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Evidence of Surface Connectivity for Texas Gulf Coast Depressional Wetlands

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Abstract Depressional wetlands are distributed throughout the United States and provide many essential ecosystem services. It is important, from both an ecological and a regulatory perspective, to understand the surface water pathways that connect such wetlands to each other and to surrounding water bodies. For many of these wetlands systems, the amount of surface water discharged is poorly quantified. In this paper we report on a 45-month study quantifying the surface discharge characteristics of a wetland on the Texas Gulf of Mexico Coastal Plain. The results of this study indicate that surface runoff, although intermittent, occurred regularly and accounted for more than 17% of watershed precipitation over the 45 months, with annual runoff ranging from 0% to 27%. Runoff typically occurred in precipitation-driven pulses and coincided with increased runoff in adjacent waterways. The detailed results of this study and similar observations from other locations run contrary to the widespread perception that depressional wetlands on the Texas Gulf Coast are hydrologically isolated—which calls into question the regulatory policies governing large tracts of coastal plain wetlands (at least 400,000 ha in Texas alone).

Introduction

Wetlands display a continuum of connectivity to surrounding surface waters. Some are strongly connected, such as wetlands in riparian corridors or along coastal areas, while others, such as playa lakes in the Great Plains, have little if any hydrological connection. Classification schemes have been developed to help determine the extent to which wetlands are connected or isolated. However, this has proved to be a challenge, precisely because wetlands in reality display a "continuum of connectivity" (Leibowitz 2003; Leibowitz and Nadeau 2003). Some are strongly connected to the surrounding landscape and others less so, but in fact few are truly isolated.

Traditionally, the term "isolated wetland" has been applied to depressional wetlands that are surrounded by uplands. However, as noted by Tiner (2003b), the term is problematic because it is a "relative term that could be defined from geographic, hydrologic, and ecologic perspectives," and as noted above, few if any wetlands are truly isolated (Leibowitz 2003; Leibowitz and Nadeau 2003). In an effort to achieve more precision, Tiner has proposed the term *"geographically isolated"* as a more useful descriptor of these wetlands. Geographic isolation is much easier to determine than either hydrologic isolation or ecologic

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isolation. He defines a geographically isolated wetland as "one that is completely surrounded by upland (e.g., hydrophytic plant communities surrounded by terrestrial plant communities or undrained hydric soils surrounded by hydric soils)" (Tiner 2003b).

Wetlands fitting this definition of geographically isolated are often considered hydrologically isolated as well; however, many are in fact connected, via subsurface pathways, with nearby water systems (Tiner 2003b; Whigham and Jordan 2003; Winter and LaBaugh 2003). Notable examples are karst-sinkhole wetlands (Tihansky and Knochenmus 2001), Carolina Bay wetlands (Pyzoha et al. 2008), vernal pools in California (Rains et al. 2006, 2008), and Sandhill wetlands (Winter 1986). In contrast, hydrological connectivity via surface processes (overtopping of wetland depressions), although observed, has seldom actually been measured. Despite the lack of data, surface connectivity is assumed to be relatively uncommon (occurring only in very wet years) and to rarely involve significant amounts of water (Leibowitz 2003). However, surface connectivity via connecting swales has been established in both prairie pothole wetlands (Leibowitz and Vining 2003) and vernal pools in California (Rains et al. 2006, 2008).

Although the definition of geographically isolated wetland is reasonably straightforward and easy to apply, for many situations there has still been some ambiguity in terms of how it has been applied. A case in point is the depressional wetlands along the Texas Gulf Coast. In this region, wetlands that are not directly adjacent to larger water bodies have been classified as geographically isolated (Tiner et al. 2002; Tiner 2003a, b). However, these wetland complexes are clearly interconnected to surrounding waters through sloughs and poorly defined drainage paths that are seasonally wet (Fig. 1). The problem is that the amount of surface runoff through these features is largely unknown (Tiner 2003a) and assumed by many to be insignificant (Sipocz 2005).

