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WETLAND RESTORATION

Locating Drainage Tiles at a Wetland Restoration Site within the Oak Openings Region of Ohio, United States Using UAV and Land Based Geophysical Techniques

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Abstract
Drainage tiles were used to drain wetlands in the midwestern United States to convert them into farmlands. With decades of farm operations, utility maps showing tiles' locations are now mostly inaccurate or simply do not exist. However, knowledge of the location of tile networks is needed to effectively restore these farmlands to their original wetlands' conditions. With many fields spanning several hectares, efficiently locating drainage tiles at large farm fields can be problematic. Drainage tiles create variations in soil physical properties including moisture content, surface temperature and dielectric permittivity within and around the pipes which can be sensed by geophysical methods. Our study assesses the application of electromagnetic radiation via visible and thermal infrared imaging using an unmanned aerial vehicle and ground penetrating radar (GPR) to locate drainage tiles at large farm field scale. The study was conducted at the Sandhill Crane wetland, a 1.1 km^2 old agricultural field located in Swanton, Ohio. A UAV equipped with visible and thermal infrared cameras acquired imagery on a regular grid and about 100 GPR lines were measured using a 250 MHz radar system. Both visible and thermal infrared images identified the drainage tiles and their orientations. GPR profiles reveal the drainage tiles mostly in a parallel East-West direction. By using a UTV to pull the GPR system, we efficiently collected data along profiles covering the entire site. The delineated tile network will improve management of the anthropogenically altered hydrology at the site as it is being restored into its original wetland conditions.

Keywords Drainage tiles · UAV · Visible light · Thermal infrared · Ground penetrating radar

Introduction

Drainage tiles have been extensively used in what was historically known as the Great Black Swamp in the Midwestern region of the United States since the late 1800s to drain excess water and lower the water table for settlement and related activities including farming (Kaatz 1955; Andreas and Knoop 1992; Gedlinske 2014). Detailed utility maps showing the location and depths of these tiles are in most cases missing due to poor land or farm management practices. In the absence of such maps, locating these drainage tiles by traditional probing using flexible metal rod and excavations are tedious and destructive (Ruark et al. 2009). The use of non-invasive techniques including vegetation analysis (Tlapáková et al. 2015), aerial photographs, remote sensing (Williamson et al. 2019) and geophysical methods such as ground penetrating radar (Chow and Rees 1989; Allred et al. 2004; Koganti et al. 2020) if applicable, provide a more efficient approach for locating the tiles. This study further evaluates the use of both unmanned aerial vehicle (UAV)-based visible and thermal infrared imaging and land-based ground penetrating radar for locating drainage tiles and mapping their network at a large field scale spanning hundreds of hectares within the Oak Openings Region of Northwestern Ohio.

Historically, Northwestern Ohio and part of Michigan and Indiana constituted a vast wetland referred to as the "Great Black Swamp" with its low lying lands partially or entirely covered with water in the winter and spring (Kaatz 1955). This once vast wetland area has been largely drained to accommodate human settlements and farmlands leaving

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behind less than 5% of the earlier wetland area (Gedlinske 2014; Lenhart and Lenhart 2014). In particular, the narrow region west of Toledo, Ohio which extends to the west of Michigan named the Oak Openings Region (OOR) provide a typical hydrological scenario requiring extensive drainage in order to farm its land (Shade and Valkenburg 1975). The unique shallow stratigraphy of the Oak Openings Region of Northwestern Ohio consisting of medium to coarse grained sand underlain by low permeability, clay-rich glacial-lacustrine sediments and glacial till (Shade and Valkenburg 1975) result in poorly drained saturated fields. These fields were extensively drained using drainage tiles to allow the cultivation of crops. Converting these wetland areas to farmlands relied on easily available technology for installing agricultural drainage tiles used to manage the excess water on the field (Gedlinske 2014).

The material composition of drainage tiles, their structure and installation techniques have evolved over the years. Earlier tiles were either made of clay, wood, or concrete with a diameter of approximately 15 cm and approximately 30 cm long (Beauchamp 1987). The tiles were typically placed end-to-end following a linear path in about 75–150 cm deep trenches either dug manually or by a trenching machine towed by a horse (Allred et al. 2005; Gedlinske 2014; Yannopoulos et al. 2020). Since the 1960's, clay, wooden and concrete tiles have been replaced by corrugated plastic tubings (CPT) which are made of high-density polyethylene and perforated to allow for infiltration. These modern tiles are installed at depths ranging from 90 cm to 150 cm with spacing ranging from 10 m to 25 m depending on site conditions including soil type, slopes, surface conditions, and crops. Modern machines can complete the process of trenching, installation, and backfilling simultaneously allowing for easy installation. This has contributed to the intensive use of drainage tiles in the Midwestern United States (Allred et al. 2005; Yannopoulos et al. 2020).

While population growth, urbanization, and the need to increase food production made the use of drainage tiles very popular within Northwestern Ohio, it also resulted in the disappearance of wetlands within the region (Kaatz 1955; Abella et al. 2001; Higgins 2003). However, the recent desire to address lake eutrophication producing harmful algae blooms and the need to protect endangered species within the OOR has increased awareness for restoring lands within Northwest Ohio to their original wetland state. Most of the lands being restored are old farm fields with a history of intense drainage using artificial agricultural drainage tile, and excessive runoff from these fields are identified as an important source of nutrient loading, specifically nitrogen and phosphorus associated with Harmful Algal Blooms (HABs) (Smith et al. 2015; Moore 2016). Unfortunately, in most instances, the location and or depths of these drainage tiles are not well documented. Restoring old farmlands back to wetland conditions will require knowledge of the tile locations to allow decommissioning the tiles which involves blocking the tile outlets and sometimes digging them out. In cases involving blocking the tile outlet to retain water within the site, knowledge of the tile network is still necessary to manage potential hydrological hazards such as flooding and blowout (Cooley and Herron 2015; Easton et al. 2016). Hence, the need for an efficient approach for locating drainage tiles mostly at the farm field scale.

Drainage tiles can be located manually within a farm field using a traditional handheld probing rod (Allred et al. 2005) consisting of an approximately 0.8 cm stainless steel rod with a rounded, welded tip to help prevent puncturing the tile. Using the handheld probe rod is very tedious and unrealistic for large field scale application. Analysis of spatial distribution of vegetation cover (e.g. cover crops) could give overview of the tile network (Tlapáková et al. 2015). However, the high variability in other properties and processes controlling the spatial and temporal distribution of vegetation cover such as soil moisture, nutrient content, and evapotranspiration limit reliance on this approach (Naz et al. 2009). Geophysical methods including ground penetrating radar, magnetometry, aerial photographs, satellite-based, and other remote sensing techniques provide a non-invasive approach for locating drainage tiles and delineating their network (Allred et al. 2004; Rogers et al. 2005).

Aerial imagery using different wavelengths of reflected and emitted electromagnetic energy including visible-color, near infrared and thermal infrared has been explored for mapping drainage tiles' locations (Abdel-Hady et al. 1970; Williamson et al. 2019; Woo et al. 2019; Allred et al. 2020; Kratt et al. 2020). Using these images relies on the contrast in reflection or emission of electromagnetic energy between soils overlying the drainage tiles and the soils between them.

Field aerial imaging including visible, infrared, thermal and multispectral imaging for mapping drainage tiles' location and network can be done using traditional satellite platforms and aircrafts (Abdel-Hady et al. 1970; Verma et al. 1996; Naz et al. 2009; Gökkaya et al. 2017). Earlier studies have shown that for the method to be effective, data acquisition should be done around 2–3 days after a rain event with 1–2 cm of precipitation (Allred et al. 2020; Kratt et al. 2020). Scheduling a conventional aircraft targeting such favourable field conditions is challenging as airplanes may not be easily available under short notices (Allred et al. 2018; Allred et al. 2020). Recent studies have focused on using unmanned aerial vehicles (UAV) equipped with multiple cameras which provides the desired flexibility for acquiring these aerial images (Williamson et al. 2019; Allred et al. 2020; Kratt et al. 2020). Validatory studies mostly in the OOR are necessary given the dependence of these techniques on the spatial and temporally varying properties such as soil type, water content, and vegetation (Naz et al. 2009) and the need to map tile network at old farm fields in the region.

While remote sensing techniques have been useful in locating drainage tiles and mapping their network, they are limited in depth estimates of individual tiles and their success rate have also varied with field site conditions (Woo et al. 2019). Hence, the need to keep exploring the use of conventional ground-based geophysical techniques including magnetic gradiometry (Allred et al. 2004; Rogers et al. 2005) and ground penetrating radar (Chow and Rees 1989). Ground penetrating radar (GPR) has been widely used to successfully locate drainage tiles and map their network relying on the contrast in the dielectric properties of the soil around the tile and that of the air, water or a combination of both within the tiles (Allred et al. 2005; Allred et al. 2004; Allred 2013; Koganti et al. 2020; Lai et al. 2018). Detecting drainage tiles using GPR is possible in a wide variety of soil types and properties with reported applications in fine and coarse loamy glacial till, sandy glaciofluvial and clayey glaciomarine sediments (Chow and Rees 1989; Allred et al. 2004). Chow and Rees (1989) demonstrated a near 100% success rate in using GPR to delineate clay and plastic drainage tiles in soils developed in a glacio-fluvial deposit. Applications in about 14 test plots in southwestern, central and northwestern Ohio have also been reported with success rate ranging from 50 to 100% (Allred et al. 2004). The success rate depends on soil types, conditions and GPR antenna frequencies and configurations (Allred et al. 2005). While most of these studies where at small scale test sites, Allred et al. (2018) highlighted the need and presented a feasibility study assessing the practicality of using GPR to delineate drainage tiles at large field scale. They emphasized the need for integrating the GPR system with a differential global positioning system to map tile network at such large field scale.

