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OCCURRENCE OF RIVERINE WETLANDS ON FLOODPLAINS ALONG A CLIMATIC GRADIENT

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Abstract: The relation between the occurrence of riverine wetlands in floodplains along a humid to semi-arid climatic continuum was studied in two regions. The first included 36 mid-reach streams from Colorado to Iowa, USA, a region with a broad range of PET ratios (potential evapotranspiration/precipitation) from 0.70 to 1.75. The second region included 16 headwater streams in eastern North Carolina with PET ratios ranging from 0.67 to 0.83. Wetland boundaries were identified in the field along transects perpendicular to the floodplain. The width of jurisdictional wetlands was compared with flood-prone width (FPW) and expressed as a percent. An increase in PET ratio corresponded to an exponential decrease in the percentage of the FPW that is wetland. Soil texture, duration of overbank flow, and stream order did not correlate with percentage of FPW that was wetland. Streams with a PET ratio greater than 0.98 did not have wetlands associated with them. Greater channel cross-sectional areas correlated positively with greater wetland widths in both study regions. Overbank flow did not appear to contribute to wetland prevalence. Supplemental ground-water sources, however, as indicated by greater base flows, could not be ruled out as sources contributing to wetland occurrence.

Key Words: riverine wetlands, riparian zones, floodplains, climatic gradient, moisture gradient, Holdridge Life Zones

INTRODUCTION

Along any latitudinal cross-section of the United States, there is a distinct change in vegetation and runoff caused by the interaction of precipitation and evapotranspiration (ET). From the Atlantic Coast westward, the climate has the natural potential to support forests on uplands to a transition at approximately 95° to 97° West longitude. At this transition, the drier climate, and secondarily fire, results in a change in plant community structure to tall grass prairie (Küchler 1967). On floodplains [geomorphically defined as horizontal or gently sloping fluvial surfaces that are inundated or saturated by the dominant discharge (roughly equivalent to bankfull discharge) at least once every 1 to 3 years (Hupp and Osterkamp 1996)], however, supplemental sources of water, such as overbank flow and ground-water discharge, have the potential to relieve vegetation of direct climatic control and thus support forests.

The humid to semi-arid transitions in plant community composition and structure are relatively well-documented for uplands (Rice 1965, Abrams 1985), but corresponding transitions on floodplains are not as well described. Many floodplains in wetter climates support hydrophytic vegetation and meet the additional criteria of hydrologic and soil characteristics for jurisdictional wetland status (as regulated under Section 404 of the Clean Water Act as defined by the U.S. Army Corps of Engineers (Corps) (Environmental Laboratory 1987), hereafter simply referred to as wetlands). As climate becomes more arid, fewer floodplains meet jurisdictional wetland status, and anoxic soils become spatially restricted, often to the vicinity of the channel itself (Friedman and Auble 2002). At the dry end of the climatic continuum, floodplains may have geomorphic features roughly similar to those of humid climates but are commonly too arid to support species recognized as hydrophytes (Reed 1988).

We considered two alternative patterns between moisture regime and wetland dominance (measured as the percent of the flood-prone area (FPA) width that is wetland) across the climatic gradient in the USA (Figure 1). The simplest is a linear relation between

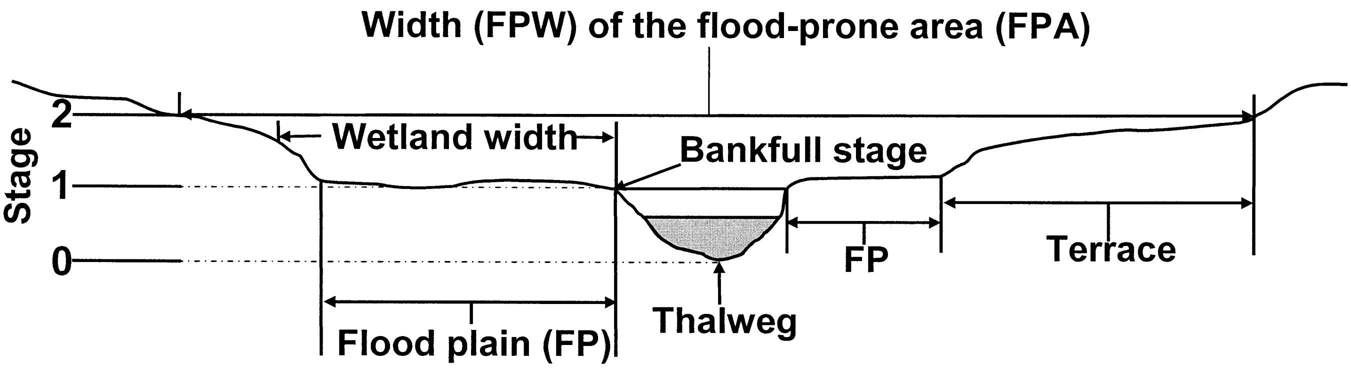

Figure 1. The flood-prone area (FPA) is the area associated with a stream that is inundated at twice the bankfull stage (recurrence interval approximately 50 yr). This includes the floodplain (FP) (recurrence interval 1–3 yr) and, in some cases, lower terraces. The distance across the FPA is referred to as the flood-prone width (FPW). If wetlands (riparian, depressional, seeps, etc.) were present within the FPW, the width of these wetlands was measured along transects and expressed as a percentage of the FPW.

wetland dominance and an index of climatic moisture regime expressed as the PET ratio (potential evapotranspiration/precipitation) (ratios >1 represent semi-arid climates and <1 humid climates). From the humid east to the semi-arid west, precipitation decreases while PET remains relatively constant [(within a range of 200 mm, except in mountainous regions (as calculated from National Climatic Data Center (NCDC) data) (Earthinfo 1995a)] along any one latitude. For this pattern, floodplain dominance by wetlands would gradually decrease with increasing PET ratio within any group of drainage basins of similar size, assuming no overriding effects of geomorphology or geology (Riggs and Harvey 1990).