Our relatively poor understanding of surface hydrological connections in wetlands that are considered to be geographically isolated underscores the broader issue: the scientific community has probably not provided the wetland regulatory community with sufficient information to credibly support policy-making and jurisdictional decisions. For example, the scientific community urgently needs to carry out research focusing on the fundamental processes of isolated wetlands (Leibowitz and Nadeau 2003)—in particular, the frequency, duration, and amount of flow from wetlands that lack a continuous surface-water connection to navigable waters (Nadeau and Rains 2007). Our lack of knowledge about the nature of runoff generated by these wetlands increases the difficulty of anticipating what will happen if they are
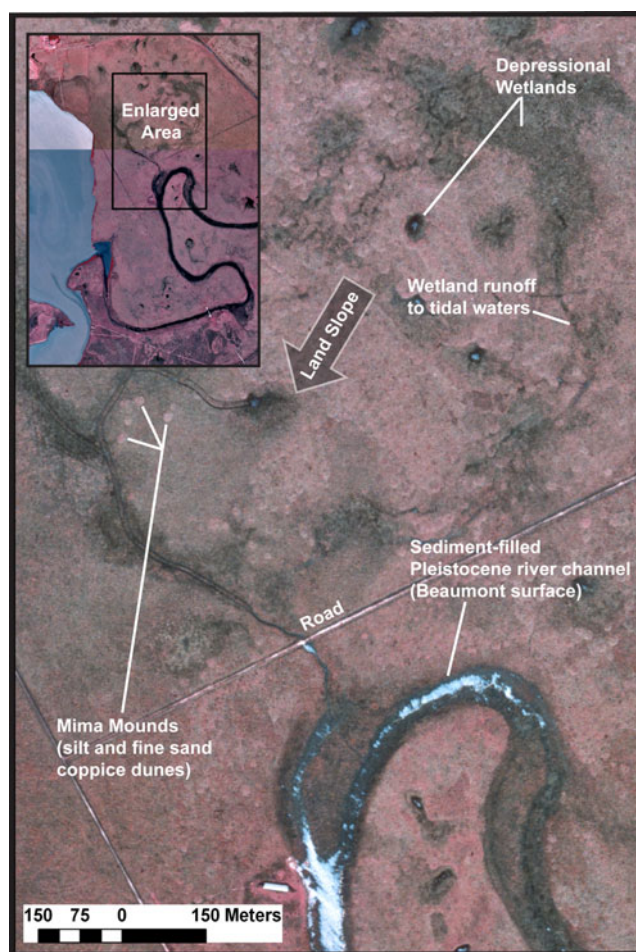
Fig. 1 A color infrared aerial photo highlighting typical features of depressional wetlands on the Texas Gulf Coast. Clearly, many of the wetland depressions are interconnected via intermittently wet swales. This image is of the Lake Austin estuary adjacent to the Matagorda Bay. This area is underlain by the same Beaumont Coastal Terrace geologic formation as the Armand Bayou study site; however, it is located in unforested prairie where wetland and runoff patterns are readily visible from the air. Lighter shaded areas correspond to growing vegetation on drier lands with darker shaded areas to senesced vegetation in wetlands. Open water is blue or white. Three paleo-river tributaries are visible as drainages, with the most recent being well-defined and tidal in its lower reach. Wind-deflated wetland basins similar to the study site are carved from the lighter textured channel and levee soils and overflow into the drainages. A ditch is dug along the length of the western-most paleo-channel in an attempt to drain the wetlands

converted to other land uses. Another important reason for gaining a better understanding of these processes is that surface hydrological connectivity is a key criterion for identifying which wetlands in the United States fall under the regulatory authority of the Clean Water Act (CWA) (Leibowitz et al. 2008).

In this paper, we report the results of a 45-month study quantifying the magnitude and timing of surface drainage or runoff discharged from a depressional wetland complex on the Pleistocene Texas Gulf Coastal

Plain. The objective of this study was to determine the true nature of surface connectivity in these wetlands. A secondary objective was to determine the extent to which urbanization may alter runoff dynamics.

