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How much surface water can gilgai microtopography capture?

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SUMMARY

Gilgai microtopography is associated with landscapes of strongly shrinking–swelling soils (Vertisols) and affects spatial and temporal variability of runoff, and thus the generation of stream flow and plant-available water. However, no report is available on the amount of surface water that a landscape with gilgai depressions can retain. Our objective was to assess water capturing capacity of a typical Vertisol landscape with gilgai depressions in the Blackland Prairie Major Land Resource Area of Texas. The 45 by 40 m study site was located on a Vertisol with circular gilgai covered by improved pasture on a summit with slope of less than 3%. A digital elevation model (DEM) with 0.25 m^2 cell size was created from elevation data acquired by using GPS. Water capturing capacity of gilgai depressions was estimated at 10 randomly selected local gilgai basins by analyzing spatial distribution of Topographic Wetness Index (TWI). Our findings indicate that the average circular gilgai depression can hold 0.78 m^3 of water leading to an estimate of 0.024 $m^3\ m^{-2}$ water capturing capacity in a circular gilgai landscape, assuming no infiltration. The gilgai could capture a maximum of 43.74 m^3 of rain and runoff water at the 1800 m^2 study site. Consequently, if the soil were saturated and not infiltrating any water, no runoff would be expected following a 24.3 mm m^{-2}, 1 h precipitation, affecting estimates of streamflow (runoff) and plant available water (redistribution and infiltration) at the m to km scale.

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1. Introduction

Landscapes with soils of high shrink-swell potential (Vertisols and Vertic intergrades) may display two unique, hydrologically important features: desiccation cracks and gilgai surface microtopography. While surface hydrology often focuses on the influence of desiccation cracks (Das Gupta et al., 2006), little is known of the potential surface water storage of gilgai depressions so called circular gilgai, such as shown in Fig. 1 that collect precipitation and modify runoff and evapotranspiration at the 1 m to 10 m scale across Vertic landscapes. This is in contrast to traditional hydrological modeling that assumes these landscapes to be topographically smooth at scales smaller than a hillslope in uniform hydrologic response units (Deb and Shukla, 2011). During rainfall events where runoff is expected because antecedent soil moisture is high, gilgai depressions can capture water that might be expected to runoff the landscape. For days or weeks, water can pond in gilgai depressions with very slow infiltration, promoting high evaporation rates, and less runoff. As a consequence, ponding of water in gilgai depressions contributes to spatial heterogeneity of partitioning between runoff and infiltration, stream flow and plant-available water (Thompson and Beckman, 1982; Thompson et al., 2010). The effect of microtopography may be not directly linkable to errors in hydrology modeling at the global scale, but at scales where it is important to assess the impact of land management on the hydrology cycle and ecosystem cycles (hillslope, 10s of m to basin-scales, kms), it can be important. No quantitative or experimental information has been found on the amount of water that can be retained in numerous gilgai depressions across a landscape; however, the effect of other (smaller, idealized) microtopographies has been simulated and shown to increase the proportion of infiltration by 20–200% relative to a state with no microtopography (Thompson et al., 2010). Therefore, we used measurements to estimate the amount water captured by circular gilgai with periodic pattern to help hydrology estimates of detention storage and redistribution of surface water on Vertic landscapes.

Vertisols contain high amounts of clay (>30%) with high shrink-swell potential, and cover about 120 thousand km^2 in the USA and 2.23% of the Earth's surface (Coulombe et al., 1996). Gilgai is a typical undulating microtopography associated with subsurface soil features (Miller et al., 2010), commonly developed in Vertisols (Wilding and Tessier, 1988), and can be circular (or normal), which is the most common formation, or linear (Paton, 1974). Linear gilgai

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Fig. 1. Water-logging in gilgai depressions at the study site in Riesel, Texas, on February 26, 2010. The horizontal distance at the foreground of the photo is approximately 16 ft. (Photo is courtesy of Dr. Kevin McInnes).