Drainage tile detection research using non-invasive geophysical methods has shown variable effectiveness at field scale with the effectiveness depending on site specific conditions such as soil type, vegetation cover, and water saturation (Jazayeri et al. 2018). An average success rate of 72% has been reported within Northwest Ohio with a 50–50 chance reported in one of the studies (Allred et al. 2005). This shows the need for more case application studies. Also, no study or application have been reported within the Oak Openings Region of Ohio using geophysical techniques to locate drainage tile within its farm fields. With the current efforts to restore multiple farm fields to their natural wetland conditions within the region, there is a need for validating the applicability of non-invasive geophysical methods for locating and mapping drainage tile networks within the region. This study investigates the use of visible and thermal infrared imaging as well as the use of ground penetrating radar for locating drainage tiles within the Oak Openings Region of Ohio with the aim of developing a detection method framework that is applicable at large field scale. The use of UAV equipped with different cameras as well as mapping from a GPR system equipped with a real time kinematic (RTK) GPS system allows a large-scale spatial coverage to be assessed. Practical aspects including suitable GPR frequencies and transect spacing are also assessed in this study.

Study Site

This study was conducted at the Sandhill Crane wetland restoration project site of The Nature Conservancy (TNC) located at Angola Road in Swanton, Ohio (Fig. 1). The site was previously an agricultural field with an approximate area of 1.1 km^2 (0.75 km × 1.4 km) and is currently being restored to a wet prairie (wetland) habitat. It has a relatively flat topography with elevation slope less than 2% and lower depressions at its western, eastern, and north central segments. The site sits in the Oak Openings Region (OOR) in Northwestern Ohio, an important wet prairie ecosystem characterized by poorly drained shallow sandy soils underlain by glacial till (Shade and Valkenburg 1975; Wijayarathne and Gomezdelcampo 2019). The subsurface at the site is characterized by fine to medium grained sand from the top to depths of 3–5 m with high organic matter content at its top 0.35 m mostly in the eastern and western flank which are inundated during the spring (Becker et al. 2020). The sand at the site is part of the reworked sands deposited along the edges of ancient Lake Wayne, Warren, and Lundy by Lake Michigan longshore currents (Brewer and Vankat 2004; Wijayarathne and Gomezdelcampo 2019). Based on interpreted electrical resistivity data acquired as part of an ongoing study (Becker et al. 2020), the sands are underlain by glacial-lacustrine sediments and glacial till (with electrical resistivity values ranging from 40 to 120 Ωm), which extends down to depth of 20 m and are followed by the bedrock (with electrical resistivity values ranging from 120 to 250 Ωm). The top sandy sediments are saturated with an average water table at a depth of 70 cm which varies seasonally.

Methods

For this study, we utilized an unmanned aerial vehicle (UAV) platform for both the visible and thermal infrared imaging while ground penetrating radar (GPR) measurements were conducted with GPR transmitting and receiving antennas mounted on a cart to ease data acquisition. We also towed the GPR system behind a utility terrain vehicle to enable us to cover our large farm field scale site.

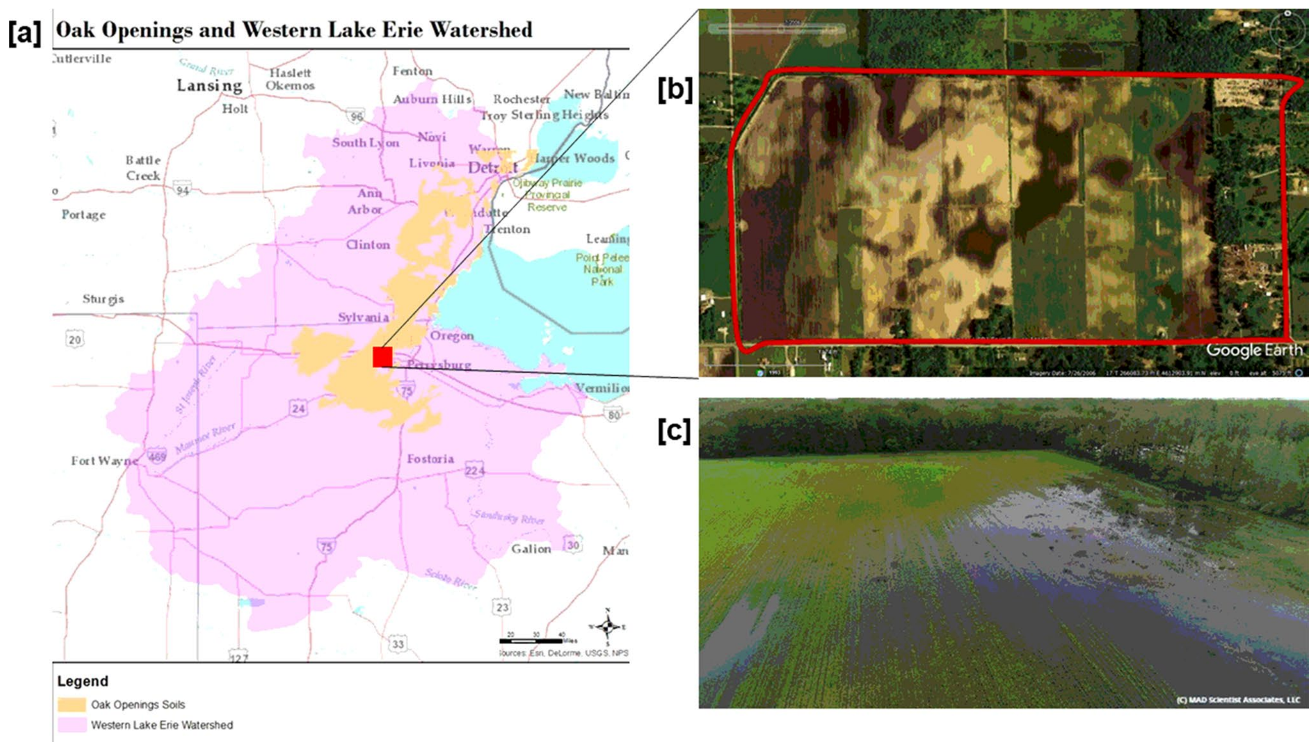

Fig. 1 (**a**) Location of the study site within the Oak Openings region in Ohio, USA, (**b**) aerial photo of the site from Google Earth (*Google Earth*, earth.google.com/web), and (**c**) photo of site in early spring with edges flooded. Modified after (TNC 2020)

Visible and Thermal Infrared Imaging

Remote sensing techniques using electromagnetic (EM) radiation with wavelengths within the visible and infrared spectrum have been used to locate subsurface drainage pipes (Naz et al. 2009; Allred et al. 2020; Kratt et al. 2020). Visible light imaging involves the use of cameras capable of sensing EM radiation with wavelengths ranging from 400 nm to 700 nm visible to the human eye. Drainage tiles allow preferential percolation of water through soils above the tiles compared to soils between tile lines resulting in the soil above tiles more drained with lower water content. The contrast between water content in soil above and between the pipes results in variability of reflectance in the visible light region. Increase in the reflected light produces a lighter shaded linear surface feature characteristic of a drainage pipe (Allred et al. 2020). Thermal infrared imaging on the other hand involves sensing EM radiation within the short-wave infrared spectrum ranging from 900 nm to 14,000 nm. Based on the differences between the specific heat capacity of water and soil materials and as a result of thermal inertia, the soil above a drainage pipe also shows temperature contrast compared to its surrounding due to differences in water content. This creates a contrast in the thermal radiation between the soil above the drainage pipe compared to its surrounding following the Stefan-Boltzmann and Kirchhoff's laws (Woo et al. 2019; Allred et al. 2020). This contrast can be observed in a thermal infrared image and provide insight to the location and network of drainage pipes. Both visible and infrared imaging can be conducted using aerial platforms including an unmanned aerial vehicle with the advantage of large spatial coverage within a short time.

For this study, we utilized a visible color camera and a FLIR Vue Pro thermal imager mounted on a DJI Phantom 3 Pro UAV. The FLIR Vue Pro imager has a 640 × 480 sensor array, with a 13 mm optic, giving a 25-degree field of view (FOV) recording thermal imagery at 30 Hz. The Phantom 3 Pro has a 4000 × 3000 Red, Green and Blue (RGB) visible light camera with a 20 mm lens, giving a 94-degree FOV. Flights were conducted under Federal Aviation Administration regulations - FAA part 107 rules. The flights were conducted between May and June 2020 on a regular grid at 50 or 100 ft above ground level, based on local airspace restrictions from the Toledo Express Airport control. Grid spacing was kept at 18.3 and 33.5 m for flight heights of 15.2 and 30.5 m respectively. At these flight heights, a ground resolution of 1.2 to 2.1 m was achieved for the visible images and 1.1 to 2.1 m for the thermal images. At the time of the flights, the weather was mostly sunny with temperatures around 21 °C with light rains 2 days prior while the fields were covered with cover crops with early-stage growth typical of the late Spring/Early summer season in Northwestern

Ohio. RGB imagery was processed in Agisoft Metashape to generate a composite orthomosaic of the field sections flown. Thermal imagery was referenced against the RGB orthomosaic.