An alternative pattern recognizes that other sources of water to floodplains, such as ground-water discharge and flooding from overbank flow, may converge along the climatic gradient to create an exponential relation between climate and wetland prevalence on floodplains. In this view, overbank flow may be derived from distant sources, such as the mountain snowmelt flowing to semi-arid regions of the high plains (Auble et al. 1994, Shafroth et al. 1998). In the case of ground-water discharge, base flow from aquifers may be recharged from distant sources, spatially and temporally. The combination of an increase in variable source area (Hewlett 1961a, b) and duration of overbank flow as climate becomes more humid could create a positive feedback that maintains water-tables near the surface in flood-prone areas (FPA). The combination of these factors may interact exponentially with decreases in the PET ratio until the entire FPA is wetland. This relation would be invalid if the correlation of PET ratio with the percent of the FPW that is wetland does not show an exponential curve (i.e., is non-linear). Some exceptions to the feedback hypothesis might occur in situations where water sources other than overbank flow and normal ground-water discharges contribute to the FPA.

This paper compares low-gradient floodplains in humid regions, where wetlands dominate the floodplain, with low-gradient floodplains in semi-arid regions, where wetlands are uncommon. This was done by examining the manner in which floodplain wetlands change as climate becomes increasingly arid. Several factors that potentially influence the development and maintenance of riparian wetlands—stream order, drainage basin area, soil, overbank flow duration, and above-average flow duration—were compared with the percent of the flood-prone width that is jurisdictional wetland. These factors were chosen to describe their changing relations with floodplain wetlands more accurately along the gradient of a PET ratio from humid to subhumid climates. Hypothetically, wetlands can occur even in the driest climatic regimes, as long as sources of water are sufficient to maintain water-tables close to the soil surface. Such geomorphic and geologic conditions for these hydrologic anomalies were avoided in site selection in order to explore the more general influence of the climatic gradient.

METHODS

Site Selection

Two regions were selected to study the effect of climate on floodplain wetlands—the central plains of the USA and the coastal plain of North Carolina. The central plain region comprises the High Plains, Osage Plains, Dissected Till Plains, and the Great Plains physiographic provinces (Hunt 1967) (hereafter referred to as central plains). The study sites in Iowa, Missouri, Kansas, Nebraska, and Colorado (Table 1, Figure 2), span the climate change from humid to sub-

Table 1. Name, location, PET ratio (potential evapotranspiration/precipitation), USGS gaging station, and National Climatic Data Center weather station for the central plains and North Carolina sites. Latitude (N), longitude (W).

Site	Stream	Latitude	Longitude	PET ratio	USGS gaging stn.	NCDC weather stn.	State
Central Plains							
1	White Breast Ck.	41.06.886	93.22.109	0.71	—	1394	IA
2	Blue R. @ Grandview	38.59.874	94.31.777	0.72	06893500	4359	MO
3	Little Platte R.	39.23.393	94.37.392	0.72	—	7862	MO
4	Indian Ck.	38.56.331	94.40.537	0.72	06893300	5972	KS
5	Blue R., upstr.	38.48.750	94.40.517	0.72	06893080	5972	KS
6	Trib to Little Blue R.	39.06.366	94.19.380	0.73	—	4850	MO
7	Elk Ck.	40.43.300	93.56.317	0.73	—	536	IA
8	102 River	40.35.202	94.47.017	0.73	06819185	576	IA
9	Soldier Ck.	39.26.929	95.57.122	0.78	06889160	1529	KS
10	Badger Ck.	41.27.178	93.46.321	0.78	—	2203	NE
11	Soldier Ck., upstr.	39.33.950	95.57.750	0.78	06889140	1529	KS
12	Turkey Ck.	39.56.867	96.06.500	0.78	06814000	1408	KS
13	Salt Ck.	38.36.533	95.38.283	0.79	06911500	4912	KS
14	Weeping Water Ck.	40.47.583	95.54.667	0.80	06806500	5810	IA
15	110 Mile Ck.	38.38.404	95.32.726	0.80	—	6498	KS
16	Mill Ck.	39.03.790	96.10.574	0.80	06888500	8563	KS
17	Soldier Ck. @ Grove	39.12.133	95.52.417	0.80	06889200	7007	KS
18	Little Timber Ck.	39.43.424	96.24.233	0.85	—	5063	KS
19	Chapman Ck.	39.01.867	97.02.400	0.87	06878000	5306	KS
20	Rock Ck.	41.01.775	96.33.171	0.88	06803530	5362	NE
21	Wildcat Ck.	41.00.173	97.21.654	0.89	—	8328	NE
22	Big Blue R.	41.06.211	97.20.819	0.89	—	8328	NE
23	Mill Ck.	39.48.833	97.02.033	0.90	06884200	8578	KS
24	White Rock Ck.	39.53.917	98.15.083	0.93	06854000	4982	KS
25	Stevens Ck.	40.51.417	96.35.700	0.93	06803520	4815	NE
26	Kings Ck.	39.06.117	96.35.700	0.95	06879650	8259	KS
27	Turkey Ck.	41.09.400	98.33.367	0.98	06784800	7515	NE
28	Elm Ck.	40.05.333	98.26.117	1.04	06852000	3395	NE
29	Salt Ck.	39.08.500	97.50.167	1.05	06876700	5363	KS
30	Thompson Ck.	40.05.350	98.45.633	1.13	06851500	7070	NE
31	Coates Ck.	40.06.132	98.54.295	1.17	—	3595	NE
32	Driftwood Ck.	40.08.827	100.40.489	1.21	06836500	5310	NE
33	S Fk Sappa Ck.	39.40.370	100.43.300	1.25	06844900	5906	KS
34	Bow Ck.	39.33.767	99.17.067	1.31	06871500	6374	KS
35	Arikaree R.	39.39.961	102.50.687	1.35	—	4380	CO
36	N Fk Smoky Hill R.	39.19.818	102.16.528	1.75	—	1121	CO
North Carolina							
A	Trib to Corduroy Swamp	36.28.583	77.15.967	0.67	—	5996	NC
B	Bluewater Branch	36.20.700	77.03.917	0.67	—	5996	NC
C	Lobelia Run	36.25.050	77.25.533	0.75	—	4456	NC
D	Collie Creek	36.22.750	77.27.733	0.75	—	4456	NC
E	Trib to Sandy Run	36.12.600	77.15.150	0.76	—	4962	NC
F	Pecan Grove Slough	36.06.833	77.29.533	0.76	—	4962	NC
G	Trib to Wildcat	36.10.266	76.58.667	0.76	—	4962	NC
H	Big Swamp	35.59.017	77.01.683	0.78	—	9440	NC
I	Etheridge Swamp	35.58.383	77.18.250	0.78	—	9440	NC
J	Phillipi Branch	35.35.250	77.15.667	0.78	—	3638	NC
K	Trib to Six Runs	34.51.717	78.10.367	0.81	—	1881	NC
L	Bulltail Creek	34.44.483	78.12.150	0.81	—	9423	NC
M	Trib to Crane Creek	34.55.367	78.16.567	0.81	—	9423	NC
N	Elm City	35.48.950	77.47.367	0.82	—	9476	NC
O	Spicer Preserve Creek	34.58.967	77.58.467	0.83	—	9081	NC