forms are microridges and microvalleys elongated downhill (Gustavson, 1976). For the purpose of estimating surface water storage, circular gilgai depressions are of particular interest because these are common gilgai features found filled with surface water. Shape and arrangement of microtopographic features of Vertic soils have several description schemes that include variants to circular- and linear-shaped gilgai (Hallsworth et al., 1955; Paton, 1974; Dudal and Eswaran, 1988; Schaetzl and Anderson, 2005; Dixon, 2009). Vertisols exhibiting gilgai occur around the world mainly in subtropical and tropical climates (Wilding and Puentes, 1988), but can also be found in warm temperate (Kovda et al., 2003, 2010; Fuchs et al., 2010), semiarid (White, 1997) and arid environments (Dixon, 2009).

Gilgai means "small waterhole" in Indigenous Australian language (Paton, 1974). Circular gilgai consists of microhighs (convex mounds or microridges), a transition zone of microslopes, and microlows (concave depressions). Height difference within a gilgai is 10–50 cm generally but can range vertically from a few cm to 3 m (Miller and Bragg, 2007; Kovda et al., 2003; Dixon, 2009). Horizontal dimensions of gilgai may reach up to 16 m (Dixon, 2009). The periodicity of repeated gilgai pattern, or the average distance between repeated similar gilgai features, has been quantified by using geostatistical analysis. On a transect with 4 m increment soil sampling, the spatial wavelength of periodicity was found to be 33 m for gilgai depressions in Australia (Webster, 1977). Similarly, a spatial periodicity ranging from 30 to 50 m was found by Milne et al. (2010) based on quantitative examination of aerial photographs. However, smaller periodicity was found in the Texas Gulf Coast Prairie where microlows repeat every 2–5 m (Miller et al., 2010).

Gilgai formation has significant influence on spatial and temporal heterogeneity of water infiltration and consequently on landscape-scale hydrology. A decade-long monitoring of soil cracking and moisture conditions of Vertisols with normal gilgai revealed significant differences in magnitude, frequency, duration of cracking across microtopography at a 100 m^2 study site (Miller et al., 2010; Kishné et al., 2009, 2010). On microhighs soil cracking developed more frequently with greater crack area density (up to 273 $cm^2\ m^{-2}$) and deeper maximum depth (up to 140 cm) than on microlows, although average crack depth was greater on microlows when cracks existed (Kishné et al., 2009). Moreover, the rate of surface soil cracking responding to change in soil moisture near the surface varied not only across gilgai features, but also seasonally and interannually (Kishné et al., 2010). Soil cracking influences infiltration and wetting the soil through vertical bypass flow (Bouma and Wösten, 1984), as well as lateral flow of water in a sloping landscape (Graham and Lin, 2011). Due to differences in pattern of desiccation and soil cracking, microtopography is a controlling factor on spatiotemporal variation of soil moisture (Wildings et al., 1990). This tendency was also demonstrated by an electrical resistivity survey conducted across several gilgai in the Blackland Prairie of Texas (Amidu and Dunbar, 2007).

The overall goal of this work is to provide information for hydrology modelers regarding the capacity for circular gilgai microtopography to alter estimates of rainfall partitioning into infiltration and runoff on Vertic landscapes. Specifically, we used GPS measurements, and GIS algorithms to estimate the capacity of gilgai depressions to capture and store surface water.

2. Materials and methods

2.1. Study site

The study site is located at the USDA-ARS Grassland, Soil and Water Research Laboratory near Riesel, McLennan County, Texas (Fig. 2). The ecoregion of the study site is the Blackland Prairie Major Land Resource Area that covers 44,500 km^2 and is a major agricultural region (Harmel et al., 2003). The climate of this area is characterized by approximately 890 mm annual precipitation for the period of 1939–1999 (Harmel et al., 2003) and 19.5 °C annual temperature (Potter, 2010). The yearly maximum of precipitation usually occurs in Spring, and the minimum is in Summer (Harmel et al., 2003). Intense precipitation is related mostly to passing of the Canadian continental and Pacific maritime fronts, occasional tropical storms, hurricanes and convective storms (Knisel and Baird, 1971). Annual runoff from a small, mixed land use watershed in the region averaged 159 mm from 1939 to 2002 but it is quite variable (Harmel et al., 2006). The soil forming geology consists mainly of weakly consolidated calcareous clays and marls of Cretaceous age (Arnold et al., 2005; Allen et al., 2005, 2011).

