Recognizing Change in Hydrologic Functions and Pathways due to Historical Agricultural Use: Implications to Hydrologic Assessments and Modeling

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Abstract

Documenting the recovery of hydrologic functions following perturbations is important to addressing issues associated with land use change and ecosystem restoration. Floodplains on the Santee Experimental Forest were used historically for rice cultivation in the early 1700s; those areas now support bottomland hardwood forests typical of the region. Recently acquired LIDAR data for the Santee Experimental Forest were used to delineate remnant historical water management structures within the watersheds. Hydrologic functions and pathways were altered during the agricultural use period, with changes to depressional storage, streamflow and runoff routing. Since the late 1800s the land was left to revert to forests without direct intervention. The resultant bottomlands, while typical in term of vegetative structure and composition, still have altered hydrologic functions as a result of the historical land use. The application of high resolution LIDAR surface elevation data is expected to improve the basis for modeling and hydrological assessments.

Keywords: LIDAR data, historical land use, rice field, forest hydrology, drainage

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Introduction

Watersheds are an organizing framework for the assessment of hydrologic and ecological functions of the landscape. Resource data characterizing the watersheds is the basis for those assessments, and their resolution may affect results and interpretations. In this paper we illustrate how the recognition of historical land use features on the landscape, as a result of high resolution spatial data, affects our understanding of hydrologic processes and pathways. We use hydrologic modeling as an illustration because resolution of the resource data (e.g., soils, land use, topography, hydrography, vegetation) used as model inputs and the model design may affect interpretations. Most process-based models require some form of calibration or validation prior to applications; that calibration process typically involves modifying parameters or coefficients to achieve reasonable performance with respect to the calibration data. The assumption is that the reasonable agreement between the simulated and measured data (e.g., stream discharge) reflects an accurate representation of the processes within the watershed. However, seemingly accurate predictions of streamflow may be achieved by complementary errors from internal processes, resulting in inaccurate predictions of in-stream flows, water table depths, etc. within the watershed (Ambroise et al. 1995, Hatterman et al. 2004).

Floodplains in the coastal plain of the southeastern United States were the principal agricultural zone during the early colonial era (e.g., late 1600s and early 1700s). In South Carolina, the freshwater flood plains were used for rice cultivation. The development of the land included reservoirs, impoundments, diversion and distribution channels, diked fields, and collection ditches (Hilliard 1978). Those manmade features remain on the landscape, but they are not apparent in the resource data that are commonly used for hydrologic assessments and modeling. The common U.S. Geological Survey (USGS) topographic survey information (e.g., 1:24,000) is of insufficient resolution to demark these features; hence, what are the potential ramifications to hydrologic assessments? To address this question we analyze LIDAR (light detection and ranging) data and summarize field observations on the Santee Experimental Forest, SC.

Approach

Site

This work was conducted on the U.S. Forest Service Santee Experimental Forest (SEF) in South Carolina. The SEF is representative of the lower coastal plain landscape, characterized by low relief, mixed hardwood-pine flatwoods and bottomland hardwood floodplains. The surface microtopography is characterized by shallow pit and mount relief, but there are also remnant structures from past agricultural use. The SEF was part of the Cypress Barony that was conveyed by the Lords Proprietors in 1681; the land was subsequently divided into three plantations in 1707, which is when the agricultural development began. The floodplains of first-, second-, and third-order streams were developed into rice fields during the early 1700s. The present topographic, hydrographic, soils, and vegetative information for the forest conveys a uniform, low-relief landscape (Figure 1). These are the typical spatial data that are used for hydrologic modeling.

