2	960
1961	125.1	3920		1987	113.0	2850
1962	84.8	1950		1988	1.2	137
1963	50.8	1640		1989	8.2	550
1964	13.1	355		1990	19.4	1040
1965	25.1	1150		1991	1.6	266
1966	14.9	1280		1992	37.0	1720
1967	133.5	2800		1993	188.7	3000
1968	20.5	2110		1994	42.8	191
1969	45.4	1940		1995	30.8	691
1970	37.9	2900		1996	67.9	1330
1971	25.9	1600		1997	78.3	2050
1972	34.9	1910		1998	54.4	943
1973	134.8	3150		1999	83.5	1770
1974	70.7	2760		2000	46.4	675
1975	26.7	2100		2001	106.4	2620
1976	19.4	1320		2002	13.5	96
1977	3.9	308		2003	4.3	232
1978	17.0	1440		2004	21.8	1000
1979	56.8	2870		2005	3.6	189
1980	12.9	974		2006	41.0	1870
1981	21.2	1550		2007	102.1	1720
1982	5.9	567		2008	60.0	2050
1983	0.1	58		2009	32.4	642
1984	2.9	440		2010	28.7	---
1985	2.2	580		**Total**	**45.8**	**1492**

We processed and evaluated these datasets according to routine procedures in remote sensing, particularly for those features typical of wetlands—water bodies, vegetation and soil (e.g. Tiner 1997; Jensen 2005, 2007; Lillesand, Kiefer and Chipman 2008). Historical airphotos were scanned and georectified to match with DOQs and then were mosaicked to create nearly continuous images. We visited TNC sites several times in spring, summer and autumn (2002-2010) to obtain ground observations and to conduct SFAP using kites or a helium blimp to lift radio-controlled camera rigs 50-150 m above the ground (Aber et al. 2006). In addition we obtained and evaluated climatic data for the region from the National Climatic Data Center based on the weather record at Great Bend and other nearby sites.

Remote sensing results

Conventional aerial photography

Conventional aerial photography includes historical airphotos and DOQs, which typically are panchromatic (visible, gray tone), have spatial resolution of 1-2 m, and have interpretability ratings of 5-6 (scale 0-9; Leachtenauer, Daniel and Vogl 1997). Such airphotos are fundamentally important for wetland assessment and mapping (Tiner 1997). We obtained and processed imagery for representative years from six decades (1957, 1965, 1973, 1980, 1991, 2002). The 1957 mosaic illustrates the values and some problems with this type of imagery (Fig. 2). Major types of land use and cover are evident—cropland, pasture, water bodies, urban, etc.

The panchromatic nature of the image, however, limits interpretation of vegetation types, and sun glint renders some water bodies quite light in tone. Because each picture in the mosaic was taken under slightly different lighting conditions, the seam lines in the mosaic are clearly evident. In some places, small black slivers separate individual tiles within the mosaic, which is quite distracting. Newer DOQ mosaics overcome some of these spatial issues, but confusing sun glint and variable lighting conditions still limit interpretability (Fig. 3). Nonetheless, these images represent snapshots in time that depict main categories of land cover and use.

Landsat imagery

Landsat imagery provides invaluable long-term documentation of global land cover and use at moderate spatial resolutions (30-80 m) since the 1970s (Lauer, Morain and Salomonson 1997). Multispectral (visible and infrared) datasets allow more sophisticated interpretation than is possible with conventional aerial photography, albeit at lower spatial resolution. We processed Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) datasets for several years spanning the period 1986 to 2009. We produced a variety of images and analysis including false-color and multitemporal composites, normalized difference vegetation index (NDVI), and cluster classification. Substantial changes in land use and cover are evident during the past quarter century, particularly in terms of human management of the wetland habitats (Fig. 4).

