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Comparison of Hydrology of Wetlands in Pennsylvania and Oregon (USA) as an Indicator of Transferability of Hydrogeomorphic (HGM) Functional Models Between Regions

CHARLES ANDREW COLE*
ROBERT P. BROOKS
Penn State Cooperative Wetlands Center
301 Forest Resources Laboratory
University Park, Pennsylvania 16802, USA

PAUL W. SHAFFER
Dynamac Corporation Environmental Services
200 SW 35th Street
Corvallis, Oregon 97333, USA

MARY E. KENTULA
United States Environmental Protection Agency
NHEERL-WED
200 SW 35th Street
Corvallis, Oregon 97333, USA

ABSTRACT / The hydrogeomorphic (HGM) approach to wetland classification and functional assessment is becoming more widespread in the United States but its use has been limited by the length of time needed to develop appropriate data sets and functional assessment models. One particularly difficult aspect is the transferability among geographic regions of specific models used to assess wetland function. Sharing of models could considerably shorten development and implementation of HGM throughout the United States and elsewhere. As hydrology is the driving force behind wetland functions, we assessed the comparability of hydrologic characteristics of three HGM subclasses (slope, headwater floodplain, mainstem floodplain) using comparable long-term hydrologic data sets from different regions of the United States (Ridge and Valley Province in Pennsylvania and the Willamette Valley in Oregon). If hydrology by HGM subclass were similar between different geographic regions, it might be possible to more readily transfer extant models between those regions. We found that slope wetlands (typically groundwater-driven) had similar hydrologic characteristics, even though absolute details (such as depth of water) differed. We did not find the floodplain subclasses to be comparable, likely due to effects of urbanization in Oregon, regional differences in soils and, perhaps, climate. Slight differences in hydrology can shift wetland functions from those mediated by aerobic processes to those dominated by anaerobic processes. Functions such as nutrient cycling can be noticeably altered as a result. Our data suggest considerable caution in the application of models outside of the region for which they were developed.

Attributing functions to various wetlands is difficult without an organizing classification scheme. Over the last 20 years in the United States, wetland classifications (and inventories) have been grounded primarily upon the method of Cowardin and others (1979). This classification is based strongly upon plants and soils (with hydrological modifiers) within a hierarchical structure of major wetland systems (i.e., marine, estuarine, riverine, lacustrine, and palustrine). The approach is not without problems, as two of the original authors of the classification scheme recently discussed (Cowardin and Golet 1995). Problems include issues with definitions of a wetland and classification taxa, as well as limits with remote sensing and wetland functional assessment. One significant problem they identified was the lack of ecological data for many wetland systems upon which to base a classification and functional assessment.

In an effort to address issues with wetland functional assessment in the United States, the US Army Corps of Engineers has promoted the development and testing of the hydrogeomorphic (HGM) approach to wetland classification and assessment (Brinson 1993, 1995, 1996). The approach compares the function of an individual wetland only to other wetlands of the same class within a region. This type of classification ignores the dependence on plants and focuses more position in the landscape, source of water, and the dynamics of that water on site. It is similar in that way to a regional

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*Author to whom correspondence should be addressed at current address: Center for Watershed Stewardship, Penn State University, 227 East Calder Way, University Park, Pennsylvania 16801, USA; *email:* cac13@psu.edu

classification scheme developed in Australia by Semeniuk (1987) and proposed for international use by Semeniuk and Semeniuk (1995).

The HGM classification differs from the classification of Cowardin and others (1979) in a number of ways. For example, three wetlands in the same slope landscape setting with similar hydrologic regimes could easily be an open meadow, a shrub thicket, and a forest. The Cowardin classification might refer to these as palustrine emergent, palustrine scrub–shrub, and palustrine forested wetlands. The HGM classification, however, would refer to these merely as slope wetlands. The vegetation component would be included in the functional assessment but not the classification of the wetlands.

According to the HGM classification hierarchy, wetlands are grouped into national-level classes (Smith and others 1995) under which regional subclasses are defined (e.g., Cole and others 1997), and an analogous structure is followed for the development of assessment models. For example, the US Army Corps of Engineers has developed national, functional assessment models for several HGM classes for use as guides for developing regional models (Smith and others 1995). The advent of the national and regional models has focused attention on HGM and its underlying assumptions (e.g., Cole and others 1997, Hruby 1997, 1998, Rheinhardt and others 1997, 1999, Hauer and Smith 1998, Gwin and others 1999, Shaffer and others 1999, Cole and Brooks 2000). What has been lacking are actual field data for use in developing regional applications and testing underlying assumptions (Shaffer and others 1999).

The HGM approach was designed to be relatively rapid in its application for wetland classification and assessment (Brinson 1995, 1996). Development of regional models and associated guidebooks has been estimated to take one to two years for each subclass in each region (Ainslie and Sparks 1999), but advancement of the approach has lagged behind projected time lines. The delays encountered are reflective of the general lack of key information on wetlands, particularly information applicable at regional scales. The effort necessary to implement specific HGM models can be illustrated by recent work in North Carolina and Pennsylvania. Rheinhardt and others (1999) closely examined *one* HGM subclass (headwater streams and associated wetlands) in North Carolina and tested a *single* function (biogeochemical cycling). Over several months, they were able to determine a subset of variables useful for assessing hydrologic alteration in the wetland system. Similarly, it has taken over four years to collect and analyze sufficient hydrologic data to support functional models of hydrology for four regional subclasses in Pennsylvania (Cole and others 1997, Cole and Brooks 2000). The development time for HGM and for other tasks requiring similar data could be shortened if we had guidelines for when regionalization was necessary or when and how available information could be extrapolated among regions.

Our work in Pennsylvania and Oregon indicates that HGM class can be used to predict wetland characteristics—hydrology (Cole and others 1997, Shaffer and others 1999, Cole and Brooks 2000), soils (Bishel-Machung and others 1996, Shaffer and Ernst 1999), vegetation (Magee and others 1999)—and confirms Brinson's (1993) premise that HGM classification groups wetlands with similar structure and function. Brinson (1993) also maintains that HGM classification emphasizes features of wetlands that are relatively independent of the biogeographical distribution of species and requires recognition of factors external to the wetland. Therefore, the conceptual framework for HGM is broad and the ability to extrapolate information is implicitly inherent to the HGM approach. An important question to ask, then, is "How well do the classes themselves (e.g., the national slope class) hold up across regions?" For example, if there are such discrete entities as "slope" wetlands, do slope systems behave similarly across a wide range of latitude and longitude? If so, this implies that slope wetlands in the central Appalachian mountains would behave similarly to slope wetlands in the Willamette Valley in Oregon. Details might differ, but relative response should be comparable. For example, as a class, slope wetlands generally might have very little surface water throughout the year, while actual water levels (or temporal patterns of water level) in slope wetlands might be reflective of regional climate patterns.