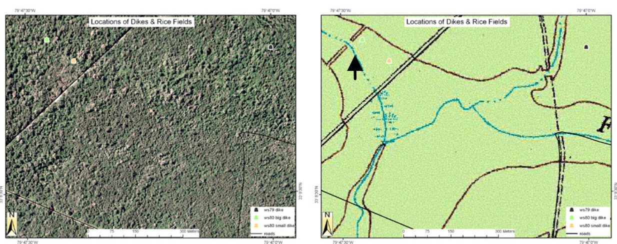

Figure 1. The aerial photograph (A, left), and USGS topographic map (1:24,000) (B, right), of a section of the Huger Creek, Santee Experimental Forest, discussed in this paper. The black arrow in 1B points to the same point in Figure 2.

LIDAR data

LIDAR data for the SEF were obtained in 2006 by Photo Science, Inc. The LIDAR data were collected at a 2-m point spacing or better and gridded with a 1-m resolution and a vertical accuracy of 0.07–0.15 m. The bare-earth return data were processed in ARCGIS to smooth the digital elevation model (DEM) and map potential stream channels using the hydrology set (flow direction, length).

Results and Discussion

Detection of historical land use features

The LIDAR data was effective in delineating the drainage and agricultural water management features associated with the rice cultivation in the floodplain (Figure 2). The features range in size from dikes and dams (0.2–1.6 m height) to ditches (0.2–0.3 m depth). It is important to note the prominence of these features on the watershed and to realize that their occurrence is within a watershed that has a total relief of less than 4 m. Within the context of this landscape, these dikes and ditches are major topographic features. The only reflection of these historical agricultural water management features on the current USGS topographic map (scale 1:24,000) are the major impoundment structures (see Figure 1B), but only a few of those existing structures are denoted.

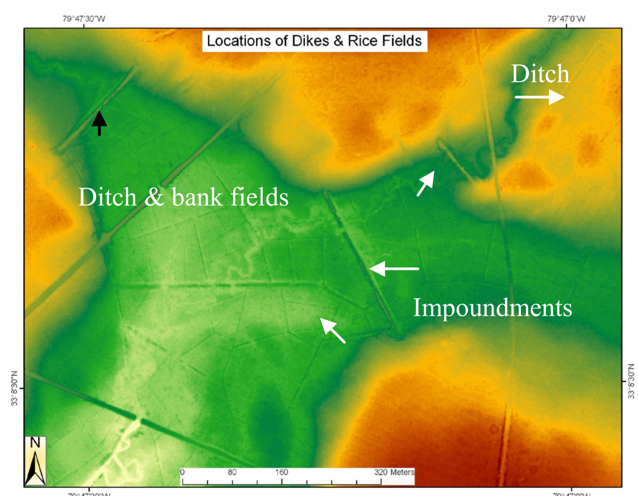

Figure 2. Depiction of surface topography derived from LIDAR data for a section of Huger Creek, Santee Experimental Forest. The location of some impoundments, ditches, and ditch and banked fields are noted.

In a similar application, James et al. (2007) used LIDAR data to map gullies and headwater streams under a forest canopy in South Carolina and found that LIDAR data provided robust detection of small gullies and channels, except where they are narrow or parallel and closely spaced. They reported that the ability of LIDAR data to map gullies and channels in a forested landscape should improve channel network maps and topological models.

Effects of historical water management features on watershed hydrology

The historical water management features are affecting current watershed hydrology in several ways. Diversion ditches are affecting upland runoff processes including overland flow paths. These ditches were constructed to shunt water from reservoirs to fields located in the floodplain; hence, they run perpendicular to the slope. The ditches, with the associated spoil bank, serve to interrupt surface runoff and to channel the runoff at points where water control structures existed (Figure 3). The presence of these features is a major contradiction to the assumptions of hill slope runoff from the traditional resource data. The effects of the collection and rechannelization are evident by drainage rivulets into the floodplain. The net effect of these ditches is to interrupt hillslope flow path and pool runoff and redirect it through small channels. It is also likely that subsurface runoff is also affected. This may also ultimately alter travel time and time to peak of flooding at the watershed outlet.