Soil of the study site has been classified as Houston Black (fine, smectitic, thermic, Udic Haplusterts) that is the dominant soil series in the Blackland Prairie. A typical particle size distribution of this soil type consists of 55% clay, 28% silt and 17% sand (Allen et al., 2011) and exhibits high shrink-swell potential quantified by high coefficient of linear extensibility up to 0.18 m m^{-1} (Dinka et al., 2012). Vertical shrinking–swelling was measured up to 90 mm in years of extreme wetting and drying cycles (Arnold et al., 2005; Dinka, 2011).

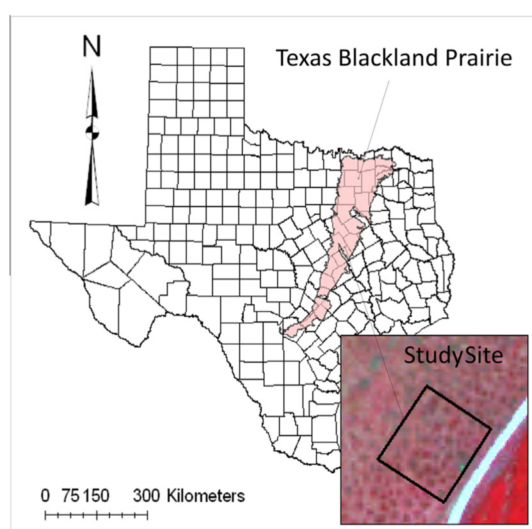

Fig. 2. Location of study site. Spatial pattern of gilgai are shown on near-infrared orthophoto with spatial resolution of 1 m^2.

The study site covered a 45 m by 40 m area. The Houston Black soil in the site has circular gilgai developed under a general slope of less than 3% and some linear gilgai on steeper slopes beyond the study site. Prairie vegetation covered the pasture dominated by Little bluestem (*Schizachyrium scoparium* (Michx.) Nash, e.g. Polley et al., 2005) and was grazed by cattle.

2.2. Data set

The data set consisted of elevation data points collected by using GPS. The elevation data was measured by using a survey quality GPS system with Trimble R7 (base station) and R8 (continuous kinematic, post processed) receivers (1 cm horizontal and 2 cm vertical accuracies, Trimble, 2003) in continuous mode using the NAD 1983 UTM 14N projection on December 21, 2010. The R8 antenna was mounted on a pole fastened onto a backpack of a surveyor walking slowly along transects approximately 2 m apart in irregular grid. The average increment of point locations was 0.5 m within transects. A total of 8377 points were collected in the grid. In addition, 105 reference points (stop-and-go, kinematic) were measured in approximate locations of microslopes (Fig. 3).

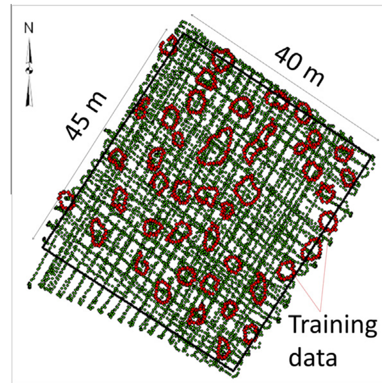

Fig. 3. Elevation data collected by using GPS at the study site. Additional data were collected at approximate locations of microslopes.

2.3. Data analysis

Data analysis was performed using ArcView (ESRI v.9.3). The DEM was created by using thin plate spline interpolation due to the advantage that it creates a surface passing exactly through the data points and with minimum curvature (Franke, 1982). The cell size was 0.25 m. A buffer of 0.5 m was kept around the study site to avoid edge effect. Outstanding elevation peaks and pits in individual cells related to surface unevenness in the walking pattern, and were smoothed by neighborhood averaging with a roving 7-by-7-cell window (Fig. 4).