Study Site

The Texas Coastal Plain is a 30,000-km^2 depositional plain located in South Texas along the northwestern side of the Gulf of Mexico. The area is characterized by very poorly drained and seasonally waterlogged soils and a lack of incised channels (Sipocz 2005). Freshwater palustrine wet-

lands at one time covered more than a third of the landscape (Moulton and Jacob 2000). As of 1992, about 1.3 million hectares of freshwater wetlands remained—some 24% of which were forested wetlands (Moulton et al. 1997). A recent inventory of isolated wetlands in the United States estimated that about 50% of wetlands on the Texas Coastal Plain were geographically isolated (Tiner et al. 2002; Tiner 2003a). Others, however, have argued on the basis of aerial imagery analysis that these wetlands are in fact connected to major waterways via intermittent and generally unmapped channel networks (Jacob and Lopez 2005; Sipocz 2005).

Our study took place in a watershed that encompasses a wetland complex overlying the Beaumont geologic formation,

Fig. 2 Location map of the study watershed, showing wetland depressions (hashmarked) and watershed boundary
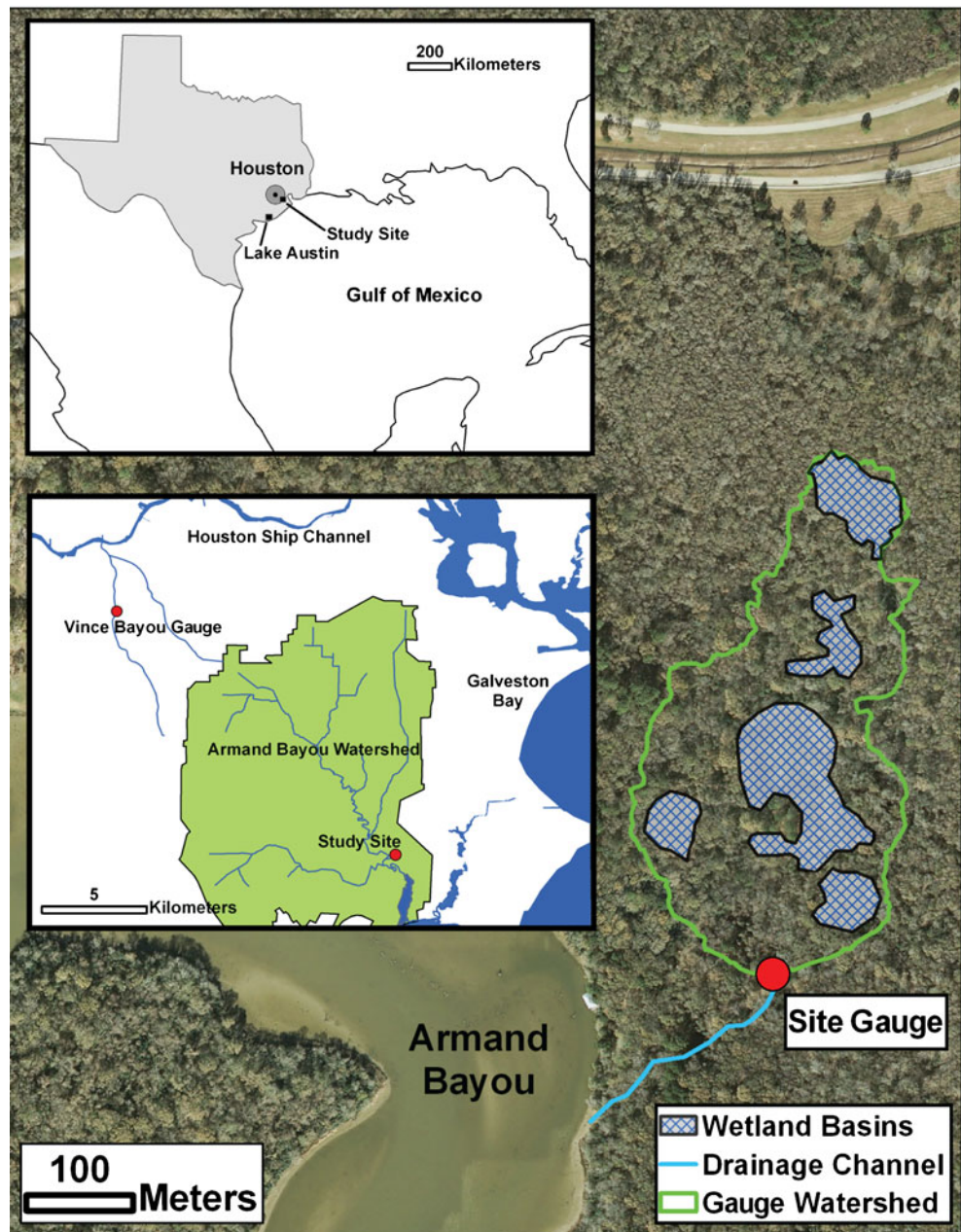
a Pleistocene-age fluvial-deltaic deposit common on the Texas Coastal Plain (Blum and Aslan 2006). Most of the wetlands on this formation took shape in meander scars or other fluvial features of the ancestral rivers that laid down the formation. The undisturbed Beaumont surface does not typically show strong visible evidence of a naturally integrated drainage system. At first glance, and especially during dry periods, it can be difficult to identify outlets from the wetland depressions. However, closer inspection reveals numerous shallow swales between depressions (Fig.1). The overall pattern is a complex mosaic of depressions, surrounding wetlands, and small non-wetland hillocks (known locally as a pothole–pimple-mound complex) which occurs in both forested and prairie landscapes (Moulton and Jacob 2000; Sipocz 2005).