During this interval, the most dramatic hydrologic changes took place between 2006 and 2009. A drought of several years duration culminated in 2006, when nearly all marshes and pools were dry (Fig. 5A). Major flooding took place in 2007, and the bottoms was converted into a large, shallow lake for several months (Fig. 5B). Flood water receded slowly during 2008, and near-normal conditions finally returned in 2009. These changes are highlighted in a multitemporal composite image using TM band 4 (near-infrared), which is particularly sensitive

Figure 2. Historical airphoto mosaic of Nature Conservancy region in June of 1957. Annual rainfall this year was 96 cm, >30 cm above average. Note the extensive flooding that extends beyond the main pool area of the CBWA in the lower right portion of the image. Standing water is also visible in several places.

Figure 3. DOQ mosaic of Nature Conservancy region in 1991. Annual rainfall this year was 47 cm, well below average. Standing water level in the CBWA pool is significantly lower than in previous image. Notice the distracting sun glint boundary across the marshes at scene center where tiles are joined in the mosaic; this confuses attempts to measure water bodies quantitatively.

Figure 4. Landsat image for July 10, 1989 showing land use and cover prior to major enhancements within the CBWA and before TNC began purchasing land for habitat preservation. False-color composite; TM bands 2, 5 and 7 color coded as blue, green and red; active vegetation appears green and water bodies are blue. Compare with Figure 1.

to active vegetation and water bodies (Fig. 6). This image also highlights the deltas built by Deception and Blood creeks respectively in the northern and western portions of the bottoms. These deltas remained above most of the 2007 flooding; whereas, nearly all the state wildlife area was submerged, and TNC marshes were inundated in the embayment between the two deltas. Landsat's multispectral datasets, long duration, and frequent coverage allow for interpretation of land use and cover and their changes through time, although without the fine spatial details visible in conventional airphotos.

Ikonos imagery

Ikonos satellite datasets have spatial resolution (1-4 m) that rivals conventional aerial photography as well as multiband spectral resolution (visible and near-infrared). This combination leads to substantial spatial detail and spectral information that allow for excellent interpretability. Ikonos imagery proved most useful for depicting spatial details of water bodies, moisture content of mud flats, and active vegetation (Fig. 7). However, the high cost of Ikonos (and other commercial satellites) limited the number of datasets we could obtain; thus, multitemporal analysis was not possible.

Small-format aerial photography

Low-height SFAP provides the highest spatial resolution (5-10 cm) and achieves interpretability levels of 7-8 (Aber, Marzolff and Ries 2010). Most photographs were acquired in normal color, and some were taken in color-infrared format (Aber et al. 2009). Vertical and oblique views were obtained in all possible orientations relative to the sun position, shadows, and ground objects. Repetitive photography from season to season and year to year displayed many changes, particularly in water bodies and vegetation cover. The sequence from 2006 to 2010 is especially dramatic (Fig. 8). In addition, SFAP documented unusual or ephemeral conditions (Fig. 9). SFAP images combined with observations on the surface provide ground truth for better understanding the dynamic environment and interpreting conventional airphotos and satellite images.

Remote sensing and climatic events

Annual precipitation data do not appear to correspond closely in all cases to the amount of standing water seen in the images. In reviewing the historical airphotos, for example, water levels displayed in 1973 appear to be lower than in both 1957 and 1965; yet both of these years experienced less rain than in