GPR Data Acquisition and Processing

GPR is a well-established geophysical technique and has been used to locate utilities (Lester and Bernold 2007; Metwaly 2015; Lai et al. 2018) within the shallow subsurface including agricultural tile drainage (Chow and Rees 1989; Allred et al. 2004; Allred et al. 2005; Allred 2013). The technique involves the emission of electromagnetic (radar) pulses by a transmitting antenna which are reflected, scattered, and attenuated depending on the subsurface properties including its dielectric permittivity and conductivity as the radar pulses travel through it (Chow and Rees 1989; Jazayeri et al. 2018). Reflected radar signals eventually travel to the surface where they are recorded by a receiving antenna to produce a signal trace which reflects changes in the wave amplitude and energy with time (Allred et al. 2005). A buried cylindrical pipe such as a drainage tile generates a characteristic diffraction hyperbola due to its shape, the spherical nature of the wave front and contrast between the dielectric properties of the air and or water inside the pipe and that of the surrounding soil (Chow and Rees 1989; Allred et al. 2005; Jazayeri et al. 2018). The diffraction hyperbolas of pipes in GPR profiles are clearly distinctive such that they can be displayed and interpreted in real time making GPR a widely used technique for real time location of subsurface utilities.

For this study, we utilized the Sensors and Software, Inc. (Mississauga, ON, Canada) PulseEkko systems which are bistatic radar systems with the transmitter and receiver separated into different units. We first tested the systems with antenna frequencies of 50, 100, 200 and 250 MHz in a rough sweep of the site to assess which is suitable for locating the drainage tile network in terms of penetration depth and resolution. We later utilized the 250 MHz antenna with a fixed transmitter and receiver antenna separation of 0.4 m for surveying the entire site. We towed the GPR system consisting of the antennas and a DVL 500 data logger behind a utility terrain vehicle to allow us to cover the entire site of approximately 1.1 km^2. We also utilized 2 units of an Emlid Reach RS2 differential GPS system (Emlid Ltd., Hong Kong.) for a real time kinematic (RTK) positioning with one positioned at a fixed base while the other was attached to the GPR system as a rover. As the location and approximate direction of the drainage tiles were not known a priori, we conducted an initial survey pushing the GPR system in different directions to obtain an overview of the general trend of the tiles. On observing the major tile directions to be in the North – South and East-West directions with a few diagonals (Northeast – Southwest direction), we later acquired GPR transects in both the North – South and the East – West directions (Fig. 2) to better capture potential

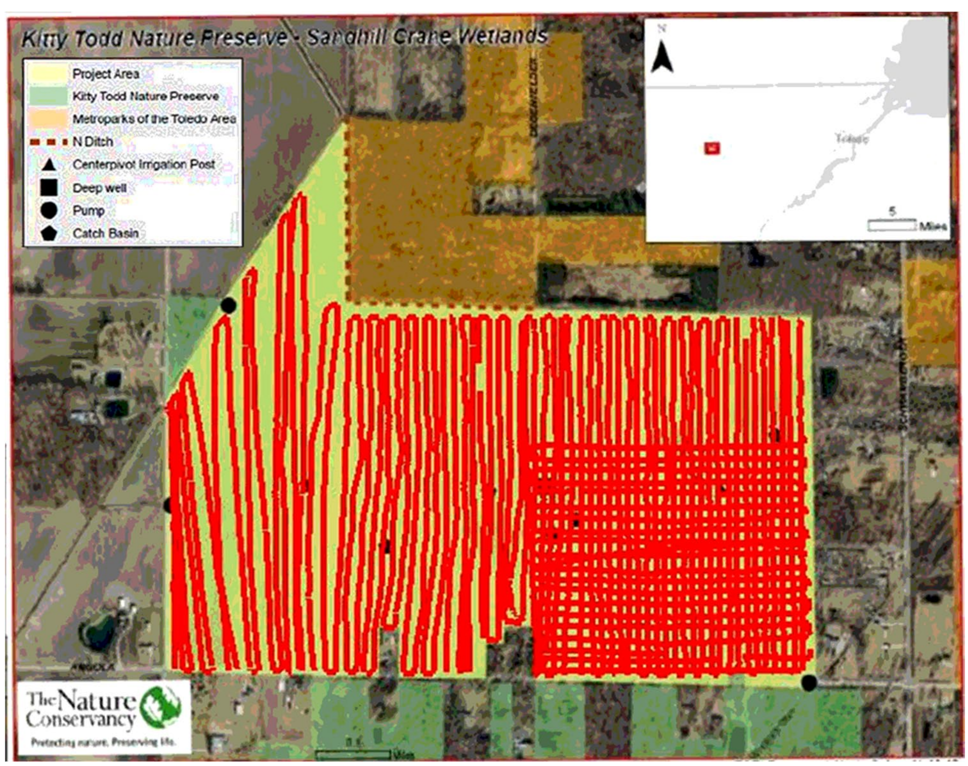

Fig. 2 Study site with GPR transects (red lines) both in the North – South direction and the East – West direction overlain on a base map of the study site (created by Sakas (2019), The Nature Conservancy)

tiles running in different directions. A major challenge in using GPR to locate drainage tiles at a large field scale is the choice of an appropriate transect spacing to adequately delineate the tile network. For this study, we assessed the impact of transect spacings on resolving the tile network by conducting different small surveys within the field with transect spacing of 2.5, 5, 10, 20 and 25 m. We maintained a spacing of 20 m between transects in the North-South direction and 25 m for transects in the East – West direction. We collected common-offset measurements with a spacing of 0.05 m, activated by an odometer wheel attached to a towing cart with an acquisition time window of 100 ns. To reduce ambient electromagnetic noise and improve signal to noise ratio, we collected 4 stacks per sample and towed the GPR system at an average speed of 6.5 km per hour following recommendations by Allred et al. (2005). The entire GPR surveys were conducted between May and September 2020 with the detailed survey involving the acquisition of about 100 transects over the 1.1 km^2 area taking 5 effective field days. During this time, the field site was covered by cover crops. The soils were generally dry with slightly wet regions at the eastern and western edges of the field.

All GPR data were processed using the Sensors & Software Inc.'s EKKO_Project software following standard GPR processing for subsurface utility identification (Annan 2009; Jazayeri et al. 2018). We applied a time-zero correction and then 'dewowed' the signals with a high-pass filter to remove low-frequency noise caused by inductive coupling effects or dynamic range limitations of the antennas (Annan 2009; Malenda et al. 2019). We applied a Spherical Exponential Calibrated Compensation (SEC 2) time gain to all transects' signals to compensate for signal losses due to spherical spreading and ohmic losses caused by soil conductivity. We set the signal attenuation at 8 dB/m to increase gains for deeper signals while start and maximum gains were set at 4.5 and 1000 respectively. To estimate the depth of the tiles, we utilized the velocity calibration approach following the hyperbola fitting technique (Sagnard and Tarel 2016; Dou et al. 2017) implemented in the Ekko_Project version 5 software.

After applying the outlined processing steps to the GPR datasets, we interpreted each profile for the presence of a characteristic hyperbola indicating possible drainage tile. We picked the peak of each hyperbola to represent the center of the drainage tile assuming that the GPR system crossed the tile perpendicularly. By plotting the center of each hyperbola on a map we were able to delineate the drainage tile network.

Results

Visible light images (Fig. 3a) obtained for our study site show color patches with contrasting light and dark colored stripes reflective of variation in soil condition and vegetation. The light colored, close stripes linear features are related to tillage lines while the dark green parallel linear features with a near uniform spacing were interpreted as drainage tiles. The dark green parallel linear features were also observable to the naked eye in the field as stripes with more greenish (healthy) cover crops preferentially lined

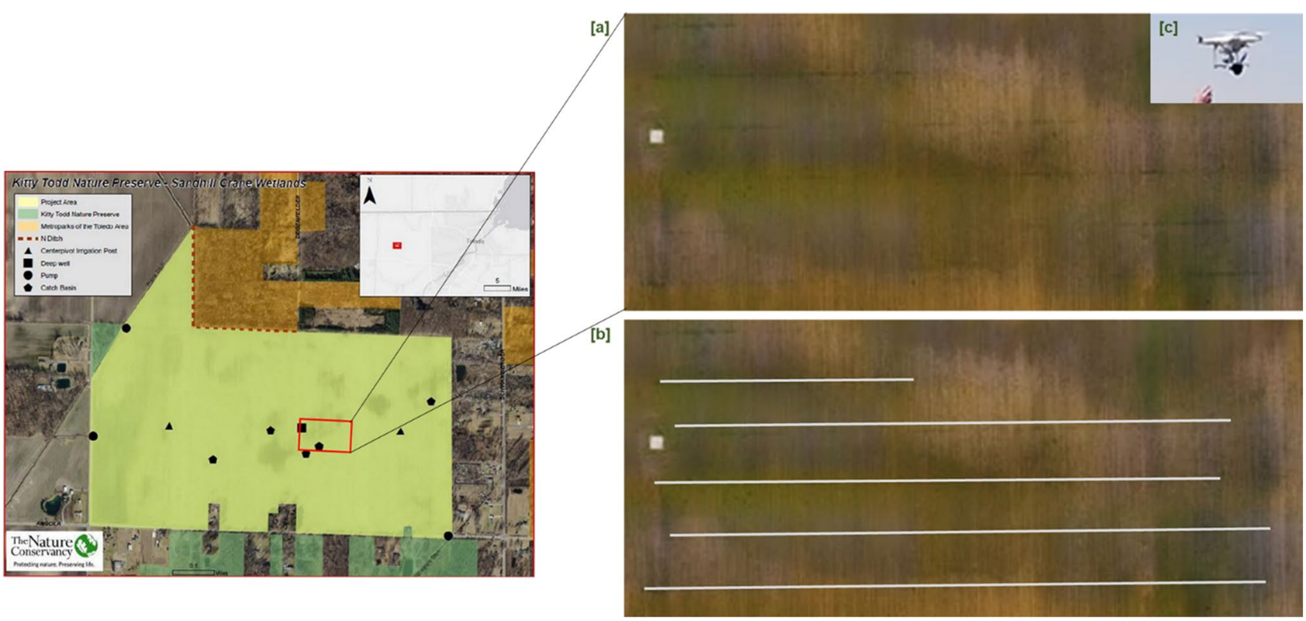

Fig. 3 (**a**) Section of visible image with dull color linear feature interpreted as drainage tile with a parallel network (in **b**). The UAV used to acquire image the site is shown in (**c**)