The study watershed (Fig. 2) is part of a pothole–pimple-mound complex in a riparian forest adjacent to a large prairie. Located in the Armand Bayou Nature Preserve, southeast of Houston, Texas, the watershed is slightly larger than 8 ha (20 ac) and lies just outside the 100-year floodplain of the bayou. About 25% of the watershed consists of wetland depressions having emergent herbaceous vegetation; these depressions are interspersed with transitional flats and forested upland mounds. Average annual rainfall is 1,330 mm (Wheeler 1976). Snowfall is negligible and soil temperatures at a 20-cm depth never drop below 4°C.

The riparian forest is dominated by willow oak (*Quercus phellos*) and swamp red oak (*Quercus pagoda-folia*). Chinese tallow (*Triadica sebifera*) is also common and spreading. Emergent species observed in the depressions include swamp smartweed (*Polygonum hydropiper-oides*), three-fingered dog shade (*Cynosciadium digitatum)*, sugarcane plume grass (*Saccharum gigan-teum*), sedges (*Carex* spp.), and palmetto (*Sabal minor*).

The study watershed is mapped as Verland silty clay loam (Fine, smectitic, hyperthermic Chromic Vertic Epiaqualfs) (http://soils.usda.gov/survey/online_surveys/texas/). Our observations suggest most of the soil in the watershed is significantly wetter than what is described for the Verland series. Depressions were not mapped separately in this area, but likely correspond to the Leton series (Fine-silty, siliceous, superactive, hyperthermic Typic Glossaqualfs), which is commonly mapped in similar depressions in this area. The typical profile for a Verland soil is 18 cm of silty
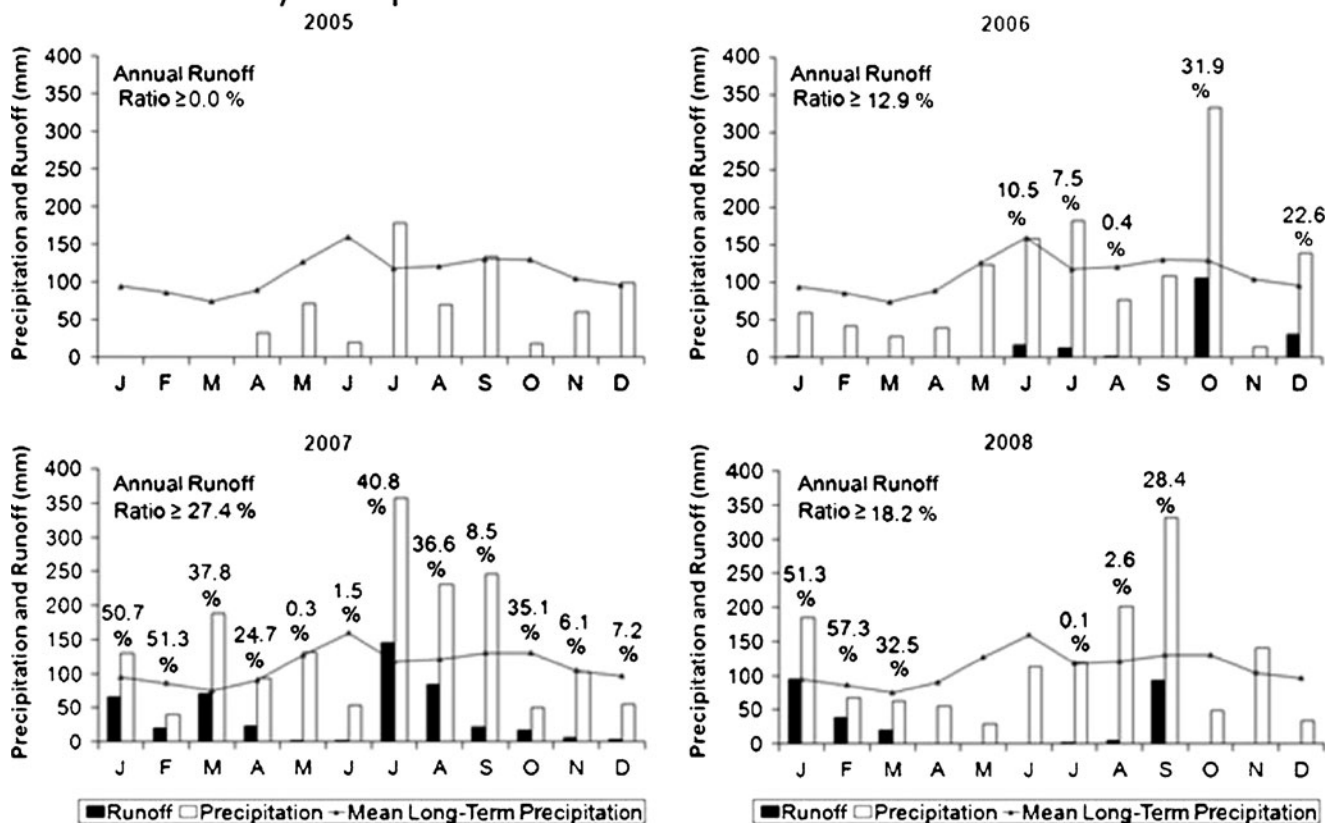
Fig. 3 Monthly precipitation and runoff for the four years of the study (2005–2008). Runoff volume is expressed as a uniform depth over the watershed (mm). The percentage of rainfall discharged as runoff is shown for each month. The line represents average monthly precipitation since 1929, for comparison