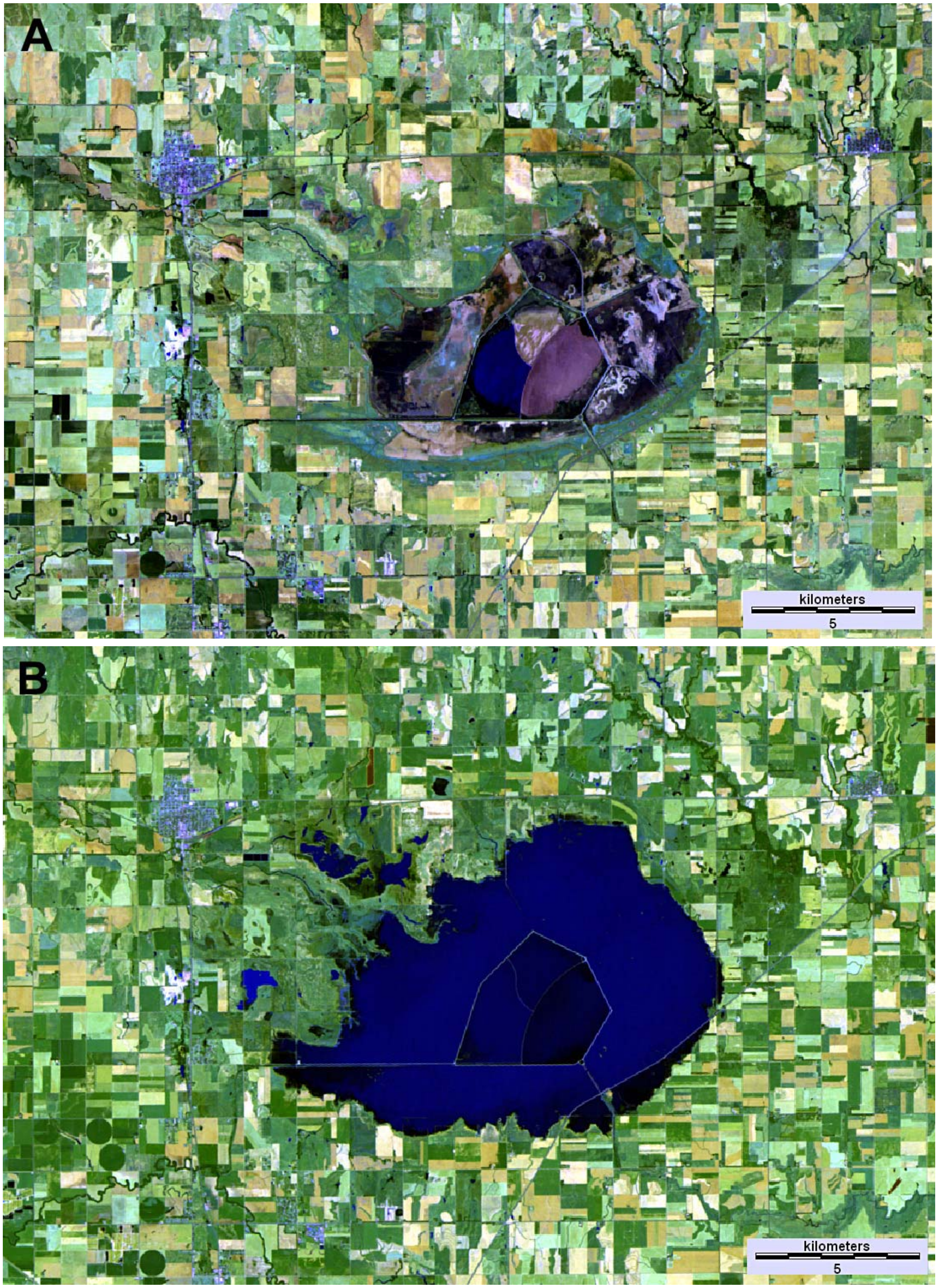

Figure 5. Landsat images for July 25, 2006 (A), a drought year, and August 13, 2007 (B), a year with flooding of historic proportion. False-color composites; TM bands 2, 5 and 7 color coded as blue, green and red; active vegetation appears green and water bodies are blue. Water bodies covered only 5.4 km^2 in 2006, mainly in the central pools of the state wildlife area, but expanded 15-fold to 81.0 km^2 in 2007.