If the HGM approach is valid and robust, we would expect broad similarities within subclasses across diverse geographic areas. Such similarities, if they exist, are important in that regionalization of HGM subclass models might be expedited if regions could readily share models and methods. Sharing models could lower costs and greatly improve implementation of HGM classification and assessments nationwide. If not true, then knowing which regional and climatic factors are important could guide the establishment of regional subclasses and indicate when regionally specific models were needed. As Montgomery (1999) has stressed, a major challenge confronting efforts to integrate an understanding of geomorphic process into ecosystem management is how to compare such influences both across and within physiographically diverse regions and to use such information to guide sampling strategies.

Our research in central Pennsylvania and Portland, Oregon, offers an opportunity to help answer questions pertaining to the scale at which regionalization is important and necessary and identify factors that limit extrapolation of data or HGM models from one locale to another. In this paper we assess the ability to generalize functions of slope and riverine wetlands in two geographically separated regions based solely on hydrologic data. Specifically, we compare the hydrologic characteristics of wetlands in central Pennsylvania and Portland, Oregon, and explore possible explanations for similarities and differences.

In this manuscript we consider the following questions, with the presumption of no difference as our null hypotheses.

1. Is the periodicity and duration of soil saturation and inundation of different subclasses (i.e., the relative wetness of each subclass) consistent between central Pennsylvania and Portland, Oregon?
2. Are the fundamental hydrodynamics of wetlands in the same HGM subclasses (i.e., magnitude of water level fluctuation) consistent between central Pennsylvania and Portland, Oregon?
3. How temporally stable are conditions and relationships in and among classes in the two regions (e.g., from year to year)?

The management implications of these hypotheses are clear. The long lead time for model development is one reason that the HGM approach has only been slowly implemented in the United States. Analyses such as are presented in this manuscript could do much to hasten the sharing of models, when applicable, and help to prevent wasting time and resources in instances where models should not be shared due to fundamental ecological differences.

Methods

The wetlands we assessed are subsets of wetlands previously characterized for a variety of ecological studies. The Portland, Oregon, wetlands (hereafter referred to as Oregon wetlands) are a subset of sites used for comparison of natural and mitigation wetlands (Shaffer and Ernst 1999, Gwin and others 1999, Magee and others 1999), with hydrologic work completed on approximately half of those sites (Shaffer and others 1999). The central Pennsylvania wetlands (hereafter referred to as Pennsylvania wetlands) are a subset of sites characterized for soils (Bishel-Machung and others 1996), plants (Goslee and others 1997), and sedimentation (Wardrop and Brooks 1998), with hydrology described by Cole and others (1997) and Cole and Brooks (2000).

In this study, we compare and contrast the wetlands in the regions, utilizing the extensive data sets available from both areas, to identify and then compare these ostensibly similar groups of wetlands as defined by their hydrogeomorphic (HGM) classifications. For the Pennsylvania sites, HGM subclasses included slope (SL), headwater floodplain (HWF), and mainstem floodplain wetlands (MSF), as defined in Cole and others (1997). Slopes typically have a strong groundwater component, whereas the floodplain classes are primarily driven by surface water. Differences in classification of wetlands in each region could have resulted in artificial differences in perceived hydrologic behavior. As such, we used the Pennsylvania HGM classification (Cole and others 1997) for all Oregon sites. Slope wetlands are located on a topographic slope with a unidirectional flow of water. The floodplains are distinguished by stream order (headwater as second order or less and mainstem third order or greater).

Site Descriptions

Pennsylvania. Wetlands were located primarily within the Ridge and Valley Province of central Pennsylvania (Shultz 1999). For our analyses, we used data from 18 wetlands (8 SL, 6 HWF, 4 MSF) (see HGM key in Cole and others 1997). Hydrologic data have been previously reported for most of the sites (Cole and others 1997, Cole and Brooks 2000). The HGM subclasses were three of the four most common to central Pennsylvania (the fourth, riparian depressions, had no Oregon analog in the sample used in this study). The Pennsylvania wetlands were all palustrine, varying from emergent (PEM) to scrub–shrub (PSS) and forested (PFO) (Cowardin and others 1979). Sites varied in area between 0.2 and 2.4 ha.

Land use surrounding the Pennsylvania wetlands varied from undisturbed forest on the ridge tops to agricultural and urban influences along the valley floors (Brooks and others 1996). Historically, almost all of Pennsylvania has been logged, leaving few truly undisturbed areas. However, many of the Pennsylvania ridgetop sites had not been logged in several decades, resulting in typically completely forested conditions. The valley sites were frequently located within an agricultural landscape.

Oregon. Oregon wetlands were located in the Portland metropolitan area (within the Portland urban growth boundary) and in the Willamette Valley plains subecoregion (Omemik 1988, Clarke and others 1991). For analyses reported here, we used data from 16 wetlands (5 SL, 6 HWF, 5 MSF). Each wetland assessed had hydrologic data from a previous study (Shaffer and others 1999). These HGM subclasses were historically

Table 1. Soils summary data from Pennsylvania and Oregon[a]

Soil series	Texture	Wetlands (N)	Parent material	Drainage	Flood frequency	Permeability	% rock >75 mm	% rock >2 mm	% rock <0.425 mm	% rock <0.074 mm
Pennsylvania[b]										
Atkins	silt loam	3	acid, sandstone, shale, floodplain, alluvium	poor	frequent	slow to moderate	0	0–10	80–100	60–95
Andover	channery loam	1	sandstone, siltstone, shale, colluvium	poor	infrequent	slow	0–10	10–30	65–85	45–65
Brinkerton	silt loam	3	siltstone, shale, sandstone, colluvium	poor	none	slow	0–10	0–10	85–100	80–100
Buchanon	silt loam	1	sandstone, siltstone, shale colluvium	moderately well	rare	moderate to slow	0–20	25–60	35–70	25–55
Dunning	Silty clay loam	3	limestone and shale colluvium	poor	frequent	slow to very slow	0	0–5	90–100	85–100
Ernest	channery silt loam	1	siltstone, shale, sandstone colluvium	moderately well	low		0–15	0–20	75–95	70–95
Lindside		1	limestone and shale colluvium	moderately well	occasional	moderate	0	0–5	90–100	70–95
Melvin	silt loam	4	limestone, shale colluvium	poor	frequent	moderate	0	0–10	80–100	65–90
Melvin & Newark	silt loam	1	limestone alluvium	poor	frequent					
Oregon[c]										
Cove	clay/silty clay loam	5	recent clayey alluvium	poor	common, brief	very slow	0	0	90–100	75–95
Huberly	silt loam	2	mixed silty alluvium	poor	none	slow	0	0	90–100	75–95
Sauvie	silt loam	1	recent alluvium, some ash	poor	frequent, long	moderately slow	0	0	90–100	80–95
Verboot	silty clay loam	4	stratified fine alluvium	poor	frequent, brief	very slow	0	0	90–100	80–95
Wapato	silty clay loam	4	recent alluvium	poor	frequent, brief	moderately slow	0	0	95–100	85–95