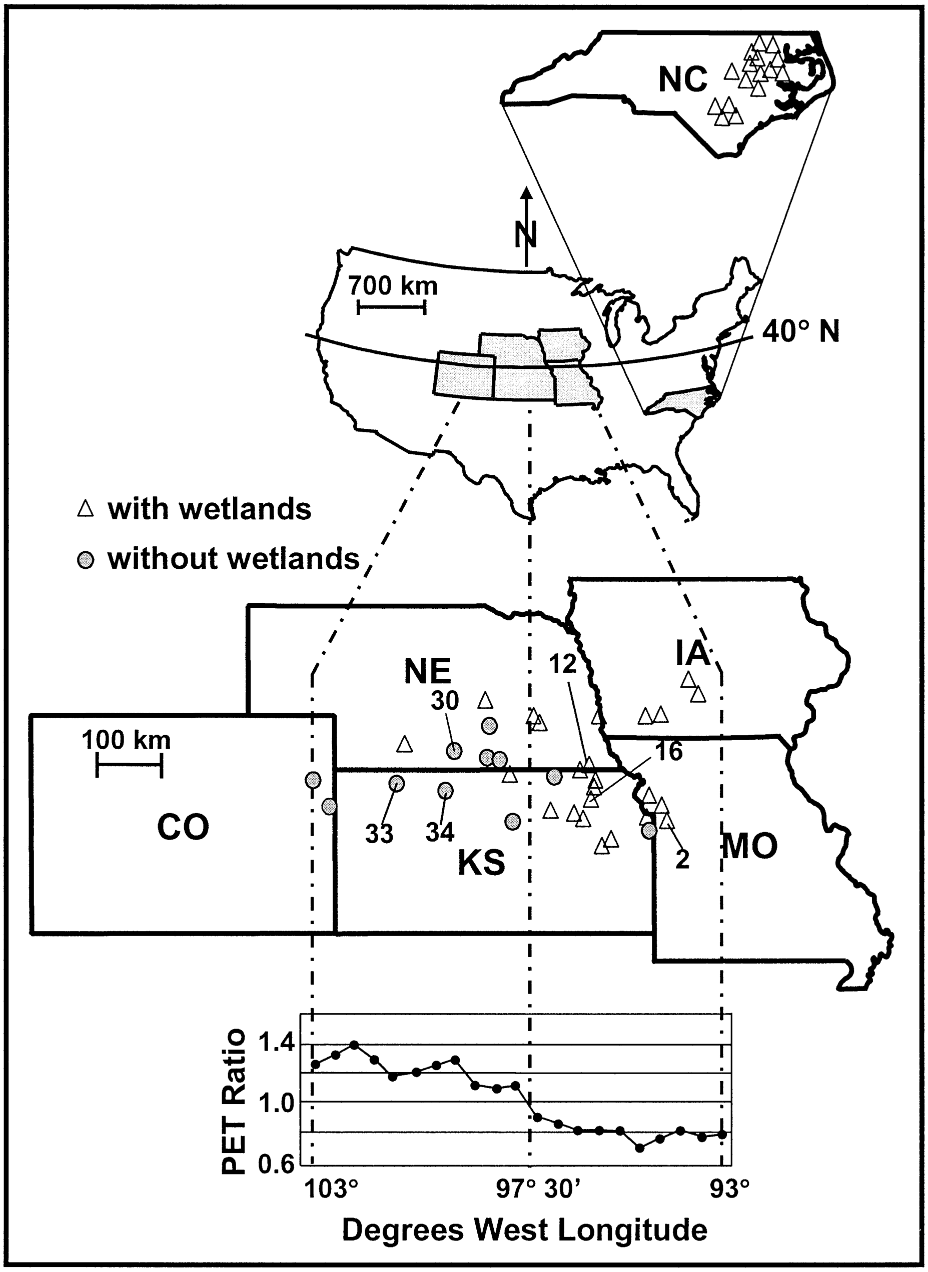

Figure 2. Distribution of sites with (triangles) and without (circles) wetlands. Base flow was determined for sites indicated by numbers. PET ratio = potential evapotranspiration/precipitation.

humid (Küchler 1967) and include the upland vegetation change from forest to grassland. Topography is classified primarily as irregular plains. Soils consist of loess, ancient alluvial deposits, and glacial deposits (Hunt 1977). The growing season ranges from 150 days on the western side of the central plains study region to 180 days on the eastern side.