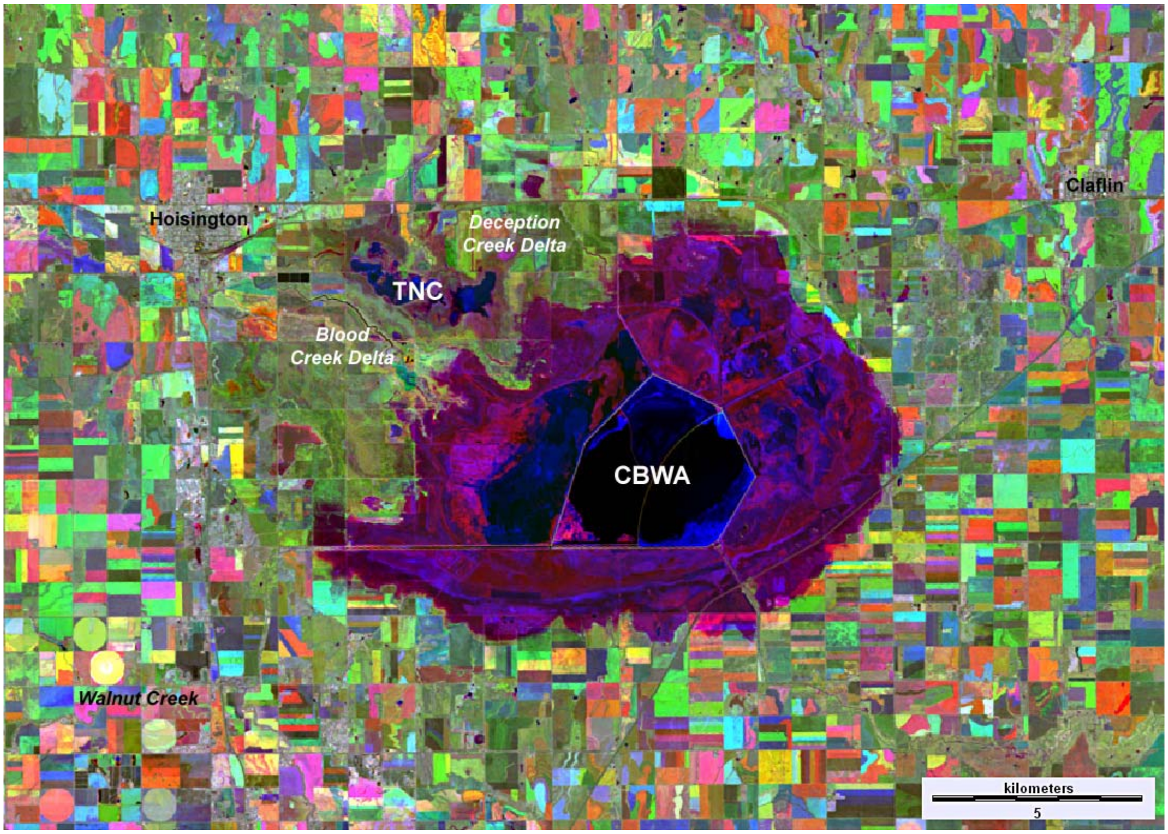

Figure 6. Multitemporal Landsat image based on TM band 4 (near-infrared) for 2006, 2007 and 2009, color coded respectively as blue, green and red. Bright colors represent significant changes in land cover from year to year. Dull-gray colors indicate little change in land cover. The broad maroon-purple zone shows the extent of high water in 2007. Compare with Figure 5.

Figure 7. False-color Ikonos image showing the north-western portion of Cheyenne Bottoms for July 11, 2003, a drought year. Annual rainfall this year was 43 cm, >20 cm below average. False-color composite in which active vegetation is green, mud flats and fallow ground are purple to light gray, and water bodies are black. Compare with Figures 2 and 3.