along a straight path. When traced (Fig. 3b), these parallel linear features show a consistent spacing of about 15 m which is typical of spacing between drainage tiles in the field in the region (Gedlinske 2014). The identified stripes (interpreted as drainage tiles) are discontinuous in some areas or at least difficult to identify.

Thermal infrared images of the study site are shown in Fig. 4 with closely spaced red, yellow, and blue color stripes with dull color stripes cutting across them. In the color table used in these images, brighter colors in the false color thermal infrared images are indicative of warmer areas while dull or darker colors are indicative of cooler areas. Drainage tiles due to their water content are cooler and are expressed as dull color linear structure in the infrared image (Fig. 4). Figure 4 shows two linear dull color parallel feature with one of them imaged at a high resolution (Fig. 4) interpreted as drainage tiles.

Representative GPR profiles from transects both in the N-S and E-W directions are shown in Fig. 5. Concave downward hyperbolas are observed in each of the profiles at an approximate depth of 1.0 m. The hyperbolas interpreted as the top center point across a drainage tile (when crossed perpendicularly) are in most cases spaced evenly at an approximate distance of 15 m. All GPR profiles (sixty-six in the N-S direction and thirty-one in the E-W) were carefully analyzed and the position of all hyperbolas highlighted with their coordinates and depths. Besides the hyperbolas, several linear and dipping reflectors are visible in the GPR profiles which are not the focus of this study but are currently being analyzed in an ongoing study to understand the soil stratigraphy. However, a consistent linear reflector at a depth of 50–75 cm visible in the GPR profile prior to applying the standard background subtraction is interpreted as the water table. We exported these details to a Google Earth map and overlaid them on a pre-restoration base map of the site (Fig. 6) to show the location where the GPR system crossed possible drainage tiles with blue dots for profiles in the N-S direction and pink for profiles in the E-W direction (Fig. 6). Although hyperbolas in GPR profiles could also result from other subsurface objects e.g., pebbles with contrasting dielectric permittivity, similar hyperbolas aligning along parallel profiles are interpreted as linear features which represent drainage tiles. We joined similar

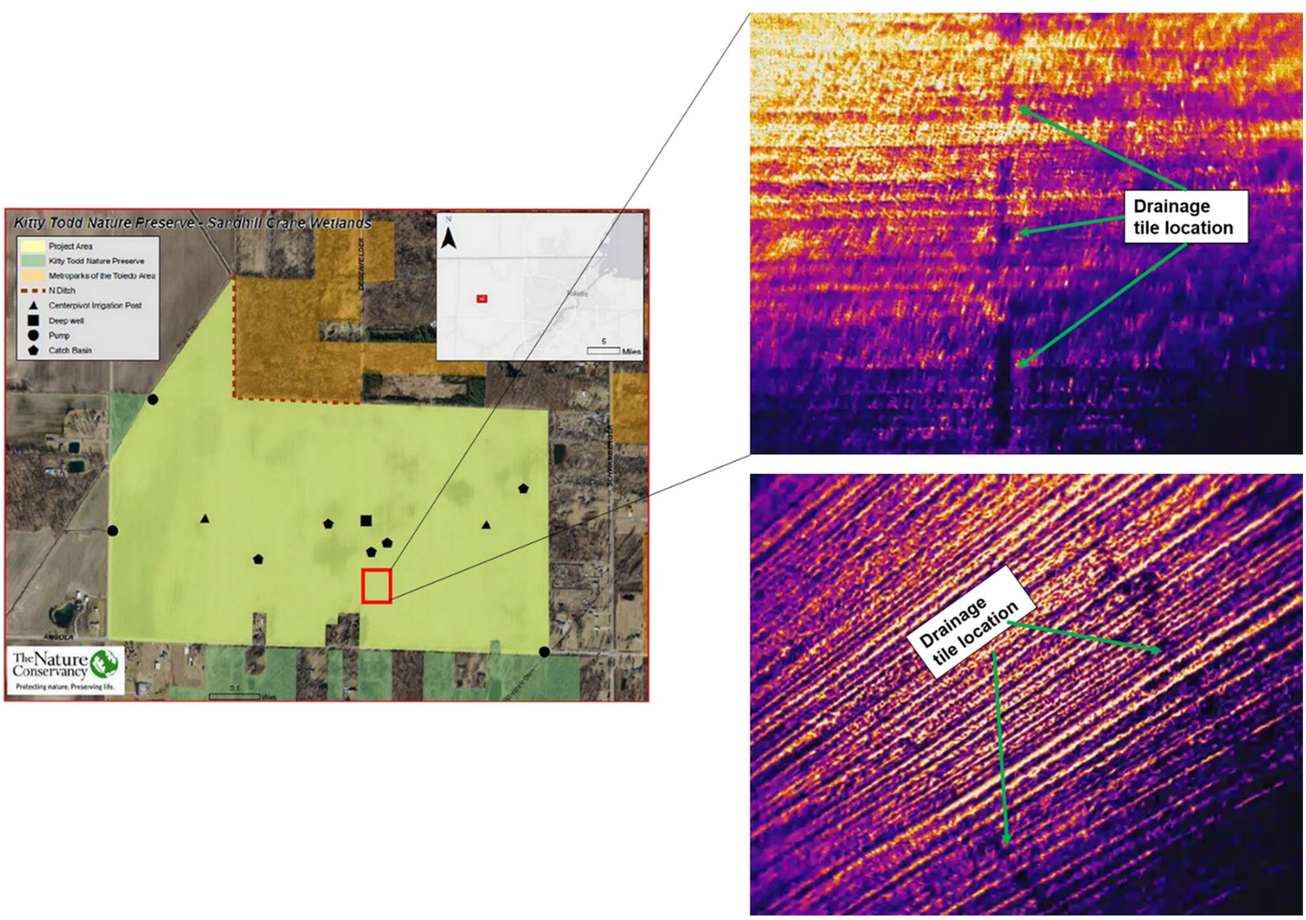

Fig. 4 A section of thermal infrared images of the study site with two identified drainage tile [lower right] and one of them imaged at a higher resolution [upper right]