[a]Cells without data indicate a lack of available information.
[b]USDA (1966, 1978, 1981a, b).
[c]Green (1982, 1983).

among the most common to the Willamette Valley, but their extent has been significantly reduced by agriculture and urbanization.

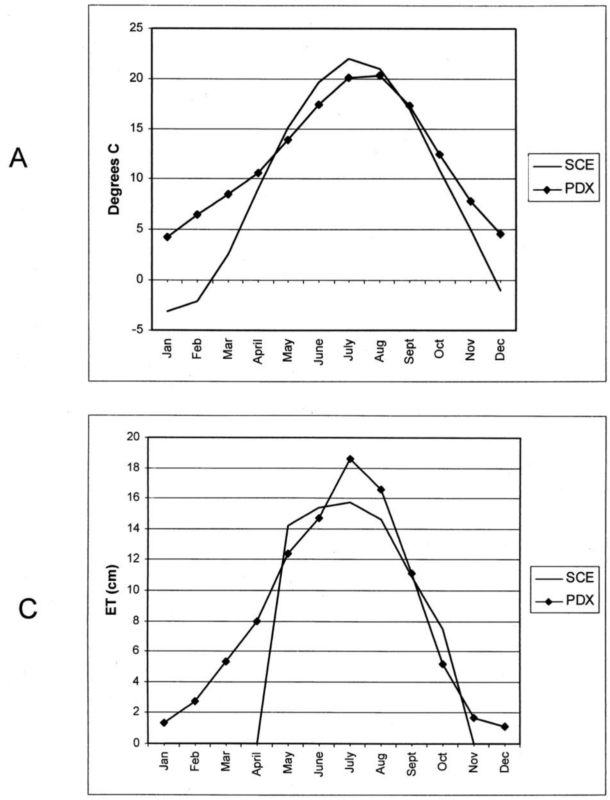
The Oregon wetlands were all palustrine, ranging from emergent (PEM) to open water (POW) (Cowardin and others 1979), and varying in size from 0.05 to 1.36 ha. The surrounding land use was variable, and included a mixture of undeveloped lands (forest, open water, scrub–shrub, and marsh), agriculture, residential, and commercial/industrial (Magee and others 1993, Shaffer and Ernst 1999). Some wetlands were altered by beaver (*Castor canadensis*) activity during the study.

Soils

A variety of soil types underlie both the Pennsylvania and the Oregon wetlands (Table 1). Most soils from both regions lack large fragments, although in Pennsylvania four sites were located on series with some rock fragments. Drainage is generally poor for both Pennsylvania and Oregon soils. Flooding ranges from none on slopes to frequent on floodplains. Fourteen of 18 Pennsylvania wetlands (78%) formed on colluvial soils, whereas all of the Oregon soils were formed on alluvial materials (Table 1). There were small but systematic differences between the regions, suggesting better water retention for Oregon wetland soils.

Climate

Pennsylvania. The regional climate is moderate, with an average annual temperature at the University Park Airport (SCE) of 10°C, with a range of monthly averages from −3°C (January) to 22°C (July) (Figure 1A).



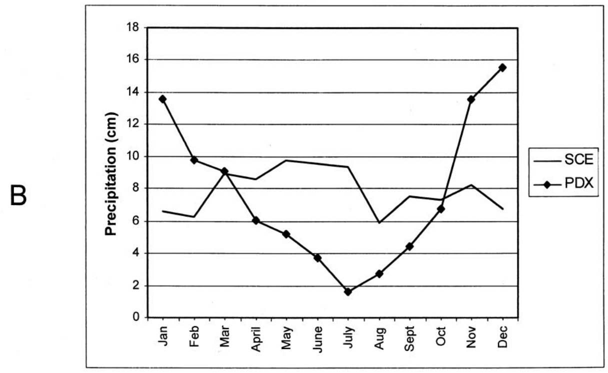


Figure 1. General climatic characteristics [**A**, air temperature; **B**, precipitation; **C**, evapotranspiration (ET)] for the study areas in Pennsylvania and Oregon. The Pennsylvania data were collected from the State College airport (SCE) and the Oregon data from the Portland International airport (PDX). All frozen precipitation is melted and recorded as liquid.

Average annual precipitation (1930–1998) is about 102 cm, but during the study ranged between 88 cm in 1995 (86% of normal) and 144 cm in 1996 (141% of normal). Precipitation is relatively evenly distributed throughout the year (Figure 1B), with frozen precipitation contributing a substantial amount. Evapotranspiration (ET) typically occurs between May and November, averaging 78 cm/yr, with a peak of 16 cm in July (Figure 1C).

Oregon. The regional climate is mild, with an average annual temperature at Portland International Airport (PDX) of 12°C, with a range of monthly averages from 4°C in January to 20°C in August (Figure 1A). Precipitation (mostly rain) at PDX is seasonal (Figure 1B) and averages 93 cm/yr (1961–1990), but varied widely during the study period. In water year (WY) 1994, the area received only 61 cm (66% of normal), while in 1996, PDX received a record 161 cm (175% of normal), resulting in two major regional floods. Precipitation is seasonal, with 74% falling between October and March. Evapotranspiration averages 99 cm/yr and occurs year round, with a low during January (1 cm) and a peak during August (19 cm) (Figure 1C).