The North Carolina study region is within the Inner Coastal Plain Physiographic Province (Hunt 1967). It is typified by flat topography with broad, frequently inundated low-gradient fluvial systems, typically with vegetation adapted to prolonged hydroperiods (Hupp 2000). The growing season is approximately 220 days (Gerlach 1970). Sites were selected from headwater streams previously sampled by Rheinhardt et al. (1998). The North Carolina streams (Table 1) were used to compare a region where wetlands dominate floodplains with those in the central plains. PET ratios (potential evapotranspiration/precipitation) on the eastern side of the central plains study region are similar to those in North Carolina.

Criteria for selecting data-collection sites near U.S.

Geological Survey (USGS) stream-gaging stations were based on sites having a synchronous period of record for mean daily discharge (October 1983–September 1993) and drainage basins ranging from 10.6 km^2 to 1260 km^2. This time interval was chosen in order to estimate climatic conditions during non-El Niño years. On the basis of field visits, sites were rejected if they were channelized, received back flooding from impoundments, received significant augmentation of flow as return flow from municipalities or agriculture, or had active beaver dams. Twenty-three gaged streams in the study region met the selection criteria. An additional 13 ungaged sites with drainage basins of varying areas were selected in order to fill spatial and climatic gaps using the same selection criteria as gaged sites except for the availability of discharge data. Although most reaches had some agricultural activity on terraces (>3 yr flood-recurrence interval) within the flood-prone area, preference was given to reaches that had low percentages of the FPA in crops. The criteria used for selecting the ungaged central plains sites were also applied in rejecting or accepting the 15 North Carolina sites.

PET Ratio

Potential evapotranspiration is the amount of water returned to the atmosphere as vapor through the combined effects of evaporation and transpiration, when water availability is unlimited. For the purpose of this study, PET was estimated as described by Holdridge et al. (1971) simply by multiplying average monthly temperatures above 0° C by 58.93; monthly averages less than 0° C are discarded [this method yields values comparable to Thornthwaite and Holzman (1942)]. Monthly PET values were then totaled for the years 1983–1993 and averaged to determine the annual PET. Annual precipitation was calculated from average daily rainfall records from the same period. Potential evapotranspiration was then divided by precipitation to determine PET ratio. Data for these calculations were obtained from climatic data collected by the National Climatic Data Center (NCDC) (Earthinfo 1995a) from the closest (<35 km) monitored weather station to each study site.

Hydrologic and Geomorphic Measurements

Flood stages typically reported by the National Weather Service (NWS) (1997) are the stage at which flood damage occurs and are not necessarily equivalent to bankfull stage. Flood stages for streams may also be estimated in the records of USGS stream-gaging stations. USGS flood stages are, however, subject to vagaries in the definition of ‘‘flooding’’ and ‘‘bankfull’’ (Williams 1978, Burke and Nutter 1995, P. Turnipseed, USGS oral communication, 1997). For more consistent estimates of hydrologic regimes, we measured bankfull depth in the field (Rosgen 1996). Average bankfull depth was determined from stream cross-sections along a reach of channel equal in length to 20 bankfull channel widths (Rosgen 1996). Visual indicators of bankfull stage (top of the point bar, vegetation change, topographic break, size distribution of surface materials, and debris deposition between rocks) were measured along three cross-sections at intervals of 10 bankfull widths (Leopold 1994, Rosgen 1996). The bankfull depths for the three cross-sections were averaged and used to calculate bankfull discharge from stage/discharge curves and tables created by USGS state representatives J.E. Putnam (Kansas), D.A. Eash (Iowa), G.B. Engel (Nebraska), and L.A. Waite (Missouri). Bankfull discharge was then compared with USGS stream discharge records (Earthinfo 1995b). Flood-prone width (FPW) is the inundated width of fluvial surfaces at a stage that is twice the bankfull stage (Figure 1) (Leopold et al. 1964, Rosgen 1996).

Determination of bankfull depth in the central plains was difficult during early summer 1998 because of the large amounts of rainfall in the Great Plains associated with an El Niño event. Frequent flooding, especially on higher order streams, required multiple visits to complete sampling, but sampling was not prevented unless the rainfall had occurred within the past few days and the flow still exceeded bankfull. When stream velocity was slow and depth from the thalweg to the surface exceeded 1.85 m, depth was measured by marking the water surface on a surveying rod after finding the thalweg.

Bankfull discharges for gaged streams were estimated by comparing field-determined bankfull depths with stage-discharge information and rating curves created by USGS offices in each state. Mean daily discharges for the period of October 1983–September 1993 (Earthinfo 1995b) were then compared with bankfull discharge. The total number of days during this period that mean daily discharge exceeded bankfull discharge was tallied for the 10-year period and averaged. Duration of flows exceeding annual mean discharge was determined as a possible measure of drainage basin ground-water input by comparing mean discharge for the period of October 1983–September 1993 with the individual days (Earthinfo 1995b) and averaging.