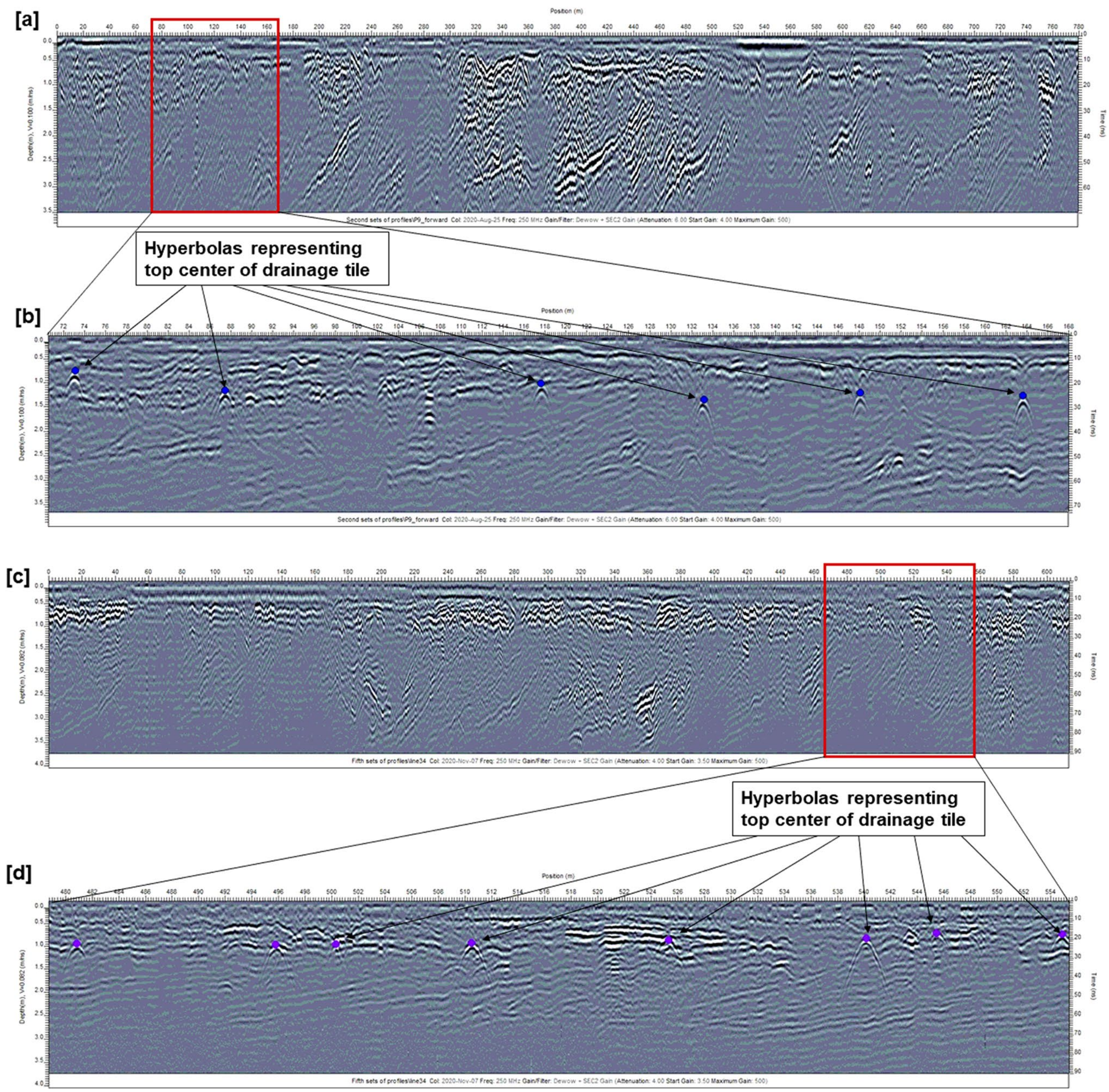

Fig. 5 Selected GPR profiles in the North – South Direction ((**a**) and (**b**)) and East – West Direction ((**c**) and (**d**)), showing measured hyperbolas representing reflection from a point source. Sub figures (**b**) and (**d**) are higher resolution sections of (**a**) and (**c**) respectively, while points on each hyperbola in (**b**) and (**d**) represent the center point at which the transmitter and receiver crossed the point object

hyperbolas with blue lines (Fig. 7) to obtain the position and network of drainage tiles in the field.

Discussion

The delineated drainage tiles at the study site follows a parallel pattern with a spacing between tiles of 15 m (Fig. 7). Tiles aligned in the E-W direction are present in the Eastern (marked A and B in Fig. 7), Western (marked G in Fig. 7) and North Central (marked D in Fig. 7) portion of the site corresponding to areas observed to be flooded in the spring. The tiles in these regions were likely installed and connected to pumps located both at the eastern and western segments to drain these sections of the field during flooding to allow farming activities (oral communication with neighbors at the site). Transects acquired in the E-W direction at the Eastern half of the site also show tiles aligned North – South

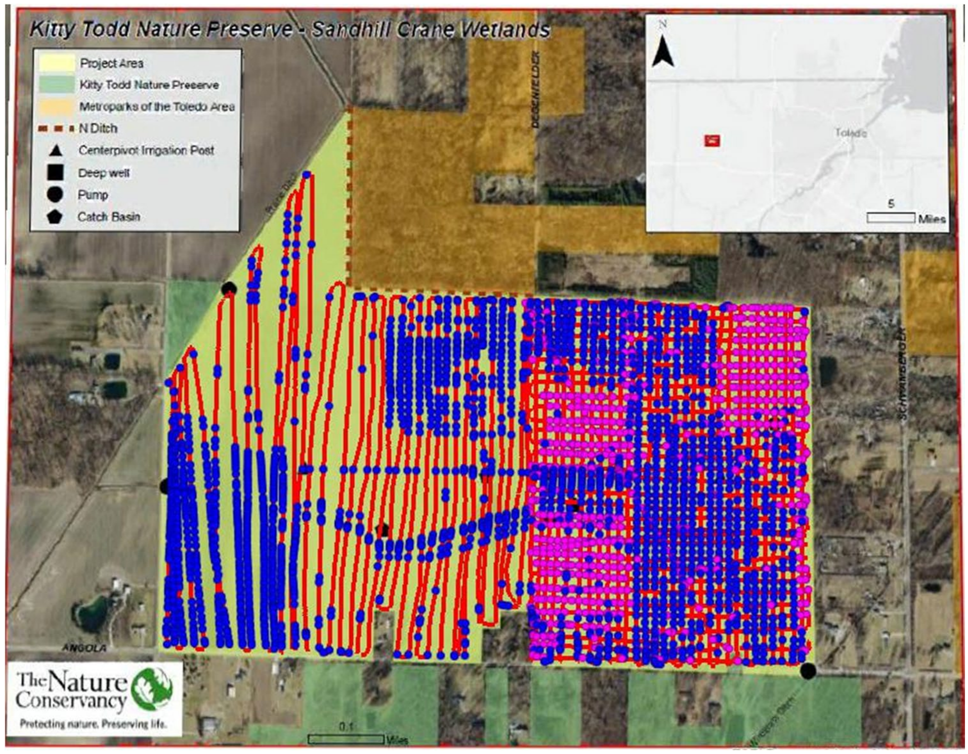

Fig. 6 Picked hyperbola center point for all GPR transects overlain on a base map of the study site (created by Sakas (2019), The Nature Conservancy). Blue dots represent center of hyperbolas on North – South transect while pink dots represent those for East – West transects

(marked C and E in Fig. 7) close to the center and at the upper right of the site (Fig. 7). These tile lines are likely feeder lines connected to the tile lines aligned East – West. Our study shows that for field sites with no prior knowledge of the tile network, acquiring the GPR transects in both North – South and East – West directions is more appropriate. This increases the field efforts though, which ensures the tile network is captured appropriately. Delineated drainage

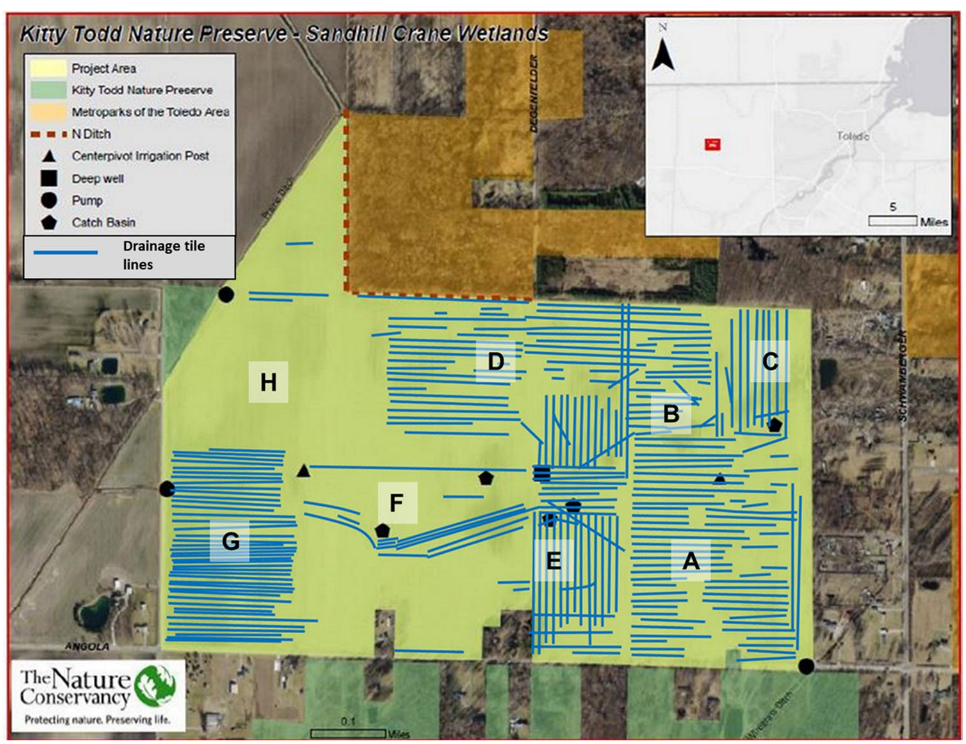

Fig. 7 Interpreted drainage tile locations overlain on base map of the site (created by Sakas (2019), The Nature Conservancy). Drainage tile lines were interpreted in both East-West and North-South directions

tile lines shown in Fig. 7 show discontinuities which are areas where no hyperbola was observed in the GPR profile or they were difficult to identify. This could be due to broken tiles or low contrast in dielectric properties between the tile and surrounding soil. The tiles are expected to have been installed following a near straight path.

Generally, the visible and thermal infrared images capture the location and trend of the drainage tiles with the thermal infrared images providing clearer contrast related to the tiles. However, discontinuities in the identified tile lines were noted more in the visible images compared to the thermal infrared. Factors including varying soil water, vegetation, ambient temperature, and evapotranspiration influence on the reflectance and radiation of electromagnetic waves, can all affect measurements (Allred et al. 2018; Allred et al. 2020; Kratt et al. 2020). Despite these limitations, both visible and thermal infrared imaging sufficiently imaged the tiles at our test site. The possibility to mount these cameras simultaneously on a UAV allow for fast acquisition of multiple data sets. For this study, we acquired the thermal images without a GPS system attached to the UAV which makes registering and mosaicking the thermal images more time consuming and problematic than processing the visible images. Hence, the precise locations from the thermal imagery are not as reliable as the other visible images as significant post processing effort would be needed to extract and align the acquired thermal images. This challenge can however be addressed by equipping the UAV with an appropriate differential GPS system such as the real time kinematics (RTK) and Wide Area Augmentation (WAA) systems as recommended by Freeland et al. (2019). It should however be noted that the visible and thermal images identified all of the same drainage tiles as the GPR (Figs. 3 and 4). While each of these techniques can be used independently, we recommend combining them to improve results and maximize data value in line with recommendations by Koganti et al. (2021).