The old field ditches and banks also affect runoff within the floodplain; these are major topographic features that will affect transport and routing, especially during flood stages. During non-flood periods, if the old ditches are not hydraulically linked to the stream, they may function as detention storage areas affecting infiltration positively and stream flow negatively.

The LIDAR data also proved useful in delineating the stream location. The USGS topographic maps convey a rather straight or direct-flowing stream; in contrast, the stream generated with the LIDAR data illustrates a meandering channel (Figure 4). The difference in stream channel configuration between the two data sources is pronounced; for the stream reaches denoted in Figure 4, the total channel length is 1,853 m on the USGS map and 2,981 m based on the LIDAR data.

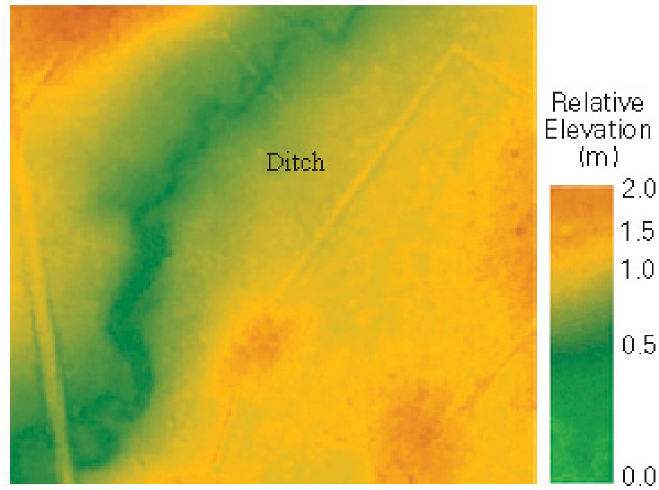

Figure 3. LIDAR image showing a stream diversion ditch running parallel to the present channel. The ditch and associated berm interrupt surface runoff.

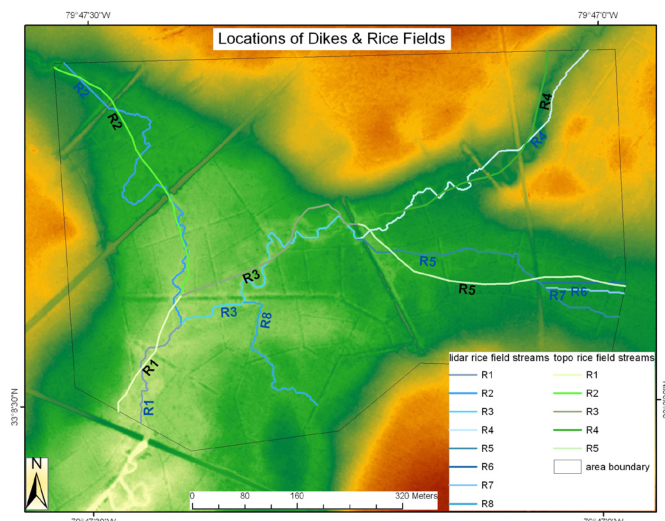

Figure 4. Overlay of the USGS topographic map (light green) and LIDAR-derived stream channel (blue).

Sinuosity, a ratio that describes whether a channel is straight or meandering, was also different when calculated with the USGS and LIDAR stream data (Table 1). None of the stream reaches would be considered meandering, a sinuosity ratio of 1.5 or greater, when calculated from the USGS topographic map. In contrast two of the stream reaches meander when calculated from the LIDAR data. The 61-percent increase in channel length and recognition of sinuosity has important ramifications when considering peak discharge, time to peak, routing, and in-stream processes.

Table 1. Stream length and sinuosity for segments identified in Figure 4.