Six gaged streams were selected to estimate and compare the ground-water input to stream discharge across the climatic gradient. Three of these streams (sites 2, 12, and 16) were in humid portions of the gradient and three sites (30, 33, and 34) were in subhumid regions (Table 1, Figure 2). Hydrographs for these six streams were created from a synchronous period from March to September 1993. Base flow separations were calculated using the fixed base method (Fetter 1994). Days after peak $[(N) = 0.827(A)^{0.2}]$ were determined where N = days from peak discharge and A = drainage basin area (km^2). The average base flow was calculated by removing the ascending and descending (days after peak) limbs of storm flow events and averaging the remaining discharges.

Stream order was determined by analysis of USGS 1:24,000-scale topographic maps using the Strahler (1957) ordering system. Maps were in digital raster graphic (DRG) (a scanned USGS topographic sheet that is georeferenced for use in a GIS program) format obtained on-line for Missouri, Kansas, and Nebraska. Maps for Colorado and Iowa were obtained from the USGS in DRG format on CD-ROM. Streams, represented by dashed or solid blue lines, with no upstream tributaries, were designated as first order.

Floodplain and Wetland Measurements

Sites were examined for a distance of 500 m to 2 km, depending on the amount of variation present in the geomorphology and vegetation, to determine the extent of channel alteration and to select a representative reach of 20 average bankfull widths. Vegetation analysis and soil sampling typically were made while the FPW and wetland width were being measured. Species that represented greater than 10 percent of the community were considered to be prevalent. Species that comprised greater than 20 percent of the community, covered the greatest percentage of area, or constituted the majority of basal area were considered to be dominant. Wetland indicator status of vegetation (obligate wetland–upland) was determined on the basis of the national list of plant species that occur in wetlands (Reed 1988).

The edge of the flood-prone area (FPA) was surveyed and marked, and the FPW was measured. On both sides of the stream, measurements of the wetland width were made along three or more transects perpendicular to the stream at intervals of 10 bankfull widths or less. Wetlands were identified using the Corps 1987 protocol (Environmental Laboratory 1987). The upper 30 cm of soils within reaches of FPA were examined for hydric soil indicators (reducing conditions, low chroma color, organic streaking, sulfidic odor) and for hydrologic indicators (current state of hydration, oxidized pore linings). Soil matrix and mottle color were determined using a Munsell soil color chart (GretagMacbeth 1996), and textures determined in the field (Thein 1979) were assigned numerical values from fine to coarse (Taylor et al. 1999). At all sites, vegetation, soil, and primary and secondary wetland indicators were considered while making the wetland determination. These same methods for determining bankfull depth and flood-prone depth were also used for large sites (>600 m FPW), but measurements of the FPW were made separately from the study site along road crossings, where no FPW constriction was visually evident and with the confirmation of topographic maps. In all cases, wetland widths were measured along at least three transects, averaged, and divided by the FPW and expressed as a percent.

Data Analyses

Data were collected for stream order, drainage basin area, stream cross-sectional area, soil, overbank flow duration, above-average flow duration, percent of the flood-prone width that is jurisdictional wetland, and wetland width. Percentages were converted to proportions and transformed using an arcsine transformation. Scatter plots were created for all quantitative data, and regression lines were drawn with the best fit. Outliers were removed in the analysis of percentage wetland on the basis of the presence of non-climatic influences (excessive withdrawal or input to stream discharge) limiting or enhancing wetland status. In the wetland width analysis for the central plains, one outlier was removed that had exceptional wetland width for cross-sectional width and one that had exceptionally low wetland width to cross-sectional area. In North Carolina, one site was removed from the wetland width analysis because of its proximity to a large river.

RESULTS

Central Plains

The wetland percentage of the flood-prone width (FPW) decreased non-linearly as PET ratios (potential evapotranspiration/precipitation) increased (Figure 3a). All central plains sites up to a PET ratio of 0.88 had wetlands associated with them. However, some floodplains maintained wetlands up to a PET ratio of 0.98, and two with PET ratios of 0.89 and 0.90 had wetlands greater than 40 m wide.

Stream order increased slightly with drainage basin area, and cross-sectional area increased with stream order, but wetland width was only weakly related to stream order (Figure 3b, Table 2). Central plains streams did not show an increase in the percentage of FPW that is wetland with increasing stream order (Figure 3c, Table 2).

The cross-sectional area of the stream channels ranged from 2.8 m^2 to 144.5 m^2. There appeared to be no relation between cross-sectional area and percent of