While average climatic conditions for the two regions are similar, a comparison of intraannual variability shows substantial differences. State College has much colder winters than does Portland and slightly warmer summers. The pattern of precipitation differs as well, as precipitation is well-distributed throughout the year in Pennsylvania, and western Oregon exhibits a strong seasonal pattern (wet winters and dry summers). Evapotranspiration temporal patterns are similar, although some 27% higher in Portland. The resulting patterns of moisture surplus/deficit (precipitation minus ET) are markedly different between State College and Portland (Figure 2) and could affect wetland water availability. In western Oregon there is an ample surplus of moisture during winter, even during drought years, and a large moisture deficit occurs every summer. State College also has consistent winter moisture surpluses, but because considerable winter precipitation occurs as snow, the timing for moisture availability as runoff or groundwater recharge varies. In some summers, State College runs a moisture deficit; in others a surplus.

Data Collection

In Pennsylvania, water level data were collected every 6 hours from October 1996 to September 1999 (three water years) using WL40 and WL20 automatic recorders (Cole and Brooks 2000). Measurements had an accuracy equal to 1% full scale and a resolution of 0.5 cm. Depth of water was determined by reference to

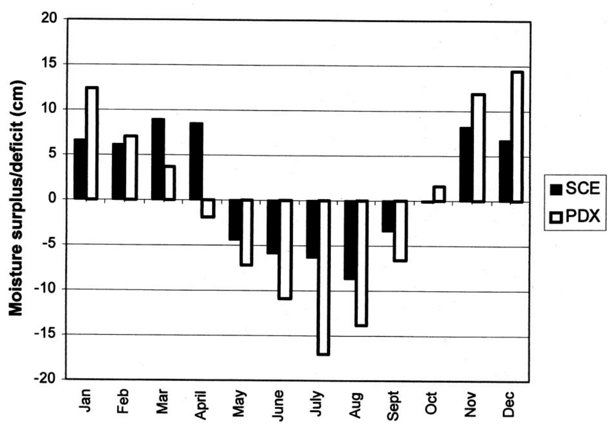


Figure 2. Average monthly moisture surplus/deficit for Pennsylvania (PA) and Oregon (OR). Surplus/deficit was calculated as precipitation minus evapotranspiration from data collected at the regional airports (SCE, University Park Airport; PDX, Portland International Airport).

a calibration point permanently marked on the exterior of the well and was recorded as positive (above ground) or negative (below ground). Gauges were spread across any perceived hydrologic gradient, covering a range of saturation and inundation levels.

Hydrologic data collection in Oregon wetlands began in late 1993 and continued through January 1997. We use calendar year data from 1994 to 1996 for the analyses in this paper. Water levels were observed every two weeks at a staff gauge (when there was standing water) or in a shallow well. Gauges were often placed near the lowest part of a wetland and likely described the wettest area of any site. See Shaffer and others (1999) for more detailed methods.

Although hydrologic data were collected at different time periods for the two regions, this should be of little consequence to the assessment. Our goal was to determine the applicability and robustness of the data across a wide longitudinal gradient. Implicit (and inevitable) in such a comparison are differences in climate and other factors that can affect comparisons, regardless of the timing of data collection. For example, an El Niño event could (and did) lead to very different climatic conditions between the two regions within the same years.

For this regional review, monthly values were used for water depth. We have found that monthly means of water depth are suitable measures for describing average hydrologic behavior (Shaffer and others 2000). For comparisons of subclass characteristics between regions, we aggregated the 6-hour data from Pennsylvania to monthly median values over the three-year period ($N = 36$). Medians were used as some readings were below detection (i.e., dry). For Oregon, the biweekly (usually 2× per month) values were combined to provide a single mean value for a month (typically equivalent to the median value). Each group also developed mean monthly values ($N = 12$) by HGM subclass by averaging monthly median values over three years for each wetland within each subclass. It is important to understand that the use of monthly averages masked instances of very high water (typically lasting for several days) in some Pennsylvania floodplains such that it appeared these sites never flooded, when in fact, they did.

Hydrologic Attributes

Choice of hydrologic attributes used in our analyses was based upon previous experience, as we have found that a few attributes are useful indicators for characterizing and comparing hydrologic conditions in and among HGM subclasses (Cole and others 1997, Cole and Brooks 2000, Shaffer and others 1999, 2000). Examples of such attributes, used here, include median depth of water (or median stage), the interquartile range of median depths, the percent time water is found in the root zone (within 30 cm of the surface), and the percent of time soils were saturated or inundated (water at or above ground surface). These select attributes are useful for representing and contrasting hydrologic regimes in groups of similar wetlands.

Statistical Analyses

We used ANOVA (Zar 1984) to assess differences between HGM subclasses within each region. We compared the three subclasses (slope, headwater floodplain, mainstem floodplain) using median depth (or stage) of water to determine if median water levels for each subclass ordered in the same way between regions. If subclasses are equivalent between regions, at a minimum, we would expect that the relationships between subclasses (in terms of water levels) within and between regions to be stable from year to year. That is, the rank order of median depth should not vary even though the median depths might vary from year to year. We also determined whether wetlands in Pennsylvania were hydrologically equivalent to wetlands in the same subclass in Oregon. We compared average median depths by HGM subclass using a paired t test (the HGM subclass in each region being the basis for pairing). We also compared the percent time water was within the root zone (by HGM subclass) using simple χ^2.

Finally, using data for monthly averages for each HGM class in each study area, we used spectral analysis (Statsoft 1999) to characterize and compare the occurrence of temporal (e.g., annual) variability in water levels among HGM classes and study areas. Spectral analysis is a form of analysis of variance of time series data, in which variance is partitioned into contributions for frequencies that are harmonics of the length of the data set (Platt and Denman 1975). Results of our analyses are plotted as spectral density against period (cycles per year), where spectral density represents the component of total variance (i.e., for all monthly values of stage) associated with the cycle for any harmonic period for the data set (e.g., an annual cycle). Platt and Denman (1975) recommended a maximum lag in spectral analyses of no more than one fourth the period of record. Our short periods of record (36 months), relative to the likely dominant period of expected variability (i.e., 12 months, or an annual cycle), leave us short of this recommended limit. Therefore, results will be presented and discussed from a qualitative perspective only. All statistical analyses were accomplished by using Minitab 12.2 (Minitab 1998) and Statistica, '99 Edition (Statsoft 1999). All differences were considered to be significant at $P < 0.10$.