2.4. Estimation of water capturing capacity of gilgai depressions

Capacity of gilgai depressions to capture water was defined here as the ratio of volume of gilgai depression up to its pour point and the horizontal area of gilgai projected vertically ($m^3\,m^{-2}$). Pour point was defined as the location along the ridge of local basin where water would pour out. To identify gilgai depressions and the elevation of pour point, water divides (ridges) were determined. Closed gilgai depressions were identified by using the basin function following the required fill and flow direction operations in Hydrology Toolbox of ArcView (ESRI v.9.3). To determine the elevation of pour point, a ridge mask was created as a pathway connecting the points of water divide surrounding a depression. The ridge mask was created by investigating Topographic Wetness Index (TWI) calculated for each cell based on DEM (Beven and Kirkby, 1979; Sørensen et al., 2006).

$$\mathrm{TWI} = \ln\left(\frac{a}{\tan\beta}\right), \quad (1)$$

where a is the local upslope contributing area (m^2) and β is slope (degree). Cells of water divide indicated by "no data" of the TWI data set showed the ridges. Then, individual scattered cells were eliminated by repeating majority filter and boundary clean functions iteratively in ArcView until no outstanding single cells were found. To fill in missing connections of ridges, bridges were digitized manually over boundaries of basins in ArcView. For considering gilgai depressions, very small basins (<1 m^2) were eliminated (dissolved). The minimum elevation was determined by zonal statistics within the ridge mask in Spatial Analysis of ArcView.

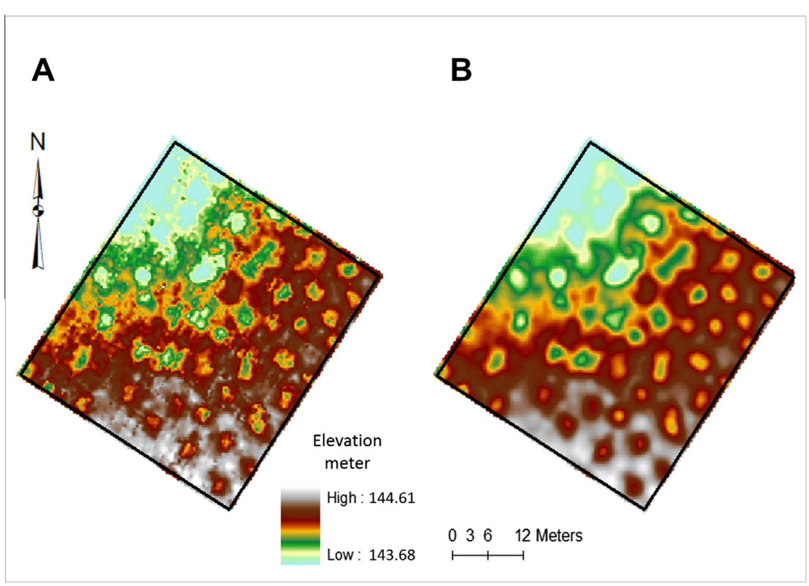

Fig. 4. Preprocessing of elevation data. (A) Raw DEM created by using thin plate spline interpolation with 0.25 m resolution; (B) Smoothed DEM created by averaging within a roving window (7 × 7 cell size).