clay loam over clay to about 2 m. It is listed on the Web Soil Survey with a moderately low saturated hydraulic conductivity (K_{sat}) class (0.2877 μm/s for the entire profile). The Leton typical profile is 30 cm of loam over clay loam to about 150 cm, with a listed K_{sat} of 2.6 μm/s for the entire profile. The depressional Leton soil, at least in this area, has a substantially lower K_{sat}. We have observed dry soil at less than 25-cm depth under ponded conditions
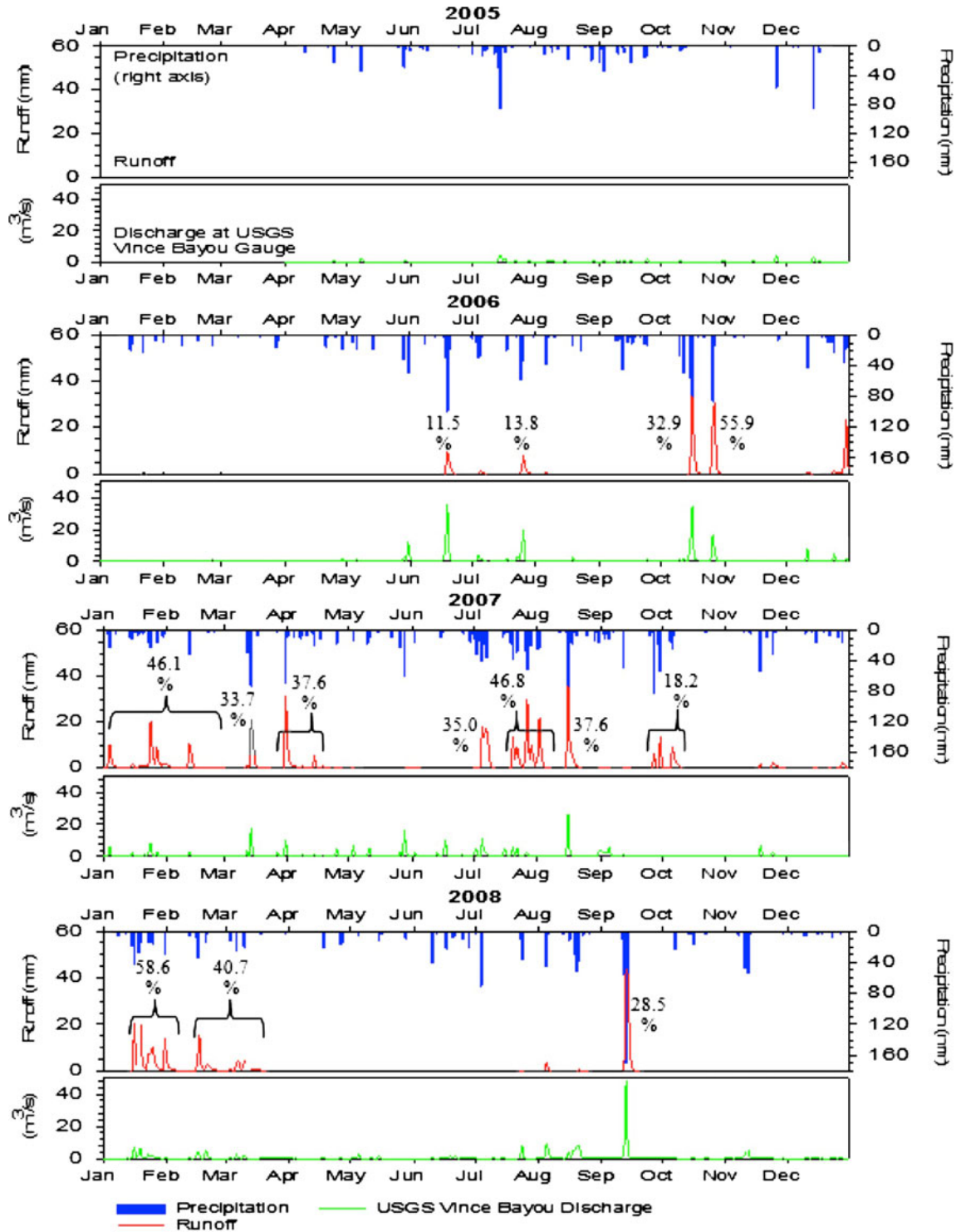
Fig. 4 Annual hydrographs (2005–2007) of daily precipitation and runoff data (axes plotted at different scales for clarity). Runoff percentages are given for major events, and the rate of runoff at the USGS gauge on Vince Bayou is shown for each year. Event-based runoff percentages were calculated from the first precipitation event following a 24-hr dry period to the beginning of the first 24-hr period with no runoff. Gaps indicate no runoff or no data

for a month or more. Saturation appears to occur from the top down, as indicated by the "Epi" formative element in the taxonomic classification of the Verland soil series.