Compared to the GPR technique, the UAV based visible and infrared imaging allows for covering large scale field sites within a short time. However, the GPR technique provides a highly accurate location of the tiles both horizontally and vertically (Figs. 5, 7 and 8) allowing a good estimation of the depth at which the tiles are buried. While UAV based methods possess a clear advantage over the land based geophysical method in terms of data acquisition time, for open fields (e.g., during post-harvest seasons), towing the GPR with a UTV at a speed of approximately 6.5 km/h significantly reduced data acquisition time. For example, the GPR data acquisition for this study took 5 effective days using a UTV to tow the GPR system while flight time took 8–12 h. Data processing, though dependent on experience, is also relatively faster with the UAV images.

Results of this study validates the recent study by Koganti et al. (2021) where they recommended UAV based imagery

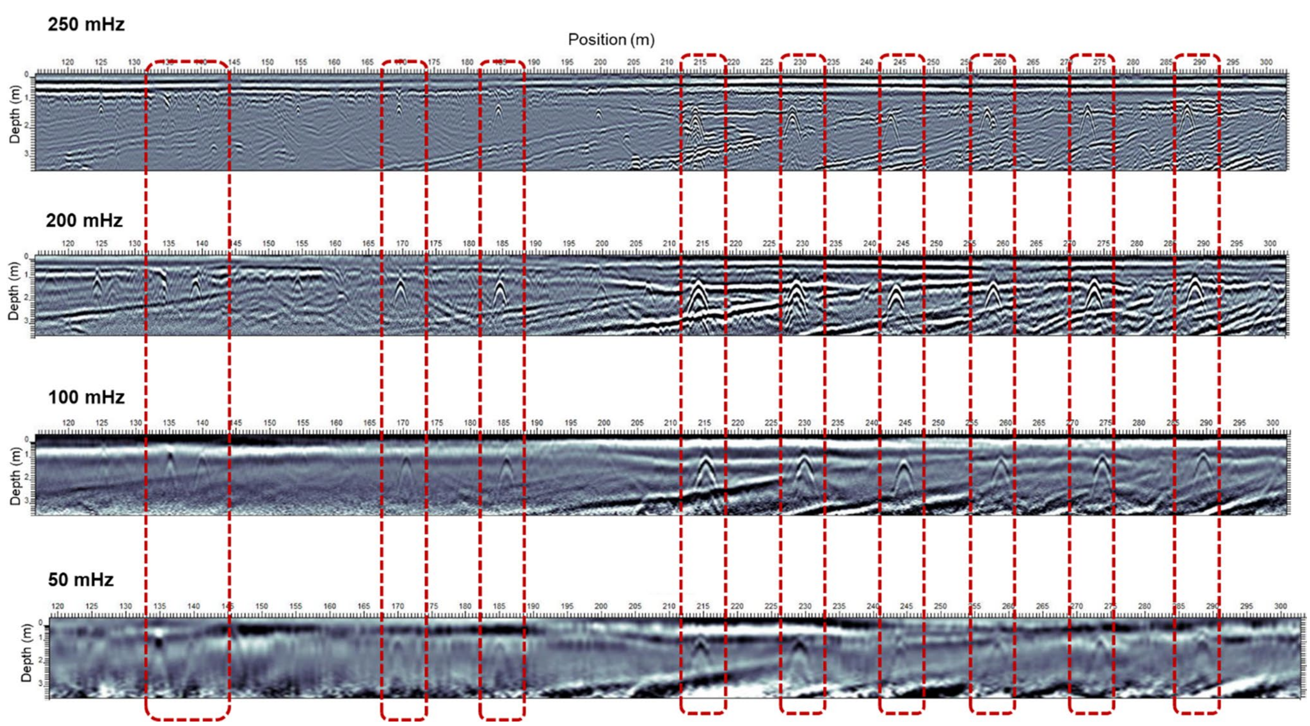

Fig. 8 Comparing different signals from different antenna frequencies with 200 MHz at the top, 100 MHz at the middle and 50 MHz at the bottom. Red dash-line box drawn over hyperbolas for easy comparison

and GPR as complimentary techniques for locating drainage tiles. For this study, the drainage tiles appear as dark green parallel features (lines) in the visible color images (Fig. 3). This corresponds to greener patches of preferentially established cover crop forming linear features observable to the naked eye. This result is similar to that from "site 2 and 3" as reported in Koganti et al. (2021) which is a direct consequence of preferential infiltration in the soil above the drainage tile creating more optimal soil-water-air conditions for plant growth directly above the tiles (Koganti et al. 2021). Similarly, the drainage tiles appear in the thermal infrared images (Fig. 4) as colder anomalies along the preferentially established cover crops validating earlier studies on the usefulness of infrared images to infer crop health (Kullberg et al. 2017; Koganti et al. 2021). With the sandy soil and field with cover crops, GPR worked well for both locating the position and estimating the depths of the tiles. Similar results were also reported in Koganti et al. (2021) except for their "site 4" where GPR failed to successfully locate the drainage tile due to limited depth of penetration associated with the conductive soils at their site. Generally, this study confirms earlier recommendations for using GPR as a viable non-destructive tool for locating drainage tiles and estimating their depth. Combining GPR with UAV based imagery will increase the efficiency of using these non-destructive technologies for locating drainage tiles in large farm fields covering hundreds of hectares (Koganti et al. 2021). However, in the absence of a UAV imaging system, towing the GPR system installed on a smart cart or sledge behind a UTV equipped with a differential GPS system as demonstrated in this study could be a useful alternative to efficiently cover such large farm fields.

In using GPR to locate drainage tiles, the choice of antenna frequency is not trivial as this in combination with soil properties and vegetation impact the resolution and ease of data acquisition. In this study, we compared four different Sensors and Software, Inc.'s PulseEkko antennas with center frequencies of 50 MHz, 100 MHz, 200 MHz and 250 MHz. Both 250 MHz and 200 MHz antennas clearly capture the hyperbolas representing the point where we crossed the drainage tile (Fig. 8). Although, the 250 MHz antenna data shows higher resolution, all tiles located by it were also resolvable by the 200 MHz antenna in this study. The 100 MHz antenna also captured over 80% of drainage tiles detected with the 250 MHz and 200 MHz antennas. While 60% of the tiles located by the 250 MHz antenna are also identifiable in the GPR profile acquired with the 50 MHz antenna, the hyperbolas appear blurred which would make interpretation difficult in areas with no prior information on the location of the tiles. Also, the 50 MHz, 100 MHz, and 200 MHz PulseEkko GPR antennas are unshielded which make them more challenging (mostly the 50 MHz and 100 MHz antennas which are over 0.5 m long) to tow over vegetated fields. Based on resolution and ease of field measurement, we recommend using the 250 MHz shielded antennas where possible for measurements within the OOR or areas with similar soil properties and conditions. However, 200 MHz and 100 MHz antennas may be used but with caution during field data acquisition and more attention to processing and interpretations.

The choice of spacing between parallel GPR transects is an important decision for surveys aimed at locating drainage tile networks at large farm fields. A finer spacing between transects may improve the likelihood of mapping potential continuity/discontinuity along the tile lines compared to coarser spacing, however, such finer spacing would significantly increase the data acquisition time which may not be feasible for a large field scale. For this study, we tested profile spacing of 2.5, 5.0, 10.0, 20 and 25 m in an initial test survey at the southeastern section of the field prior to the full survey. The tile lines were observed to be mainly continuous extending over 50 m hence, the decision for transect spacing of 20 m and 25 m in the North-South and East-West direction respectively. While these transect spacings sufficiently mapped the tile network at most sections of the field, the few gaps between delineated tile lines observed in the eastern (marked A and B in Fig. 7) and northcentral (marked D in Fig. 7) section of the field may have been better resolved by finer transect spacing, assuming sufficient GPR penetration depth and signal strength.

While location and network of drainage tiles can be interpreted from picking the peak (center point) of an observed hyperbola in the GPR profile and connecting similar hyperbola peaks across parallel profiles, the tile network can also be interpreted using the GPR amplitude maps (Allred et al. 2005; Karásek and Nováková 2020). However, the resolution of the GPR amplitude map generated by interpolating across profiles decreases with increased profile spacing. In this study, we also assessed a suitable transect spacing for generating amplitude maps sufficient to reveal the tile network at the site by comparing measurements using spacing of 2.5, 5.0, 10.0, 20 m and 25 m at a small section of the field site. While measurements with transects spacing of 10, 20 and 25 m sufficiently delineated the drainage tile network, their amplitude maps show smearing effects due to the larger interpolation distance between lines. GPR amplitude maps are used to show correlation in the 2D distribution of the amount of electromagnetic radar energy reflected back to the surface from a two−way travel time (Allred 2013). GPR amplitude maps are useful in confirming the drainage tile network (Karásek and Nováková 2020). In our study, amplitude maps generated from grid measurements using both 2.5 m and 5 m spacing between transects in the x- and y-directions in a 100 m X 100 m domain at the eastern section of our site reveal the tile network (Fig. 9). The stronger amplitude represented by dark coloration is stronger reflected energy. A grid with 5 m transects spacing sufficiently capture the tile network and is recommended.