	Stream length (m)		Sinuosity	
Reach	**USGS**	**LIDAR**	**USGS**	**LIDAR**
R1	203.9	210.3	1.0	1.3
R2	432.3	692.6	1.1	1.6
R3	339.8	495.8	1.2	1.7
R4	438.2	562.7	1.1	1.2
R5	439.2	468.2	1.0	1.1
R6	N/A	130.3	N/A	1.0
R7	N/A	123.0	N/A	1.0
R8	N/A	279.2	N/A	1.4
Total	1853.4	2962.1		

Changes in hydrologic functions

Water management structures that were devised for rice cultivation in the floodplain that began 300 years ago are affecting contemporary surface water hydrology and stream channel hydraulics. As a result, hydrologic and hydraulic functions of the watershed have been altered from conditions that were presumed to exist in these now forested watersheds (Table 2). The changes are associated with alterations to hill slope runoff including its pathways, structures within the floodplain changing depressional storage, and increased channel length and flow routing, which results in longer time to peak and reduced peak runoff rate. While active water management structures increase surface depressional storage, enhancing the wetland hydrologic functions (e.g. water table elevations and soil moisture; Skaggs et al. 1994), it is uncertain how these relic structures affect depressional storage since the control structures are not functional.

Implications for modeling

When modeling hydrology on the SEF watershed, the landscape is represented by the readily available resource data (e.g. Figure 1). During model calibration, parameters and coefficients may be modified to achieve reasonable simulations, as compared to measured stream discharge. As an example, a common parameter to adjust for peak flow rates during calibration is depressional storage, which is also a parameter that is very difficult to measure directly (Amoah 2008). It is evident that adjustments to depressional storage could mask or compensate for the effects of the actual channel and stream routing (Figure 4) and hill slope runoff (Figure 3). For example, depressional storage is a key parameter in the DRAINMOD model that controls the surface runoff rate after the soil is saturated and the surface storage is filled (Skaggs 1980, Konyha and Skaggs 1992, Haan and Skaggs 2003). The effect is to modify the model behavior to achieve more accurate output, but if that calibration does not reflect actual hydrological processes, then the end results do not reflect accurately simulated processes within the watershed. Recently, Amoah (2008) developed a geographic information system–based depressional storage capacity (DSC) model using USGS DEM data; for one of the SEF

Table 2. Effects of historical agricultural water management systems on hydrologic functions in floodplains of the Santee Experimental Forest.

Function	Rationale for altered functionality
Surface storage	Interruptions in overland runoff may retard the runoff rate and increase infiltration and ET.
Runoff routing	Interruptions in overland runoff effectively pool runoff and channelize the flow into the riparian zone.
Stream routing	Development of a meandering stream system following agricultural abandonment has resulted in longer flow path than represented on topographic maps.
Flood storage	Flood storage is likely increased with the presence of the dikes within the floodplain.
Water table depth	Longer surface water retention due to structures increase the water table elevation and soil moisture.

watersheds (WS-77), he estimated 1 cm of effective depressional storage. When that storage factor was used to simulate stream discharge for the watershed using both DRAINMOD and its watershed-scale version, DRAINWAT (Amatya et al. 1997), Amoah (2008) found higher simulated peak flow rates by both models for the 2003–07 simulation period. That effect is likely due to an underestimation of the surface storage parameter for this watershed, which could result from not recognizing the historical water management structures that are not reflected in current DEMs.

Summary and Perspectives

There is a tremendous need to accurately represent environmental processes on the landscape. Questions involving climate change, land use effects, urbanization, etc. require a thorough understanding of the processes regulated by hydrology because the consequential thresholds are usually small. While models are the principal tool for conducting assessments, representations from spatially distributed, physically based models may only be as effective as the mathematical representation of the processes and the accuracy and resolution of the supporting data. We have shown that historical land use features may affect contemporary watershed hydrologic processes, to illustrate that the modeling process (e.g., calibration) may compensate for inherent features in the landscape. Adoption of higher resolution data, whenever available, will challenge and ultimately improve our understanding of hydrologic processes and hence model applications. In areas where water resources are critical and existing data relatively poor (e.g., coastal plain), acquisition of high resolution topographic data will greatly enhance our ability to assess hydrologic functions including water, nutrient, and carbon balances.

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