Results

General Hydrologic Characteristics and Relationships Among Classes Within Regions

Different patterns were evident in water levels among the three subclasses in Pennsylvania and Oregon (Figure 3). In Pennsylvania, the three subclasses were significantly different ($F = 7.36$, $df = 2$, $P = 0.001$) as SL had the highest water levels, followed by HWF and then MSF wetlands. In Oregon, the three subclasses differed from each other ($F = 11.81$, $df = 2$, $P < 0.001$)) but in a different order. MSF had the highest water levels, followed by HWF, with the lowest water levels in SL. In Pennsylvania, SL had the highest water levels in all three years, including the drought year of 1999 (Figure 3). MSF always had the lowest water levels in Pennsylvania, whereas SL always had the lowest water levels for Oregon (Figure 3). Within each region, the floodplain wetlands were relatively more similar to one another than to the slope wetlands (Figure 3). Absolute changes in water levels between years for Pennsylvania were not large (<25 cm) and were even smaller in the Oregon wetlands (<20 cm) (Figure 3). The small changes in Pennsylvania wetlands were, however, sufficient to drop median water levels below the root zone for some instances, and significantly affected the percentage of time that water was within the root zone for HWF and SL between years.

In general, the timing of maximum and minimum water levels for all subclasses is different between the regions (Figure 4). The wettest periods in Pennsylvania occur somewhat later than in Oregon (March–April vs December–February). The driest periods also occurred later in Pennsylvania (November–December) than in Oregon (August–September).

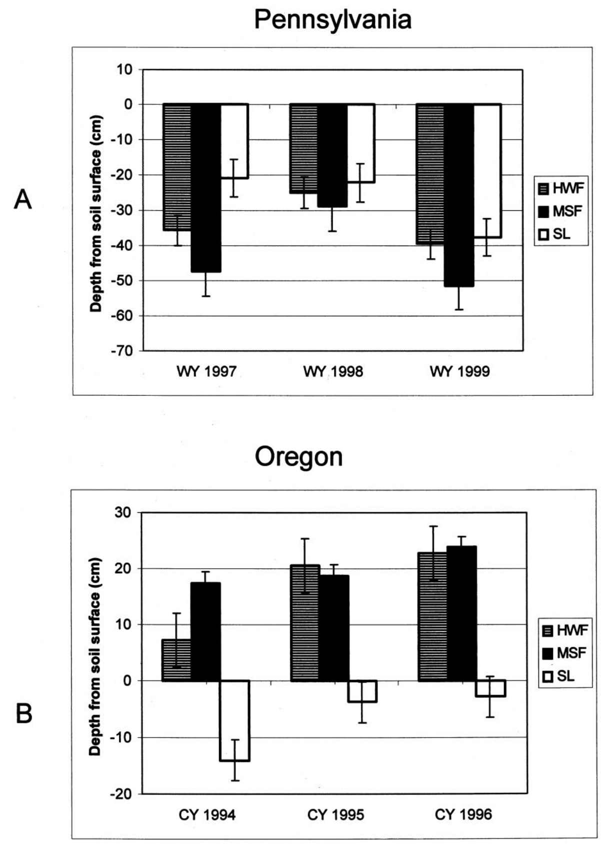


Figure 3. Interannual comparisons of average median water levels (cm) for slope (SL), headwater floodplain (HWF), and mainstem floodplain (MSF) wetlands. Data are for water years (WY) 1997–1999 in **A** Pennsylvania and calendar years (CY) 1994–1996 in **B** Oregon. Bars are standard errors of the mean.

Comparative Hydrology

Slope wetlands. Figure 4A shows annual patterns of water levels in SLs in the two regions. Water levels were lower in Pennsylvania SLs than in Oregon (Table 2). Median depth of water in Pennsylvania was −21.0 cm compared with −2.7 cm in Oregon ($t = -4.68$, $df = 62$, $P < 0.001$) and Pennsylvania SLs had water within the root zone 58% of the time as compared with 78% in Oregon ($\chi^2_{0.05,1} = 4.42$, $P < 0.05$). The average depth of water for Oregon indicates shallow standing water during winter. Standing water is not typical for SLs, but in this instance resulted from the location of some SLs on the sides of terraces adjacent to river floodplains,

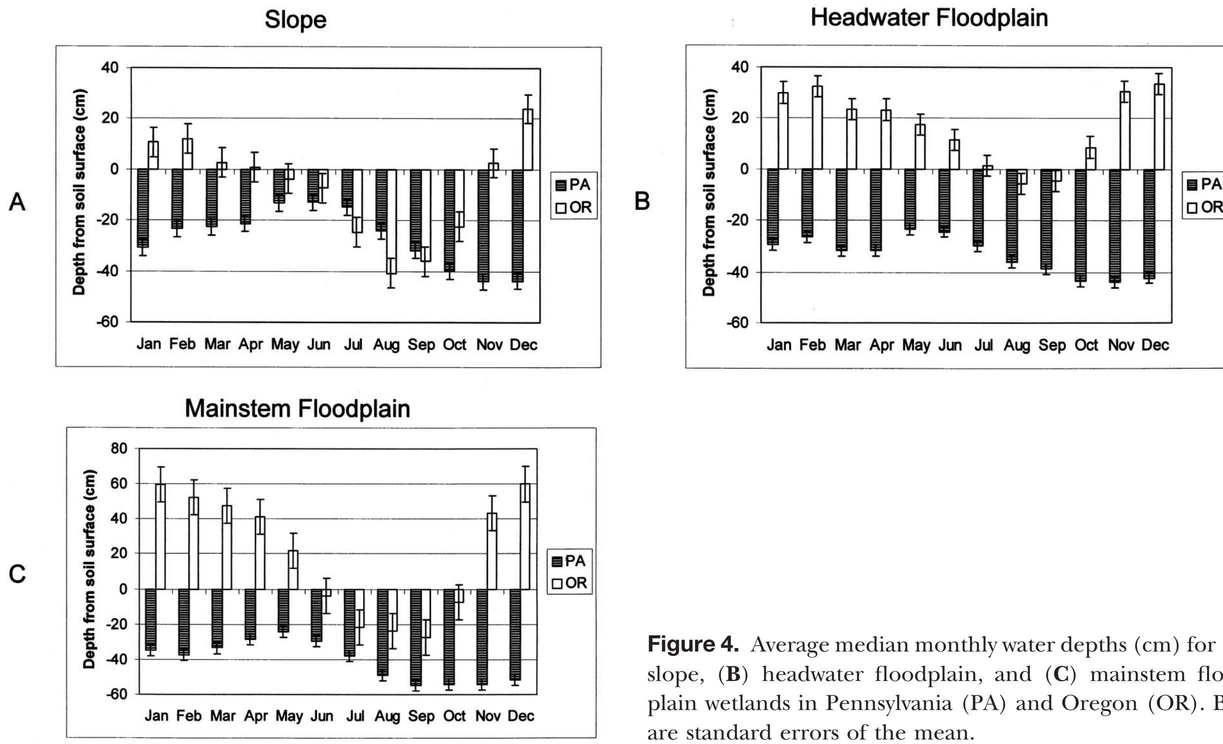


Figure 4. Average median monthly water depths (cm) for (**A**) slope, (**B**) headwater floodplain, and (**C**) mainstem floodplain wetlands in Pennsylvania (PA) and Oregon (OR). Bars are standard errors of the mean.