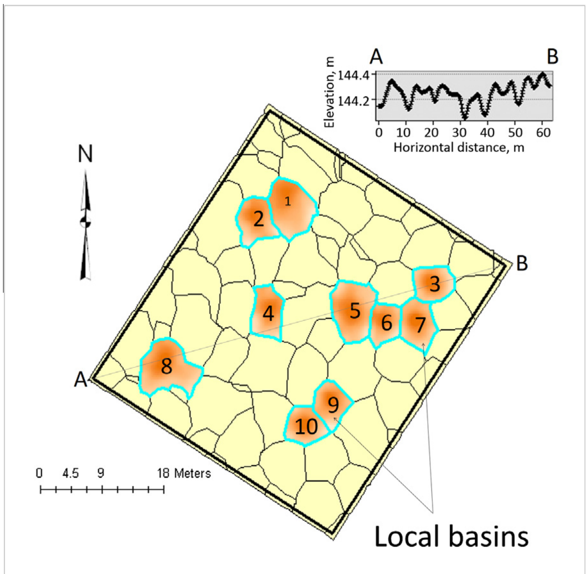

Fig. 5. Location of randomly selected basins for estimation of capturing water and a transect illustrating the elevation change across the study site.

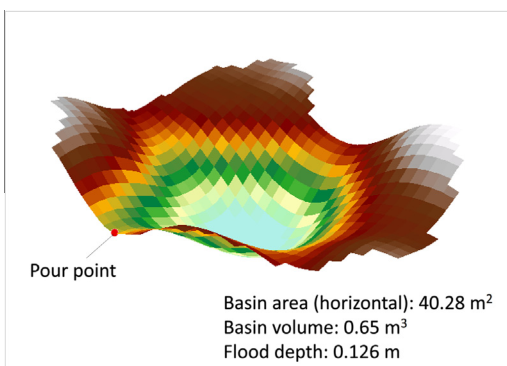

Fig. 6. An example of selected basins (#5) illustrated in 3-D using ArcScene. The cell size was 0.25 m.

To assess the water capturing capacity of gilgai depressions, ten closed basins were selected randomly inside the study area by numbering all closed basins and selecting 10 numbers from a randomly generated list (Fig. 5). For each basin, its pour point was determined using the ridge mask defined earlier. As an example, the shape of a basin and its pour point are demonstrated in Fig. 6.

3. Results

This study documented that topographic measures, such as slope, curvature, and TWI derived from high spatial resolution DEM can be used to identify gilgai depressions (Figs. 4 and 5). In addition, volume of gilgai depressions can be assessed by using ArcScene (Fig. 6).

For the ten randomly selected basins, area, volume and the rate of water capturing capacity are shown in Table 1. Volume of individual basins ranged between 0.06 m^3 and 2.6 m^3 with an average amount of 0.78 m^3. The total volume of the ten selected basins was 7.76 m^3 at 320 m^2 horizontal area. Thus, the estimated rate of water capturing capacity, the ratio of total volume and horizontal area of the ten basins was 0.024 $m^3\ m^{-2}$.

For the whole study site, an estimated 44 m^3 of surface water can be retained. Consequently, no surface runoff would be expected following an intensive 24.3 mm, 1 h rainfall over a 1 km^2 area similar to the study site. Assuming 4 mm daily evapotranspiration, estimated at daily temperature ranging between 19 and 30 °C in April in this region (Fay et al., 2009), ponding of water in gilgai depressions can last about 6 days. Seasonal ponding pattern, however, may vary with temperatures of air and soil as well as composition and density of vegetation.

Table 1
Basic statistics of horizontal area, volume and rate of water capturing capacity for the selected basins.

Basin	Area (m^2)	Volume (m^3)	Volume/Area (m^3/m^2)
Minimum	22.70	0.06	0.0026
Maximum	48.32	2.60	0.1035
Mean	31.97	0.78	0.0250
Median	28.60	0.56	0.0178
Standard deviation	9.21	0.83	0.0299
N	10	10	10
Total	319.72	7.76	0.0243

The estimated maximum volume of water captured in gilgai depressions (Table 1) documents that gilgai microtopography associated with subsurface features of Vertisols may substantially impact runoff (stream flows), thus infiltration (soil storage) of water in a landscape.

4. Discussion

In the study site, circular gilgai depressions had high water capturing capacity of 0.024 $m^3\ m^{-2}$. These gilgai depressions were developed on marl and chalk parent material with a less than 3% slope at a summit landscape position. In addition to upland locations, circular gilgai commonly develop on footslopes. How common is this pattern? The orthophoto in Fig. 1 shows that the gilgai pattern continues outside the study area across the pasture and this pattern can be expected on Houston Black soil with similar land use where gilgai have not been recently affected by tillage in pasture and cultivated fields extending through the Blackland Prairie Major Land Resource Area. Linear gilgai may exhibit different water capturing capacity depending on the shape that phenomenon needs to be investigated.