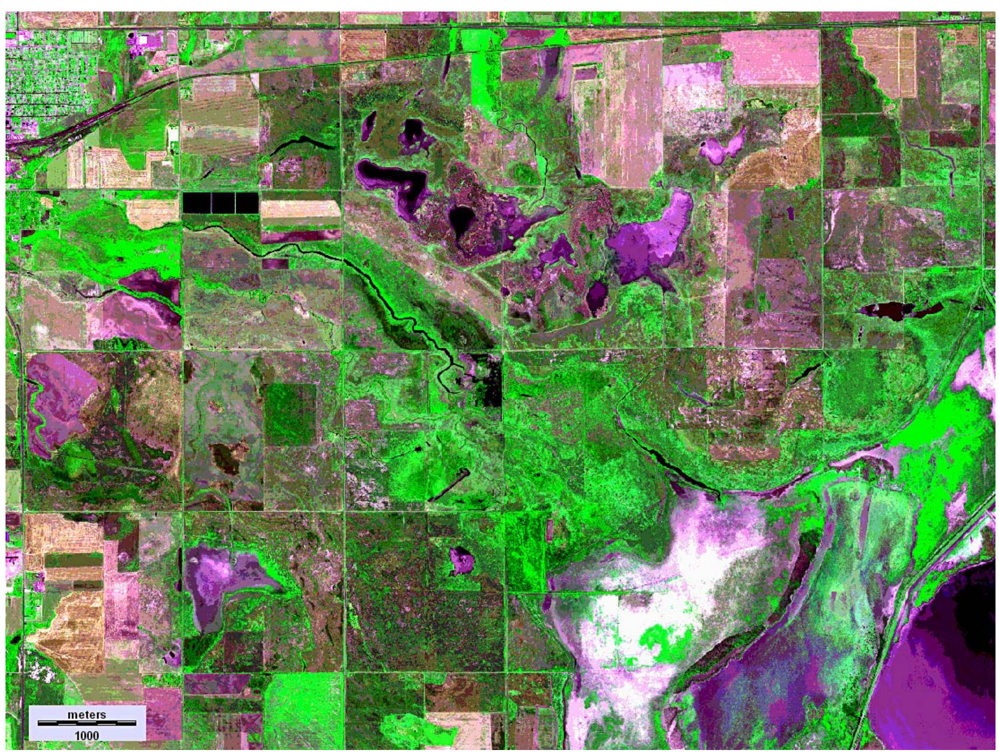

Figure 8. Series of small-format aerial photographs of TNC marsh at Cheyenne Bottoms; comparable overviews looking northward. 2006 – completely dry mud flat was disked and dead thatch was mowed in October. 2007 – waxing flood partly inundated the marsh in May. Flooding expanded considerably in June and July. 2008 – receding water allowed some emergent vegetation to reestablish in September. 2009 – bloom of *Azolla* (maroon) covered much of the open water (Aber et al. 2010), as marsh returned to near-normal water level in October. 2010 – *Azolla* bloom had dissipated and cattails (green) had expanded in October.

1973 (Fig. 10; Tables 1 and 2). Similar discrepancies are apparent in Landsat imagery, particularly for drought conditions. Low water levels are evident in 1991, 1995, 2003, and 2006; but precipitation varied by more than 25 cm for these years and exceeded the long-term average (65 cm) for two years, 1995 and 2006 (Fig. 11). Major flood events, in contrast, are well represented in both aerial photography and satellite imagery.

One reason for the lack of correspondence between water bodies seen in imagery and annual precipitation may relate to when rainfall was received in relation to image acquisition dates. In both the 1957 and 1965 airphotos, roughly half of the total annual precipitation had fallen by the date the photos were taken. The 1973 airphoto, in contrast, was acquired when less than 20 percent of the total annual rain had fallen. Another complicating factor could be antecedent conditions, namely precipitation, runoff and water levels of the previous year.

Water levels in both the CBWA and TNC reflect upstream precipitation and runoff; thus, heavy storms some distance away may cause rapid water rises in the bottoms. Furthermore, the waters supplied to the CBWA and TNC come from different

Figure 9. Erecting the Kansas Wetland Education Center next to Kansas highway 156 and the outlet canal for CBWA. Work had to be halted and the foundation raised during flooding of 2007; construction resumed in 2008, when this picture was taken. Note the semi-circular plan of the building and the demonstration marsh behind the building (on left). Kite flyers in lower right corner; May 2008.