Results of this study validate earlier results showing UAV mounted visible and thermal infrared (Allred et al. 2020) and ground penetrating radar (Allred et al. 2004) locate drainage tiles and demonstrates that these techniques can be used within the Oak Openings Region. We, however, recommend further testing of the visible and thermal infrared imaging under different seasons and soil conditions including varying soil water content, vegetation cover and time of day.

The location and network of drainage tiles delineated in this study will guide current efforts to restore the site from an old agricultural field to its original wetland (wet prairie) conditions. Figure 7 in a digitized form will guide site managers in locating tile outlets for decommissioning (blocking to prevent outflow). It should however be noted that the current drainage tile map shows gaps in areas marked F and H (Fig. 7). These regions likely contain tiles running in the north-south direction which can be mapped by completing the east-west transects of the GPR survey. Recall that only the first eastern half of the site was covered in both north-south and east-west transects (Fig. 2). The site's drainage tile location map (Fig. 7) will also be useful in the future in locating individual tiles should there be need to block such tiles due to potential blow-out resulting from blockage of tile outlets. There is also the need to improve the understanding of the site's hydrology which has been largely altered by the artificial tile drainage and intense farming. Results of this study also provides location and depth of tiles that can be included in a groundwater flow and transport model for predicting the hydrological response (including potential flooding and flow redistribution) due to drainage tiles decommissioning and other restoration activities.

Conclusions

Pre-restoration wetland characterization sometimes requires knowing the locations and depths of drainage tiles when the restored site is an old agricultural field with a history of tile drainage. When farm utility maps showing the tile locations are missing, locating these tiles manually is impracticable at farm field scale. Our study shows that combining remote sensing and ground based geophysical techniques provide an efficient framework for locating the tiles.

In this study, we used visible light and infrared imaging to locate drainage tiles and map their network within the Oak Openings Region of Ohio. Mounting the appropriate cameras on a UAV platform allows for fast data acquisition which can be used to cover a large-scale field site within a short duration. We observed discontinuities in interpreted drainage tiles from both visible and thermal infrared images which can be related to the effects of varying moisture content and vegetation type. Targeting optimum field conditions for visible and thermal infrared imaging for locating drainage tiles to minimize these effects is a major challenge and requires further testing at sites with different soil, vegetation, and hydrological properties.

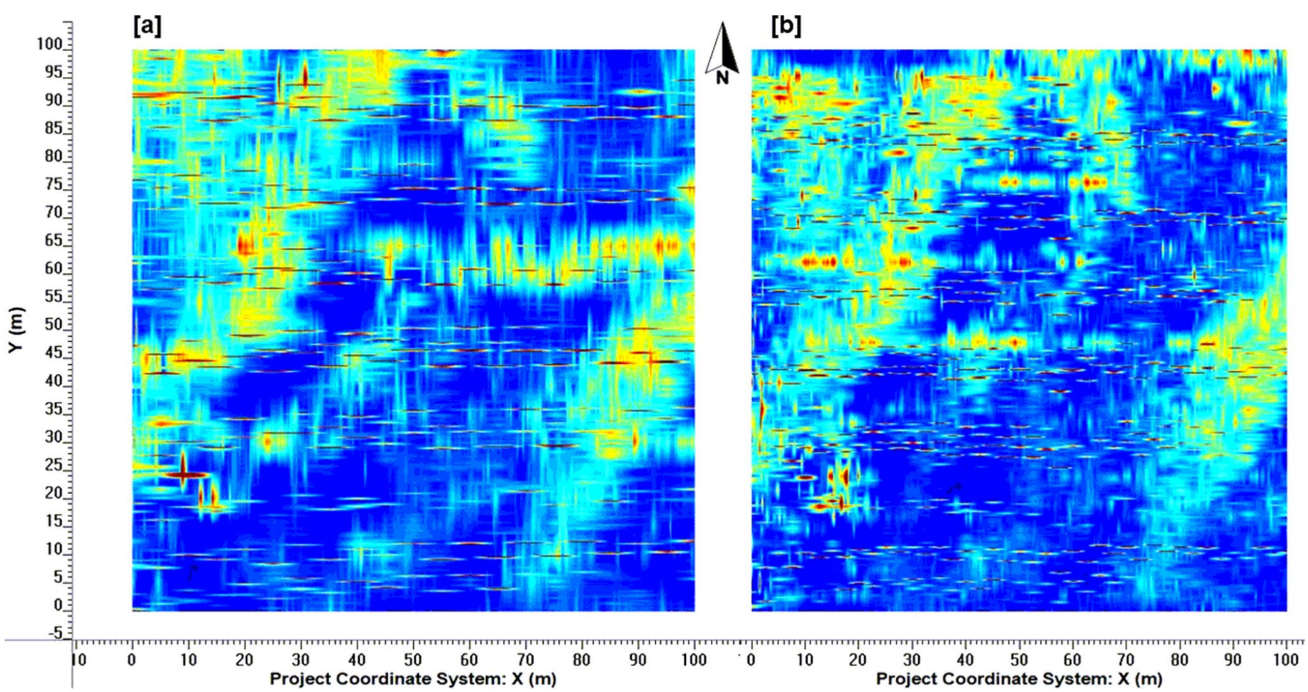

Fig. 9 GPR amplitude map of a 100 m × 100 m grid at the eastern section of the site (**a**) Grid acquired with 5 m spacing and (**b**) 2.5 m spacing

Our study also shows ground penetrating radar to be a more effective geophysical technique for obtaining details of drainage tile location and depth within the Oak Openings Region. This is in line with other studies at sites with similar soil properties within the Midwestern United States (Allred et al. 2004, 2005). However, for large field scale application, we recommend towing the GPR behind a vehicle at a speed of about 7 km/h to reduce field efforts and data acquisition times. For large field scale application as demonstrated in this study, a profile spacing of 20 m reveals tile location and network, with a trade off on amplitude maps which are useful for confirming the tile network at a high resolution. Where higher resolution is desired, a maximum profile spacing of 5 m is recommended.

This study also shows that geophysical sensing using suites of electromagnetic radiation (visible, infrared and radio waves) provides non-invasive approaches for locating drainage tiles in old farm fields within the OOR. With current wetland restoration efforts within Ohio aimed at reducing nutrient loads into Lake Erie, there is need to locate drainage tiles within these old farm fields, and this study demonstrated the application of geophysical techniques for such purpose. A delineated drainage tile network (Fig. 7) can be incorporated into a flow and transport model for the site and will be useful for predicting post-restoration hydrological regimes.

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Authors' Contributions AMB is an undergraduate student researcher who acquired and analyzed the data and wrote the initial draft of the manuscript as part of her honors thesis. RHB acquired and analyzed the UAV based data and reviewed the manuscript prior to submission while KOD developed the research ideas, acquired, and analyzed data, wrote manuscript, and supervised AMB.

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Data Availability The raw datasets acquired and analyzed during the current study are available from the corresponding author on reasonable request.

Code Availability Not applicable.

Declarations

Ethics Approval Ethics approval was not required for this study according to the University of Toledo research ethics policy and the Ohio State legislation.

Consent to Participate Not applicable as this study does not involve human subjects.

Consent for Publication All authors gave consent to publish results of this work. The study does not involve patients and human subjects hence to consent required.

Conflict of Interest/Competing Interests The authors have no conflict of interest to declare.

References

Abdel-Hady M, Abdel-Hafez MA, Karbs HH (1970) Subsurface drainage mapping by airborne infrared imagery techniques. Proceedings of the Oklahoma Academy of Science 50:10–18

Abella S, Jaeger J, Gehring D, Jacksy R, Menard K, High K (2001) Restoring historic plant communities in the Oak Openings Region of Northwest Ohio. Ecological Restoration 19:155–160. https://doi.org/10.3368/er.19.3.155

Allred BJ (2013) A GPR agricultural drainage pipe detection case study: effects of antenna orientation relative to drainage pipe directional trend. Journal of Environmental and Engineering Geophysics 18(1):55–69. https://doi.org/10.2113/JEEG18.1.55

Allred B, Fausey NR, Peters L, Chen CC, Daniels J, Youn H (2004) Detection of buried agricultural drainage pipe with geophysical methods. Applied Engineering in Agriculture 20(3):307–318. https://doi.org/10.13031/2013.16067

Allred B, Daniels J, Fausey NR, Chen CC, Peters L, Youn H (2005) Important considerations for locating buried agricultural drainage pipe using ground penetrating radar. Applied E ngineering in Agriculture 219(1):71–87. https://doi.org/10.13031/2013.17915

Allred B, Eash N, Freeland R, Martinez L, Wishart D (2018) Effective and efficient agricultural drainage pipe mapping with UAS thermal infrared imagery: a case study. Agricultural Water Management 197:132–137. https://doi.org/10.1016/j.agwat.2017.11.011

Allred B, Martinez L, Fessehazion MK, Rouse G, Williamson TN, Wishart D, Koganti T, Freeland R, Eash N, Batschelet A, Featheringill R (2020) Overall results and key findings on the use of UAV visible-color, multispectral, and thermal infrared imagery to map agricultural drainage pipes. Agricultural Water Management 232:106036. https://doi.org/10.1016/j.agwat.2020.106036

Andreas B, Knoop J (1992) 100 years of changes in Ohio Peatlands. The Ohio Journal of Science 92(5): 130–138. http://hdl.handle.net/1811/23525