Table 2. Descriptive statistics of monthly water levels in wetlands of Pennsylvania (PA) and Oregon (OR)[a]

	PA SL	OR SL	PA HWF	OR HWF	PA MSF	OR MSF
Median depth (cm)	**21.0**	**2.7**	**87.6**	**22.9**	**46.3**	**36.0**
% time in root zone (>−30 cm)	**58**	**78**	**33**	**100**	**22**	**89**
% time > 0 cm (inundated)	0	42	0	86	0	64
Maximum depth (cm)	−10.0	30.3	−8.2	39.5	−4.8	69.2
Minimum depth (cm)	−50.6	−46.0	−50.7	−26.0	−61.3	−38.4
Quartile range (cm)	30.0	23.6	18.0	23.0	20.9	62.9

[a]HGM subclasses are slope (SL), headwater floodplain (HWF), and mainstem floodplain (MSF). Cells within a subclass that are bold indicate significant difference ($\alpha < 0.05$) between Pennsylvania and Oregon for median depth or percent time in the root zone. It was not possible to statistically test for differences for the remaining characteristics as some wells were unable to record inundation, floods overran some recorders, leaving true maximum values unknown, and some wells went dry, leaving true minimum values unknown.

where water backed up into the wetlands during major regional flooding in the winters of 1995–1996 and 1996–1997.

Year-to-year variability in annual high and low water levels, and in the timing of changes, were more erratic for the Pennsylvania SLs than the Oregon SLs. The Oregon SLs showed similar seasonal patterns from year to year over the study period, with regular annual wet and dry periods.

Headwater floodplain wetlands. Water levels are very different in HWFs in Pennsylvania as compared to Oregon HWFs (Figure 4B). Monthly values for Pennsylvania rarely exceed −25 cm whereas Oregon HWF's have water above ground level for all months except August and September. Pennsylvania headwater wetlands often become completely dry by October (i.e., water drops substantially below the root zone). Median depth of water was below ground in Pennsylvania HWFs (−37.6 cm) whereas Oregon HWFs were generally inundated (22.9 cm) ($t = -14.28$, $df = 64$, $P < 0.001$) (Table 2). Headwater floodplain wetlands in Pennsylvania had water in the root zone much less than did the Oregon HWFs (33% vs 100%) ($\chi^2_{0.05,\ 1} = 44.11$, $P < 0.001$).

In Pennsylvania HWFs, water levels are generally at or below the bottom of the recorder during the summer and rise near (or above) the surface only during late winter and early spring. Oregon HWFs fluctuate above and below the surface, depending upon the

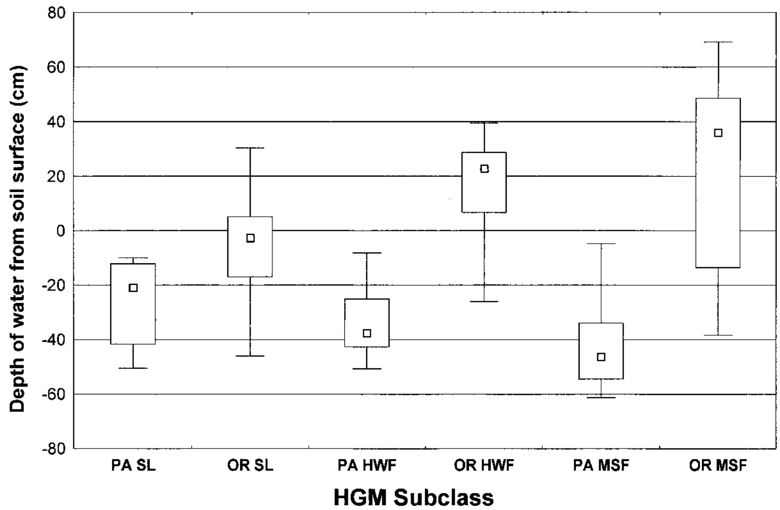


Figure 5. Box-and-whisker plot of median depth of water, by HGM subclass, in Pennsylvania (PA) and Oregon (OR). The whisker indicates the range, the large outer box delineates the 25th and 75th quartiles, and the small middle box shows the median depth. SL = slope; HWF = headwater floodplain; MSF = mainstem floodplain.

amount of precipitation. The timing and duration of seasonal changes was more variable for HWFs for both regions than was seen for SLs.

Mainstem floodplain wetlands. As was the case with HWFs, water levels in Pennsylvania MSFs were much lower than in their Oregon counterparts (−46.3 cm vs +36 cm) ($t = -9.34$, $df = 50$, $P < 0.001$) (Figure 4C). Water was correspondingly much less prevalent in the root zone in Pennsylvania MSFs (22%) than in comparable Oregon sites (89%) ($\chi^2_{0.05,\,1} = 37.90$, $P < 0.001$).

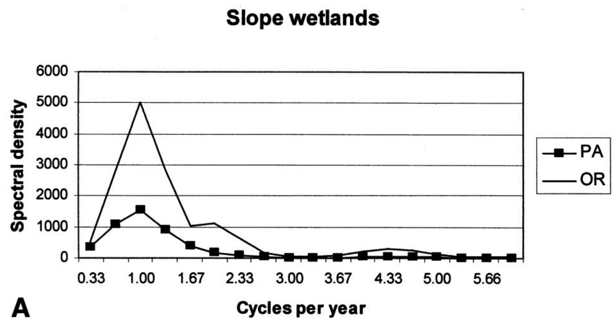
None of the Pennsylvania MSF sites had a monthly average water level above ground surface, whereas the Oregon mainstem sites frequently had standing water from November through March. In the Pennsylvania sites, summer and winter water levels varied substantially from year to year. In contrast, summer and winter levels showed little year-to-year variation in Oregon, despite considerable difference in annual precipitation during the study.