Drainage features are quite subtle, with the watershed's outlet stream—which becomes evident about 60 m from the center of the largest, farthest-downslope depression—only about 2 m wide and 10 cm deep. Towards the base of the study watershed, a small incised channel has developed that drains into the nearby tidal Armand Bayou.

Methods

We delineated the boundaries of the watershed during a period of saturation and runoff, using flags and a handheld GPS unit. Most of the boundary was easily discernible, but in some instances flow direction had to be used to identify its location. An elevated trail formed the southern boundary of the watershed (see Fig. 2).

We measured watershed runoff at the outlet using a 90° V-notch weir equipped with a sonar water-level recorder (Infinities USA) and rainfall was measured with a tipping-bucket rain gauge (Infinities USA). The weir was installed across the head of the incised, intermittent stream channel that runs from the watershed outlet into the Armand Bayou (an intermittent channel is one that holds water during wet periods of the year but is periodically dry—Svec et al. 2003). The water level in the weir was converted to runoff in m^3/sec by means of the Kindsvater-Shen equation (USBR 1997). The volume of water per unit of time was converted to depth of water per unit of time by dividing the volume by the area of the watershed. Readings from the water-level recorder and the rain gauge were collected at 10-min sampling intervals until January 19, 2008, and at 20-min intervals thereafter. The flow data were compared with data from the 23-km^2 watershed of the USGS-gauged Vince Bayou (USGS-08075500) (http://waterdata.usgs.gov/tx/nwis/current/?type=flow), a site near Armand Bayou that is largely urbanized (Fig. 2).

There were occasional data gaps due to equipment problems. For the precipitation record, we were able to supplement the on-site measurements with daily rainfall data from the nearest official National Climatic Data Center (http://www.ncdc.noaa.gov/oa/ncdc.html) weather station, which is about 18 km to the south of our study area (Houston NWSO, 29°28′N/95°05′W, records available November 1990–present).

Results

The 45 months during which we studied this wetland complex (Fig. 3) included years with significantly below-average

(2005), near-average (2006 and 2008), and above-average (2007) rainfall. There was no wetland outflow during 2005, which was among the driest years on record for this region. When rainfall was about average or above, surface runoff ranged between 13% and 28% of watershed precipitation. The highest runoff volume occurred in 2007. Over the study period as a whole, including 2005, surface runoff from the wetland accounted for more than 17% of watershed precipitation.

Wetland runoff occurred throughout the year and was observed during 21 of the 45 months of the study, most often when monthly precipitation approached or exceeded the long-term monthly average. Occasionally, runoff occurred in months of below-average rainfall, but in most of these cases rainfall had been above average in the preceding months. During normal years, the monthly runoff threshold corresponded to around 130 mm of rainfall.

Runoff was measured during 37 days in 2006, 180 days in 2007, and 80 days in 2008. In general, runoff was highly episodic and strongly associated with individual rainfall events (Fig. 4), but there were occasional periods of extended flows, the longest being 68 days, that lasted well beyond the rainfall event. Periods of continuous runoff ranged from four days to 68 days, and averaged 17 days. For some individual events, runoff accounted for as much as 60% of watershed rainfall.

The episodic nature of the runoff is explained in part by the fact that precipitation from smaller events can be completely stored within the wetland depressions and shallow soil horizons, and in part by the fact that a significant portion of annual precipitation comes by way of large storms. From 2006 to 2008, storms that produced major runoff events accounted for between 37% and 62% of annual rainfall.

Interestingly, runoff from the study site was synchronous with that measured from the nearby Vince Bayou USGS location (Fig. 4). Baseflow in Vince Bayou is minuscule, with median flow rates ranging from 0.05 to 0.08 m^3 s^{-1} (0.2–0.3 mm/day); however, during major events, the rate of flow through the bayou was as high as 48.14 m^3 s^{-1} (180 mm/day). Runoff from Vince Bayou is largely episodic, exhibiting strong similarities with the hydrographs of runoff from the study watershed near Armand Bayou. The urbanized Vince Bayou watershed was slightly more responsive to rainfall than the study watershed, probably because of its limited water-storage capacity. Once the storage capacity of the study watershed was satisfied, its runoff response was very similar to that of Vince Bayou.