Annan AP (2009) Electromagnetic principles of ground penetrating radar. In: Jol HM (ed) Ground penetrating radar theory and applications. Elsevier, Amsterdam, pp 4–38

Beauchamp KH (1987) A history of drainage and drainage methods. In: Pavelis GA (ed) Farm drainage in the United States. History, Status, and Prospects, Economic Research Service (DOA), Washington, D.C., pp 13–28

Becker AM, Becker RH, Doro KO (2020) Pre-restoration shallow subsurface characterization of a Wetland in the Oak Openings Region, Ohio using drone- and land-based geophysical techniques. AGU Fall Meeting Abstracts 2020:NS011–NS005

Brewer LG, Vankat JL (2004) Description of Vegetation of the Oak Openings of Northwestern Ohio at the Time of Euro-American Settlement. The Ohio Journal of Science 104(4): 76–85. http://hdl.handle.net/1811/25159. Accessed 22 Mar 2021

Chow TL, Rees HW (1989) Identification of subsurface drain locations with ground-penetrating radar. Canadian Journal of Soil Science 69(2):223–234. https://doi.org/10.4141/cjss89-023

Cooley E, Herron C (2015) Fixing Tile Blowouts: What You Need to Know, UW Extension University of Wisconsin-Extension, Pigeon Falls

Dou Q, Wei L, Magee DR, Cohn AG (2017) Real-time hyperbola recognition and fitting in GPR data. IEEE Transactions on Geoscience and Remote Sensing 55(1):51–62. https://doi.org/10.1109/TGRS.2016.2592679

Easton ZM, Bock E, Collick AS (2016) Factors when considering an agricultural drainage system, communications and marketing, College of Agriculture and Life Sciences, Virginia Tech, Blacksburg, VA. VT/0117/BSE-20

Freeland R, Allred B, Eash N, Martinez L, Wishart D (2019) Agricultural drainage tile surveying using an unmanned aircraft vehicle paired with real-time kinematic positioning—a case study. Computers and Electronics in Agriculture 165:104946. https://doi.org/10.1016/j.compag.2019.104946

Gedlinske BB (2014) Agricultural drainage tiles: an overview of their use, benefits, and effect on hydrology and water quality. Other Faculty and Staff Publications. https://scholarworks.uni.edu/other_facpub/1. Accessed 22 Mar 2021

Gökkaya K, Budhathoki M, Christopher SF, Hanrahan BR, Tank JL (2017) Subsurface tile drained area detection using GIS and remote sensing in an agricultural watershed. Ecological Engineering 108(Part B):370–379. https://doi.org/10.1016/j.ecoleng.2017.06.048

Higgins JB (2003) Emergy analysis of the Oak Openings region. Ecological Engineering 21(1):75–109. https://doi.org/10.1016/j.ecoleng.2003.09.007

Jazayeri S, Klotzsche A, Kruse S (2018) Improving estimates of buried pipe diameter and infilling material from ground-penetrating radar profiles with full-waveform inversion. Geophysics 83(4):H27–H41. https://doi.org/10.1190/geo2017-0617.1

Kaatz MR (1955) The black swamp: a study in historical geography. Annals of the Association of American Geographers 45(1):1–35. https://doi.org/10.1111/j.1467-8306.1955.tb01481.x

Karásek P, Nováková E (2020) Agricultural tile drainage detection within the year using ground penetrating radar. Journal of Ecological Engineering 21(4):203–211. https://doi.org/10.12911/22998993/119976

Koganti T, Van De Vijver E, Allred BJ, Greve MH, Ringgaard J, Iversen BV (2020) Mapping of agricultural subsurface drainage systems using a frequency-domain ground penetrating radar and evaluating its performance using a single-frequency multi-receiver electromagnetic induction instrument. Sensors (Basel) 20(8):3922. https://doi.org/10.3390/s21082800

Koganti T, Ghane E, Martinez LR, Iversen BV, Allred BJ (2021) Mapping of agricultural subsurface drainage systems using unmanned aerial vehicle imagery and ground penetrating radar. Sensors 21(8):2800. https://doi.org/10.3390/s21082800

Kratt CB, Woo DK, Johnson KN, Haagsma M, Kumar P, Selker J, Tyler S (2020) Field trials to detect drainage pipe networks using thermal and RGB data from unmanned aircraft. Agricultural Water Management 229:105895. https://doi.org/10.1016/j.agwat.2019.105895

Kullberg EG, DeJonge KC, Chávez JL (2017) Evaluation of thermal remote sensing indices to estimate crop evapotranspiration coefficients. Agricultural Water Management 179:64–73. https://doi.org/10.1016/j.agwat.2016.07.007

Lai WWL, Dérobert X, Annan P (2018) A review of ground penetrating radar application in civil engineering: a 30-year journey from locating and testing to imaging and diagnosis. NDT & E International 96:58–78. https://doi.org/10.1016/j.ndteint.2017.04.002

Lenhart CF, Lenhart PC (2014) Restoration of Wetland and Prairie on farmland in the former great black swamp of Ohio, U.S.A. Ecological Restoration 32(4):441–449. https://doi.org/10.3368/er.32.4.441

Lester J, Bernold LE (2007) Innovative process to characterize buried utilities using ground penetrating radar. Automation in Construction 16(4):546–555. https://doi.org/10.1016/j.autcon.2006.09.004

Malenda HF, Sutfin NA, Guryan G, Stauffer S, Rowland JC, Williams KH, Singha K (2019) From grain to floodplain: evaluating heterogeneity of floodplain hydrostatigraphy using sedimentology, geophysics, and remote sensing. Earth Surface Processes and Landforms 44(9):1799–1815. https://doi.org/10.1002/esp.4613

Metwaly M (2015) Application of GPR technique for subsurface utility mapping: a case study from urban area of Holy Mecca, Saudi Arabia. Measurement 60:139–145. https://doi.org/10.1016/j.measurement.2014.09.064

Moore J (2016) Literature review: Tile drainage and phosphorus losses from agricultural land, Lake Champlain Basin program and New England interstate water pollution control commission, Grand Isle

Naz BS, Ale S, Bowling LC (2009) Detecting subsurface drainage systems and estimating drain spacing in intensively managed agricultural landscapes. Agricultural Water Management 96(4):627–637. https://doi.org/10.1016/j.agwat.2008.10.002

Rogers M, Cassidy J, Dragila M (2005) Ground-based magnetic surveys as a new technique to locate subsurface drainage pipes: a case study. Applied Engineering in Agriculture 21(3):421–426. https://doi.org/10.13031/2013.18461

Ruark MD, Panuska JC, Cooley ET, Pagel J (2009) Understanding and Locating Tile Drainage Systems. University of Wisconsin–Extension Discovery-Farms Fact Sheet GWQ 054

Sagnard F, Tarel JP (2016) Template-matching based detection of hyperbolas in ground-penetrating radargrams for buried utilities. Journal of Geophysics and Engineering 13(4):491–504. https://doi.org/10.1088/1742-2132/13/4/491

Sakas A (2019) Pre-restoration map of the Kitty Todd nature preserve - Sandhill Crane Wetlands. The Nature Conservancy, Toledo

Shade JW, Valkenburg N (1975) Comparison of the base flow and groundwater chemistry, Oak Openings Sand, Lucas County, Ohio. The Ohio Journal of Science 75(3):138–146

Smith D, King K, Williams M (2015) What is causing the harmful algal blooms in Lake Erie? Journal of Soil and Water Conservation 70(2):27A–29A. https://doi.org/10.2489/jswc.70.2.27A

Tlapáková L, Žaloudík J, Kulhavý Z, Pelíšek I (2015) Use of remote sensing for identification and description of subsurface drainage system condition. Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis 63:1587–1599. https://doi.org/10.11118/actaun20156305158

TNC (2020) The Sandhill Crane Wetland project series. Part 2: Hydrologic connections, The Green Ribbon Initiative (GRI) E-Newsletter, Online, https://mailchi.mp/267b0a1d8348/oak-openings-gri-november-newsletter?fbclid=IwAR1oAZBHlRg1q7xgAVvGJleNo7UKvoY0eauPAVHnI8Ee1r26PAIoCc2iTD0. Accessed 25 Mar 2021

Verma AK, Cooke RA, Wendte L (1996) Mapping subsurface drainage systems with color infrared aerial photographs. In Proceedings of the American Water Resource Association Symposium on GIS and Water Resources, Ft. Lauderdale, FL, USA, pp. 457–466

Wijayarathne DB, Gomezdelcampo E (2019) Using shallow groundwater modeling to frame the restoration of a wet prairie in the Oak Openings Region, Ohio, USA: GSSHA model implementation. Environmental Earth Sciences 78(6):216. https://doi.org/10.1007/s12665-019-8208-1

Williamson T, Dobrowolski EG, Meyer SM, Frey J, Allred B (2019) Delineation of tile-drain networks using thermal and multispectral imagery—implications for water quantity and quality differences from paired edge-of-field sites. Journal of Soil and Water Conservation 74(1):1–11. https://doi.org/10.2489/jswc.74.1.1

Woo DK, Song H, Kumar P (2019) Mapping subsurface tile drainage systems with thermal images. Agricultural Water Management 218:94–101. https://doi.org/10.1016/j.agwat.2019.01.031

Yannopoulos SI, Grismer ME, Bali KM, Angelakis AN (2020) Evolution of the materials and methods used for subsurface drainage of agricultural lands from antiquity to the present. Water 12(6):1767. https://doi.org/10.3390/w12061767