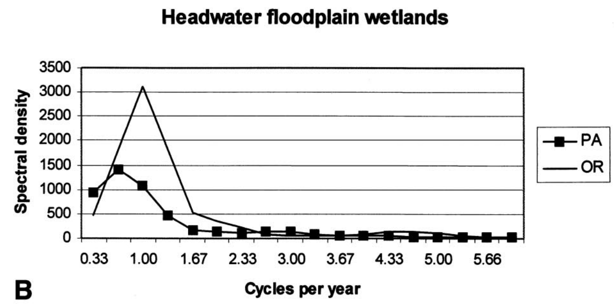
Figure 5 summarizes water conditions for the three HGM subclasses for the Pennsylvania and Oregon wetlands sampled. While data show there is considerable overlap in water level distribution for SLs in the two regions, water regimes for HWFs and MSFs are highly dissimilar between regions. HWFs and MSFs within each region are more similar to each other than the same subclass between regions.

Spectral Analysis of Monthly Water Levels

Results of spectral analysis (Figure 6) show that for slope wetlands in both Pennsylvania and Oregon, there is a clear annual cycle in water level (i.e., a peak in spectral density at a period of one cycle per year). The shoulder on the curve for spectral density for a six-month period (i.e., 2/yr) for Oregon slope sites is unlikely to be a secondary cycle, but rather a harmonic of the annual cycle. Spectral density is much lower for the Pennsylvania slope data; the difference does not indicate a less well-defined annual cycle for Pennsylvania sites, but rather results from an annual range in water level for Pennsylvania sites that is only about half the range in Oregon slope wetlands (Figure 4A).

Like the spectrum for slopes, spectral density data for headwater and mainstem floodplains in Oregon demonstrate a very clear annual cycle, but no semiannual or other temporal cycles in the data (Figure 6). For Pennsylvania wetlands, however, spectra for both headwater and mainstem floodplain wetlands show a less well-defined maxima at a 0.67 cycles per year, suggesting an 18-month periodicity in water level rather than an annual cycle. Rather than a true 18-month cycle, we interpret these results as a reflection of the short data record and erratic seasonality of water levels in Pennsylvania floodplain wetlands during the study. With a longer period of record, it is likely that an annual cycle would be identified in the data. However, because annual wet and dry cycles are much less consistent in Pennsylvania wetlands than in Oregon analogs, the peak in spectral density would probably remain less well-defined than for Oregon sites. Even viewed as an exploratory analysis for our short data set, the spectral analyses suggest systematic differences between floodplain wetlands in the two study areas, as





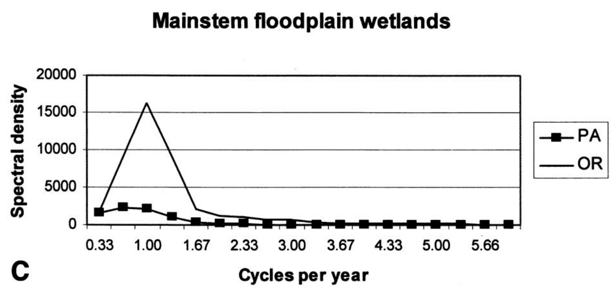


Figure 6. Spectral analysis for **A** slope, **B** headwater floodplain, and **C** mainstem floodplain wetlands in Pennsylvania (PA) and Oregon (OR). Period (the time of return for a cycle) is measured in months. All analyses are for a 36-month period, from October 1996 to September 1999 for Pennsylvania, and January 1994 to December 1996 for Oregon.

more erratic rainfall and runoff results in similarly erratic patterns in water level for associated wetlands.

Discussion

For wetlands in each of the three HGM subclasses, we see strong differences between Pennsylvania and Oregon. Although the regions have generally similar climate in terms of precipitation and temperature, wetlands with similar morphologies have very different water regimes in the two states, with lower water levels, and shorter duration of inundation and water in the root zone in Pennsylvania for all three subclasses. Moreover, the relative hydrologic patterns are different in each state. In Pennsylvania, SLs have the highest water levels and longest duration of water in the root zone; the opposite is true in Oregon. Although median depth of water for SLs is somewhat the same between the two states, the median depth of water for both floodplain wetland subclasses are much different between Pennsylvania and Oregon.

The Pennsylvania classification system (Cole and others 1997) was used in both states, and we saw no evidence to suggest that fundamental hydrologic drivers (e.g., sources of water) were different between regions. We have visited each others' study sites and do not see any inconsistencies that might explain extant differences in hydrology.

Semeniuk and Semeniuk (1995) suggest that climate may play a large role in the overall availability of wetlands throughout a landscape, with drier regions having fewer than more humid regions. Although Oregon was somewhat drier, we do not see the large climatic difference suggested by Semeniuk and Semeniuk (1995) that would lead to large differences in wetland types and character. Both regions experienced large year-to-year differences in precipitation during the study, yet hydrologic patterns remained generally consistent from year-to-year within each region. The large differences in water levels that might be expected if short-term climatic variability was a factor were not evident.

Annual precipitation patterns are very different between the regions, with precipitation generally evenly spread throughout the year for Pennsylvania, and strongly seasonal in western Oregon. As a result, Oregon wetlands appear to always have excess water during winter and experience large moisture deficits during summer. In contrast, while Pennsylvania often has excess water in the winter, it may be stored as a snow pack for considerable periods of time or be locked up in frozen soils. This, then, leads to temporally variable delivery of water to both groundwater and surface water sources. In addition, summer moisture deficits are more erratic in Pennsylvania than in Oregon. The end result is that annual hydrologic patterns are more variable in Pennsylvania and more consistent in Oregon. In addition, there was a more predictable inflow of water into Oregon wetlands during the study period. By contrast, the Pennsylvania floodplain wetlands were relatively dry and subject to a more varied precipitation regime. There was not a significant and persistent snowfall during the three years of hydrologic analysis in Pennsylvania. As a result, these wetlands did not receive a strong inflow of water early in the year. This lack of inflow from annual spring snow melt in Pennsylvania is a possible contributing factor in differing hydrologic patterns in Pennsylvania and Oregon.

The data indicate that there are fundamental differences in the floodplain wetlands between Pennsylvania and Oregon. In Pennsylvania, we do not expect the headwater floodplain wetlands to flood much under any circumstances, as they derive most of their water from overland flow during rain events or snow melt (Cole and others 1997). On top of that distinction, there have been low snowfall totals in central Pennsylvania since 1996. In contrast, it is possible that the Oregon floodplain wetlands have too much water as a result of the effects of urbanization. Thus, it may appear that the Pennsylvania floodplain wetlands do not flood much, when in fact, it is likely that the Oregon floodplain wetlands flood too much (relative to a hypothetical undisturbed condition).