Discussion and Conclusions

Our results demonstrate that the Armand Bayou wetland complex has a strong surface-water connection with the

surrounding waterways. In fact, as highlighted in the comparison with Vince Bayou, the surface connectivity of the wetland complex was not very different from that of the surrounding urban landscape. This is perhaps not a surprising result given that streams originating within the Coastal Plain typically exhibit episodic flow regimes because of the lack of baseflow, attributable to the very low permeability of the region's soils, which inhibits groundwater input.

An important question, of course, is whether our results can be generalized for depressional wetlands on the Pleistocene Texas Gulf Coastal Plain. We believe they can. As noted earlier, most of these wetlands appear to be connected by intermittently flowing channels that are vegetated with wetland plants and containing wetland soils (Jacob and Lopez 2005; Sipocz 2005); on that basis, they do not strictly meet the definition of geographic isolation. Further confirmation of surface hydrological connectivity is provided by Forbes et al. (2009), who monitored outflow for one year at six wetland locations on the Texas Gulf Coast. They reported that runoff occurred from all of the monitored locations. Coupled with these observations, our findings provide strong evidence that shallow wetland depressions on the Pleistocene Texas Coastal Plain are not closed systems. Whenever their storage capacity is exceeded, they discharge excess water downslope, and their runoff is significant.

The issue of hydrological connectivity is not simply an academic one. Under current interpretations, whether or not a wetland is regulated under the CWA depends largely on its connection to traditionally navigable waters of the U.S. (Leibowitz et al. 2008). Wetlands have well-documented functions, such as serving as pollutant sinks, that can play a critical role in maintaining the water quality of receiving streams (Mitsch and Gosselink 2000). A critical question in terms of wetland jurisdiction and regulation under the CWA is the nature of the connection to receiving water bodies: is it significant enough to affect "the chemical, physical, and biological integrity of the nation's waters"—the maintenance of which is the purpose of the CWA (33 U.S.C. §§ 1251–1387).

The idea of a "significant nexus" has emerged as perhaps the most important legal concept for wetlands jurisdiction (Murphy 2007) and is a common thread in several recent Supreme Court rulings on wetlands, especially in Rapanos v. United States (2006), their most recent case on this issue. In a complex and unusual 4–1–4 split ruling, the actual documentation of the significant nexus from seasonally saturated wetlands to "waters more readily understood as navigable" emerged as a deciding factor in assigning jurisdiction where the hydrologic connection is "not relatively permanent" (Leibowitz et al. 2008). Justice Kennedy, the "1" in the 4–1–4 ruling,

specified that the significant nexus would have to be more than "speculative or insubstantial," and thus set the stage for scientific documentation of the "flow characteristics and functions" of headwater wetlands adjacent to non-navigable tributaries (USEPA 2008), precisely the wetland type examined in this study.

In summary, our detailed evaluation of runoff over nearly four years reveals that surface outflow, although episodic, is a common event in wetlands that have been considered to be geographically isolated, and accounts for a substantial percentage of the water budget. In other words, hydrological connectivity is clearly present and is not limited to an occasional event or an extraordinarily wet period. The findings of our study are important because they fundamentally contradict the notion that wetland depressions on the Pleistocene Texas Gulf Coastal Plain are hydrologically isolated from adjacent waterways (Tiner et al. 2002; Tiner 2003b).

This study provides the kind of documentation called for by Justice Kennedy in the Rapanos decision (see above). It demonstrates a "substantial" nexus between headwater depressional wetlands on the Pleistocene Texas Coastal Plain and navigable waters of the U.S.—a nexus that is not speculative but is the result of scientific observation. While further study is warranted and needed, this study and that of Forbes et al. (2009) suggest that unless demonstrated otherwise, depressional headwater wetlands—at least on the Upper Texas Gulf Coastal Plain as a class—should be considered as hydrologically connected to navigable waters of the U.S. and thus may play a critical role in the maintenance of the aquatic and biological integrity of U.S. waters in this region.

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