Light Detection and Ranging (LIDAR), a laser-based optical remote sensing technology, is expected to provide an improved opportunity for surveying detailed landscapes over large areas. LIDAR can be useful for identifying presence and density of gilgai at 0.5 m horizontal resolution because diameters of gilgai are 1 m or greater, and several cells are needed to identify local basins. For detailed analysis of elevation needed for investigating gilgai, vertical accuracy of LIDAR-derived bare-earth elevation may be too coarse, 0.18 m in upland and 0.46 m in lowland with marsh vegetation (Schmid et al., 2011). While improving horizontal and vertical resolution of remotely sensed data, investigation of the effect of cell size on the estimates of gilgai microtopography is warranted for different Vertisol landscapes.

Currently, aerial photography, such as that available in some websites (e.g. Google Earth) are sufficient for determining presence of gilgai in grassed lands and savannah. A qualitative source of information on occurrence of gilgai for a given soil series is available through the USDA NRCS Soil Survey Official Series Descriptions (OSDs) (Soil Survey Staff, NRCS, USDA). If a soil has gilgai this information is included in the description of the soil.

In addition to water ponding on the soil surface, infiltration increases the amount of water retained, or detained, by gilgai. Once the water is detained, it either infiltrates or evaporates. The infiltration rate is determined by the hydraulic conductivity of the soil matrix, soil structure and macroporosity. Patchiness of retained water contributes to spatial variability of vegetation species. Ponding water in gilgai depressions may last from a few days in subtropical climate up to several months in temperate climate (Kovda et al., 2010). Hydrophilic vegetation may occur in microlows and more drought tolerant vegetation may grow more abundantly on microhighs. In turn, difference in density and root depth of vegetation may accentuate differences in evapotranspiration, soil cracking, infiltration of water and organic carbon accumulation in the soil (Kovda et al., 2010). Furthermore, patchiness of vegetation influences diversity of vegetation, birds, mammals and insects, the ecosystem services of the region.

Knowledge of spatial and temporal variability of available water influences the prediction results obtained by rainfall-runoff models (Arnold et al., 2005). In addition to spatial variability of precipitation and runoff (Das Gupta et al., 2006), both circular and linear gilgai may re-direct surface runoff along slopes and modify the amount of water available for infiltration, runoff and evapotranspiration. Thus, quantifying location, density, and shape of gilgai and its influence on available water might be beneficial to improve distributed hydrologic models in watersheds containing Vertisols with extensive gilgai development.

5. Conclusions

We have demonstrated that topographic measures, such as slope, curvature, and TWI derived from high spatial resolution DEM can be used to identify gilgai depressions. In addition, volume of gilgai depression up to the pour point can be determined by using ArcScene to assess water capturing capacity of gilgai depressions while assuming no water infiltration into soils. Average normal gilgai depressions can store 0.024 $m^3\,m^{-2}$ precipitation and runoff water in the Blackland Prairies of Texas. The average storage of an individual microdepression is 0.78 m^3 with a standard deviation of 0.83 m^3. At this rate, circular gilgai depressions can capture 24.3 mm m^{-2} of rainfall with no soil infiltration. Hydrology modelers wanting to detain storage of surface water from gilgai can estimate gilgai density in a given hydrology unit using one of the following three data sources with decreasing spatial accuracy, high resolution (0.5 m spacing) LIDAR, aerial imagery, or the NRCS Soil Survey descriptions of a soil mapping unit. The effect of microtopography may be not directly linkable to errors in hydrology modeling at the global scale, but at scales where it is necessary to assess the impact of land management on the hydrology cycle and ecosystem cycles (hillslope, 10s of m to basin-scales, kms), it can be important.

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