It also seems likely that soils play a large role in regional hydrology. In Pennsylvania, many of the SLs are formed on colluvial deposits at the base of ridges, often leading to a semipermeable layer (Cole and others 1997). The floodplain sites are alluvial in nature, but with a substantial proportion of larger fragments (Table 1). In contrast, the Oregon soils are all fine-grained alluvial materials. There is no coarse material > 2 mm; most soils are silty clays and clay loams with poor drainage and slow or very slow permeability (Table 1). When streams overflow during floods, the resulting flood water is retained in localized depressions at the surface by these impermeable soils for long periods of time. Moreover, as water levels drop during spring and summer, the clays provide considerable capillary rise, maintaining saturated soils even as the water table drops (P. W. Shaffer, unpublished data). With coarser soils in the Pennsylvania wetlands, flood waters may not be retained, but rather drain quickly off the site. These coarser soils also do not provide the substantial capillary rise observed in Oregon wetland soils.

Effects of Hydrology on Function

The importance of constant saturation in Oregon wetlands versus the cyclic wetting and drying in Pennsylvania sites can be inferred by reviewing some functions commonly employed in an HGM assessment. Wardrop and others (1998) developed a set of peer-reviewed HGM models for use in Pennsylvania's Ridge and Valley wetlands. One particular function (cycling of redox-sensitive compounds) clearly shows possible differences based upon hydrology. Fully vegetated sites with a fluctuating water level can be expected to have high nutrient cycling whereas those that are fully vegetated, but with stable water levels, typically have low ability to cycle nutrients. Soils in the Oregon and Pennsylvania slope wetlands were each saturated for long periods and could be expected to be similar in terms of this function. The floodplain wetlands, however, would not be equivalent. The Oregon wetlands would be expected to have a much lower ability to cycle nutrients than the Pennsylvania wetlands due to higher, and more constant, water levels.

An additional function (export of dissolved organic matter) further illustrates this point. The function assumes export of dissolved organic matter is higher in wetlands with a strong anaerobic environment. Wetlands are more anaerobic when there is a more constant water level than when there is not. As a result, the Oregon floodplain wetlands will presumably be functionally very different from their Pennsylvania counterparts in this regard. The SLs, by way of contrast, likely perform this function relatively equally in Oregon and Pennsylvania. The lengthy seasonal inundation of Oregon floodplain sites would be expected to make their soils far more reduced in nature, thus favoring functions occurring in anaerobic conditions. The Pennsylvania floodplain soils, alternating more frequently between wet and dry conditions (and with a shorter duration of wet conditions), would follow a more aerobic functional pathway. These differences in hydrology and soils would likely be reflected in differences in functions and models and would need to be developed for each region as typically suggested for HGM analysis (Smith and others 1995).

Hydrologic Stability

For the three-year periods in both Oregon and Pennsylvania, hydrology remained relatively consistent among subclasses. In Oregon, HWFs always had the greatest median water level, followed by MSFs and then SLs. In Pennsylvania, SLs always had the highest median water level, followed by HWFs and then MSFs. Our assessment seems to indicate that HGM subclass distinctions are consistent and reliable. The HGM classification for Pennsylvania was useful in classifying Oregon wetlands (even if functional assessments were likely different for the floodplain wetlands).

Although we found differences between regions relative to HGM subclass hydrology, we also found similarities. How, then, might we apply the knowledge from one region to another without overstepping reasonable bounds? Our most successful comparisons were with SLs. Although not identical, general hydrologic characteristics (e.g., median depth) were more similar with this subgroup than with the floodplain subclasses. Slope wetlands in both regions were generally saturated for much of the year, although Oregon sites were saturated for longer periods. As a result of these similarities, we believe that a SL model developed for one region might well be successfully applied in the other. As a result of similar hydrologic regimes, both Pennsylvania and Oregon slope wetlands are likely to develop similar functions, even if some details (such as plant community composition) are likely to be different. The floodplain subclasses, however, appear to be fundamentally different between Pennsylvania and Oregon, likely due to a combination of the effects of urbanization, dissimilar soils, and differences in climate. In summary, it seems probable that a model developed for an HGM subclass that is principally driven by groundwater might be more readily transferable across regions than a model for a subclass driven primarily by surface water.

Conclusions

Our assessment of the comparability of the hydrologic characteristics HGM subclasses across a large distance indicated some instances where the ability to extrapolate information is more likely than others. For the subclasses and geographic settings considered here, similarly classified wetlands that are surface-water driven are more likely to be functionally different than wetlands that are groundwater-driven. This is especially true when the variation in hydrology leads to differences in the depth and/or duration of soil saturation or inundation, where relatively small differences in water level could be enough to change a wetland's basic character from one dominated by anaerobic processes to one dominated by aerobic processes. Such a change can significantly alter the basic functioning of the wetlands involved. Some functions may not be affected (e.g., long-term surface water storage), but others (e.g., cycling of redox-sensitive compounds) will be greatly affected. In groundwater-driven sites, conditions seem to favor hydrologic characteristics that dampen differences and lead to the possibility of subclass comparability between regions.

Although it is tempting to try to use an HGM model (or any regionally developed model) in an area where it was not developed, our data indicate that such transference might not always be advisable and could lead to serious errors in interpretation of a site or group of sites. Regional modification of national models was designed into the HGM process for good reason. Wetlands do not necessarily function in the same way, even if they are classified similarly or referred to by similar nomenclature.

Regardless of the classification scheme used, be it based on the approach of Cowardin and others (1979) or the geomorphically based approaches of Semeniuk (1987) or Brinson (1993), attempts must be made to generalize results from one region to another. Resources are limited with respect to wetland classification and assessment and results should be shared across political and ecological boundaries whenever possible. Our results indicate that this sharing should be done with care. It is easy to make broad statements regarding the functions of all floodplain wetlands, when in fact, functions might be quite different even if sites are classified similarly. The scale at which similarities break down is unknown. We suspect that functional assessment models developed for the mid-Appalachian mountains of the eastern United States would also apply further north and south down that same mountain chain. We have shown that problems exists moving west and our models may not translate well, for example, in Europe. We urge sharing of models across regions if for no other reason than to stimulate discussion. We also, however, urge caution in employing those models without some deeper understanding of the ecological forces that drive them and the regional factors that affect the response to those driving forces.

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