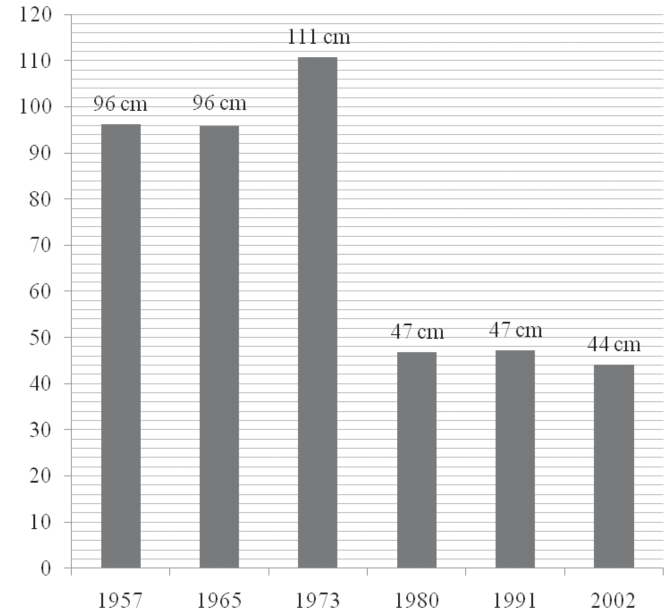

Figure 10. Annual precipitation (cm) received for the years in which conventional aerial photography images were taken.

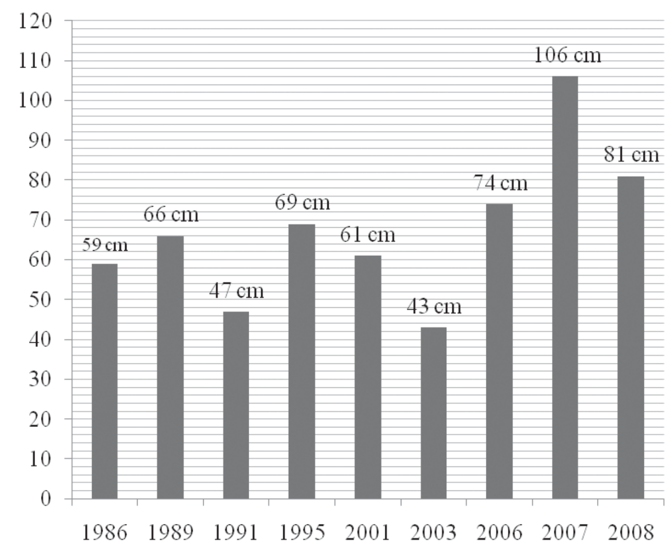

Figure 11. Annual precipitation (cm) received for the years in which Landsat images were taken.

drainage basins. The climatic records from scattered weather stations do not fully represent these possible variables in precipitation and runoff, particularly for dry periods, that may impact different portions of Cheyenne Bottoms.

Conclusions

Remotely sensed imagery spanning the past half century demonstrates substantial changes in land cover and use at Cheyenne Bottoms as consequences of climatic events and human management. The bottoms has varied from mostly dry drought status to major flooding that turned the basin into a lake. Water management capability has been improved at the state wildlife area, and the Nature Conservancy has restored and preserved wetland habitats. Conventional aerial photography provides snapshots in time covering large areas at high spatial resolution, but the panchromatic format and variable lighting conditions, especially sun glint, limit interpretability. Landsat's multispectral datasets, long duration, and frequent coverage allow for interpretation of land use and cover and their changes through time, albeit without the fine spatial details visible in conventional airphotos. Ikonos (and other commercial satellites) combine the high spatial resolution of conventional airphotos with multispectral capability, but high cost is a major limitation for routine use. For ground truth, small-format aerial photography and surface observations provide the highest spatial resolution.

These diverse types of remote sensing demonstrate the highly dynamic nature of Cheyenne Bottoms in terms of water bodies and vegetation cover. The water bodies seen in individual images, however, do not correspond to the record of annual precipitation or stream flow in many cases. One explanation is that the date of imagery during the year may not coincide with the timing of precipitation and runoff during that year, and antecedent conditions also could affect water levels. Water levels in the bottoms respond to upstream storm events and runoff, which may differ considerably for each drainage basin. Given the variable nature of Cheyenne Bottoms, it is likely that large fluctuations in water bodies, vegetation, and other features will take place during the twenty-first century. We plan to continue monitoring environmental conditions at Cheyenne Bottoms, particularly for TNC marshes, using available remote sensing techniques. With sufficient data, it may become possible to model the responses of the state wildlife area and TNC land under different management schemes and climatic fluctuations.

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