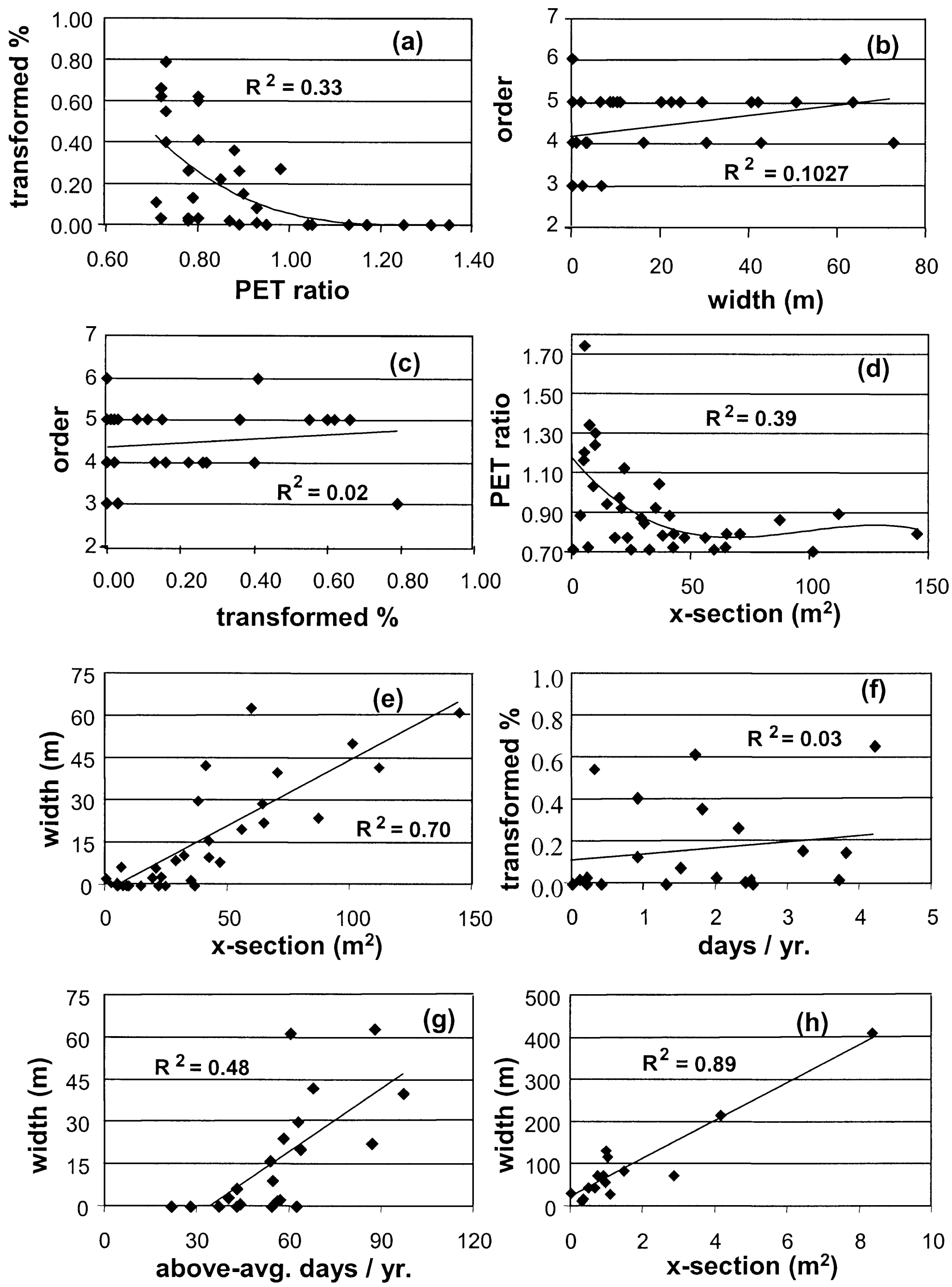

Figure 3. Relation between climatic, geomorphic, hydrologic, and wetland variables: (a) transformed percent of the flood-prone width (FPW) that is wetland as a function of the PET ratio (potential evapotranspiration/precipitation) (central plains), (b) wetland width as a function of stream order (central plains), (c) transformed percent of the FPW as a function of stream order (central plains), (d) cross-sectional area of the stream as a function of PET ratio (central plains), (e) wetland width as a function of cross-sectional area (central plains), (f) transformed percent of the FPW that is wetland as a function of overbank flow duration (yearly averages, central plains), (g) wetland width as a function of the duration of flow exceeding average (yearly averages, central plains), (h) wetland width as a function of cross-sectional area (North Carolina).

FPW that is wetland at the central plains sites. Cross-sectional areas decreased in response to a rise in the PET ratio (Figure 3d). Greater channel cross-sectional areas were associated with greater wetland widths. With the removal of two outliers (sites 9 and 18), the r^2 was 0.70 (Figure 3e, Table 2). Drainage basin areas did not correlate with the percentage of the FPW that is wetland or with wetland width (Table 2). Gaged drainage basin size increased with PET ratio as a result of selecting USGS stations that monitor mean daily

Table 2. Regression coefficients (r^2) and p-values for central plains and North Carolina study sites. PET ratio = potential evapotranspiration/precipitation. FPW = flood-prone width.

Correlation	Central Plains		North Carolina	
	r^2	p	r^2	p
Percent of the FPW that is wetland as a function of:				
PET ratio	0.33	0.01	—	—
Drainage basin area (km^2)	<0.01	0.89	—	—
Stream order	0.02	0.42	—	—
Channel cross-sectional area (m^2)	0.03	0.34	—	—
Overbank flow duration (d)	0.03	0.44	—	—
Above-average flow duration (d)	0.30	0.02	—	—
Soil texture	0.02	0.55	—	—
Wetland width (m) as a function of:				
PET ratio	0.21	0.02	0.00	0.99
Drainage basin area	0.06	0.22	0.64	<0.01
Stream order	0.10	0.06	0.01	0.68
Channel cross-sectional area	0.70	<0.01	0.89	<0.01
Overbank flow duration	0.14	0.08	—	—
Above-average flow duration	0.48	<0.01	—	—
Soil texture	0.04	0.27	0.08	0.36
Channel cross-sectional (m^2) area as a function of:				
PET ratio	0.39	<0.01	0.01	0.66
Drainage basin area	0.09	0.13	0.68	<0.01
Stream order	0.42	<0.01	0.00	0.94
Overbank flow duration	0.11	0.11	—	—
Above-average flow duration	0.32	0.01	—	—
Soil texture	0.08	0.05	0.15	0.20
Overbank flow duration (d) as a function of:				
PET ratio	<0.01	0.99	—	—
Drainage basin area	0.13	0.10	—	—
Stream order	0.15	0.07	—	—
Soil texture	0.07	0.24	—	—
Above-average flow duration (d) as a function of				
PET ratio	0.41	<0.01	—	—
Drainage basin area	<0.01	0.92	—	—
Stream order	0.13	0.11	—	—
Soil texture	0.15	0.09	—	—

discharge. Most streams that have no flow for much of the year are not monitored for mean daily discharge.

Soil texture showed no relation with the width or the percentage of FPW that is wetland. Soil texture was not correlated with the duration of overbank flow. Fine-grained soils were associated with a slightly longer duration of above-average flow durations than coarse-grained soils (Table 2). Fine-grained soils generally sustained steeper banks with greater bankfull depths than the coarse-grained soils.

The average annual duration of overbank flow for streams ranged from 0 to 4.2 days per year. Generally, streams would not exceed bankfull discharge for several years and then, during a wet year, bankfull would be exceeded several times. During the study period, bankfull discharge was exceeded several times on many streams. The best correlations with overbank flow duration for the central plains streams were drainage basin area and stream order (Table 2). For the 23 gaged sites, duration of overbank flow was unrelated to the percent of the FPW that is wetland or to wetland width (Figure 3f).

Above-average flow duration was associated with greater wetland width (Figure 3g) and the percent of the FPW that is wetland (Table 2). The duration of time that stream flow exceeded average discharge responded linearly to increases in PET ratio. Greater durations were also associated with finer soil textures. Above-average flow duration was not a function of drainage basin area or of stream order (Table 2).

Table 3. Average base flow calculated for 6 streams in the central plains, three in relatively humid regions [potential evapotranspiration/precipitation (PET ratio) <1.0] and three in semi-arid regions (PET ratio >1.0).

Locations	Base flow (m^3/sec)	Normalized base flow (m^3/sec/1000 km^2)
Sites with PET ratios <1.0		
Site 2	3.43	7.04
Site 12	3.44	4.81
Site 16	5.72	9.17
Sites with PET ratios >1.0		
Site 30	0.76	1.05
Site 33	0.03	0.03
Site 34	0.65	0.74

Average base flows for the three streams with PET ratios less than 1.0 were one to two orders of magnitude greater than the three sites in more arid regions (Table 3). Differences were more pronounced when normalized by watershed area.

North Carolina

All of the North Carolina sites were 100 percent wetland, except for Phillipi Branch, which was 97 percent. In North Carolina, the stream cross-sections ranged from 0.004 m^2 (20 cm × 2 cm) to 21.6 m^2, consistent with their lower stream orders. North Carolina stream cross-sectional areas did not show a relation with changing PET ratios (Table 2). Increasing cross-sectional areas correlated strongly with increasing wetland width, with an r^2 of 0.89 for North Carolina streams (Figure 3h).

DISCUSSION

The capacity of climate to support wetlands on floodplains diminishes above a PET ratio (potential evapotranspiration/precipitation) of ~1.0 around 97° West longitude and 40° North latitude in North America (Figure 2). This occurs roughly in the grassland region of Küchler (1964), where upland forests are lacking and the Holdridge Life Zone scheme (Holdridge et al. 1971) changes from humid to subhumid provinces (Lugo et al. 1999). Even so, the large variation among floodplain sites suggests that factors other than climate are involved. Moreover, the differences in spatial scale between a broad environmental gradient, dictated by climate, and a more local presence of wetland indicators, dictated by water-table position and inundation, may be responsible for the large variation in this relationship.

Ultimately, the maintenance of wetlands is a function of the proximity of the water-table and the land surface. PET ratios can be expected to explain, at best, only some of the factors involved in supporting wetland conditions. In wetland flats where precipitation is the dominant source of water (Brinson and Malvárez 2002), wetland prevalence is determined more by a lack of effective drainage than by supplemental supplies of water, which typically are lacking in extensive, flat geographic regions (Comerford et al. 1996). In the floodplain sites, two additional sources of water besides precipitation contribute toward maintaining water-tables near the soil surface: (1) sources adjacent to the floodplain as ground-water discharge and overland flow and (2) channel sources through overbank flow and through subsurface movement to the floodplain at high stages. We examine the possibility of these two sources that are not under direct climatic control.

We have no direct measurements of ground-water discharge or water-table positions to explain the presence of wetlands at the study sites. Of the six central plains sites analyzed for base flow, a potential indicator of ground-water discharge to floodplains (Hunt 1999), the three sites with PET ratios <1.0 had discharges one to two orders of magnitude greater than the three sites with PET ratios >1.0. Such differences may be analogous to gaining and losing streams. Duration of flows exceeding the annual mean discharge correlated strongly with higher percentages of wetlands and wider wetlands (Table 2, Figure 3g). This relationship appears to be an effective method of estimating relative ground-water contributions to stream systems where discharge data are available. The duration of above-average discharge method was much more predictive of wetlands than overbank flow duration.

On one hand, greater base flow indicates a greater supply of through-flow in shallow aquifers of floodplains. Conversely, high stream stages supported by base flows derived from upstream variable source areas (Hewlett 1961a, b) can locally reduce water-table gradients across floodplains and thus contribute to the capacity to retain ground water and maintain higher water-tables, possibly leading to greater percentages of wetlands in the floodplain. This pattern takes the form of a positive feedback leading to a greater prevalence of wetlands because of the interaction between base flows and local ground-water tables (Figures 3 and 4). Multiple sources of water may be one explanation for the suggested exponential increase in the proportion of flood-prone area occupied by wetland. In fact, in areas with little topographic relief, such as in the North Carolina coastal plain, wetlands can extend beyond the floodplain.

Interestingly, the duration of overbank flow was not related to percentage of FPW that is wetlands. This may have been due to the small difference between

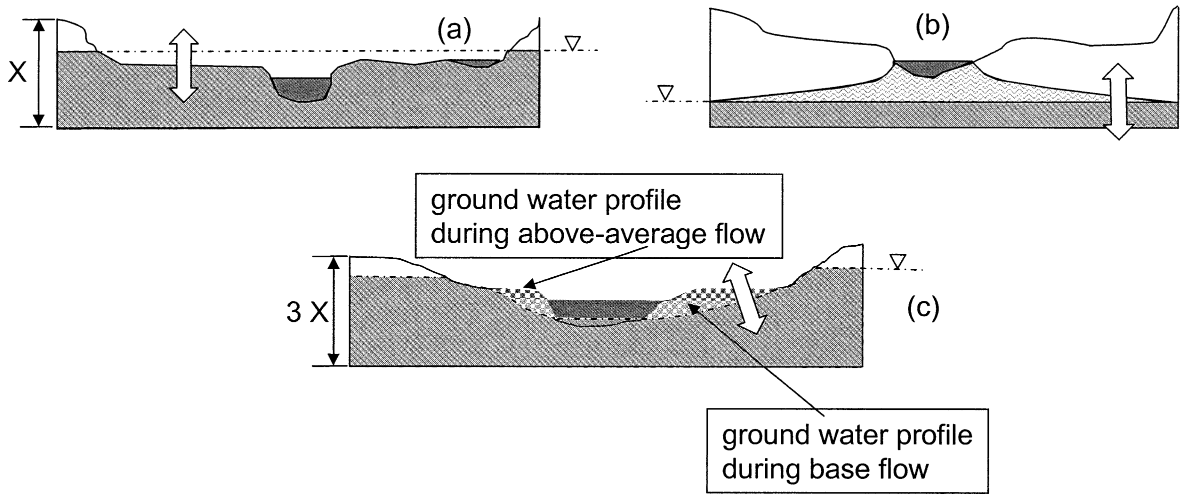

Figure 4. Cross-sections of streams showing contrasting hydrologic regimes of floodplains. (a) In humid regions (North Carolina coastal plain) where ground water supports stream flow and floodplain hydrology, overbank flow is not necessary to maintain wetlands. (b) In semi-arid regions (west side of central plains study region) where stream flow is lost to ground water, wetlands can be maintained by supplemental sources (irrigation return flow, stream flow from outside the region). (c) In humid regions (east side of central plains study region) where ground-water levels are normally too deep to support high percentages of the flood-prone width as wetland but high enough to support stream flow (high hydraulic gradient), there may be an interaction between high stream stages and the water table that supports wetlands. ∇ = water-table level.

the lowest and highest duration (0.0 and 4.2 d, respectively), too small to show an effect by overbank flow. Our estimate is conservative, given that in order for a day to be counted as bankfull flow, average daily discharge had to be greater than or equal to bankfull discharge. Some short overbank events (less than 1 d), which probably exceeded bankfull, may not have been counted because of their low average daily discharge, and peak daily discharge values are not widely available. While a lack of correlation may be due to the low resolution of our overbank calculations, we also observed that the central plains streams had little capacity to pond water after overbank flow events, in contrast to those in North Carolina.

Additional sources of variation between wetland extent and climate may be due to disturbance by cropland encroachment on portions of some FPAs, especially during the growing season when data were collected. (All crops were obligate upland species.) Although preference was given to non-agriculturally altered reaches, complete avoidance of agricultural influences was impossible. Entrenched streams were common and might have been influential in more rapid ground-water drainage from floodplains due to increased hydraulic gradients. However, greater stream cross-sections (width × depth), regardless of drainage basin area, stream order, or PET ratio, showed increased wetland width (Figure 3e). We observed that deeper channels tended to be cut into fine-grained soils whose hydraulic conductivities are low and have thicker capillary fringes (Hunt 1999), thus possibly counteracting the potentially better drainage that might otherwise be associated with channel entrenchment. The lack of correlation between basin area and any of the indices of wetland prevalence may have been due to bias introduced by selecting only gaged streams. Stage data are generally available only for perennial and some intermittent streams. As climate becomes drier (higher PET ratio), larger watersheds are required to sustain sufficient flow to warrant monitoring. Consequently, the driest study sites had the largest watersheds, while the methods used in this study were inappropriate for equivalent sized watersheds in humid climates.

PET ratio was the dominant factor in determining the percentage of FPW as wetland. At PET ratios below 0.98, it would appear that a decrease in this ratio generally allows greater proportions of floodplains to be occupied by vegetation and soils reflective of high water-tables. In north central Oklahoma, just south of the study area, floodplain forest composition increases in species richness and diversity in response to increasing wetness in the climatic moisture gradient (Collins et al. 1981), a trend that was observed in this study.

Hypothetically, wetlands can occur in the driest climatic regimes, as long as sources of water are available to maintain water-tables close to the soil surface. Such geomorphic and geologic conditions for these hydrologic anomalies were avoided in site selection in order to explore the influence of the climatic gradient of moisture regime. In the more typical situations studied, however, there is no reason to expect that semi-arid floodplain hydrology is fundamentally different from that of more humid climates but is mainly a response to a climatic gradient. This study strengthens the evidence that floodplains lacking wetlands in semiarid climates function similarly to floodplains in humid climates (NRC 2002).

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