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CHARACTERIZATION OF WETLAND HYDROLOGY USING HYDROGEOMORPHIC CLASSIFICATION

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Abstract: Hydrologic data are essential for understanding relationships between wetland morphology and function and for characterizing landscape-scale patterns of wetland occurrence. We monitored water levels in 45 wetlands for three years to characterize the hydrology of wetlands in the vicinity of Portland, Oregon, USA and classified wetlands by hydrogeomorphic (HGM) class to determine whether hydrologic regimes differed in wetlands in different HGM classes. We also compared hydrologic regimes in naturally occurring wetlands (NOWs) and mitigation wetlands (MWs) and in wetlands with/without a human-made water-retention structure to determine whether and how human modifications are changing the hydrology of wetlands. We found no relationship between hydrologic attributes and land use, soil association, or wetland area. We did find significant differences related to presence of a water-retention structure and to wetland type (NOW or MW). Water levels were higher and had less temporal variability and more extensive inundation (as % wetland area) in MWs and in wetlands modified to include a retention structure. HGM class was very effective for characterizing wetland hydrology, with significant differences among HGM classes for water level and for extent and duration of inundation. For three regional classes, we found the lowest water levels and lowest extent/duration of inundation in slope wetlands, intermediate conditions in riverine wetlands, and the highest water levels and greatest extent and duration of inundation in depressions. In "atypical" classes (Gwin et al. 1999), average water level and extent of inundation were similar to conditions in depressions, but the within-site variability in water levels in depressions-in-slope-setting and in-stream-depressions was significantly smaller than in the regional classes ($p \leq 0.001$). Results highlight the importance of both geomorphic setting and wetland structure in defining wetland hydrology and support the use of HGM for wetland classification. Because hydrology is an important determinant of many wetland functions, resource managers using restoration and mitigation to offset wetland losses should strive for project design and siting that re-establish the hydrogeomorphology of natural wetlands to improve the likelihood of replacing wetland functions.

Key Words: hydrogeomorphic setting, water retention, wetland hydrology, wetland mitigation, wetland morphology, wetland restoration, Portland, Oregon, USA

INTRODUCTION

Despite the recognized importance of hydrology in the establishment and persistence of wetlands and in regulation of wetland functions (e.g., Mitsch and Gosselink 1993), hydrology remains poorly characterized in many types of wetlands. An improved understanding of hydrology has been cited as a critical need to support a variety of wetland research and management objectives (Kusler and Kentula 1990, NRC 1995). Several broad needs exist, including 1) characterization of site-level hydrology in different kinds of wetlands, 2) information describing relationships between wetland hydrology and landscape setting, and 3) a mechanism for placing site-level data within a population or landscape framework so that cumulative effects of management actions can be recognized and so data for single sites or small groups of sites can be reliably used to describe other similar wetlands in the same landscape.

At the site level, successful wetland restoration and creation are dependent on the ability to recreate the hydrologic regimes of functional wetlands. Doing so, however, requires information that is rarely available—an understanding of the water regime to be re-established and of where and how that regime can be found or recreated in the landscape. Hydrologic success of past mitigation and restoration projects has been problematic, as mitigation wetlands have frequently had hydrologic regimes significantly different from those of "analogous" naturally occurring wetlands they were meant to replace (Owen 1990, Confer and Niering 1992, Kentula et al. 1992a). Moreover, inappropriate hydrology has been cited as a primary cause of failure of wetland mitigation projects in Florida (Erwin 1991) and in restored Prairie Pothole wetlands, where Galatowitsch and van der Valk (1996) characterized about 20% of study wetlands as "hydrologic failures."

Successful management of wetland resources at the landscape scale also requires an improved understanding of hydrologic conditions. As management activities change the numbers, types, and positions of wetlands on the landscape, especially in urban areas (e.g., Kentula et al. 1992a, b, Holland et al. 1995, Bedford 1996, Gwin et al. 1999), maintaining the diversity of hydrologic regimes will be essential to preserving the diversity of wetland functions. Bedford (1996) has recommended landscape-level analyses of wetlands to assess the cumulative effects of past management decisions and to guide future management decisions toward preserving and restoring the natural mosaic. As a tool to guide decisions, Bedford (1996) proposed the use of landscape profiles to describe the numbers and kinds of wetlands on the landscape, using classes defined in terms of hydrogeomorphic factors that cause specific types of wetlands to form and that support their functions.

Bedford (1996) recognized hydrogeomorphic (HGM) classification as an evolving, potentially valuable tool for developing landscape profiles. The HGM approach (Brinson 1993, Smith et al. 1995) has been developed as a tool for classification and functional assessment of wetlands, with classes closely tied to landscape setting and hydrologic processes through three interrelated factors: 1) wetland position in the landscape, 2) dominant source of water, and 3) hydrodynamics. The utility of the approach is premised on the assumption that these factors substantively influence the nature and level of important wetland functions. The HGM approach shows significant promise for classification and functional assessment, although it has not yet been widely tested to determine its reliability or sensitivity to variability among wetlands. The utility of the HGM approach for generalizing data from one wetland to others is likewise largely untested. Cole et al. (1997) recently used HGM to classify reference wetlands in central Pennsylvania and found significant differences in hydrologic attributes of wetlands in different HGM classes. The authors concluded that HGM was an effective "organizing variable" for wetland classification.

Gwin et al. (1999) demonstrated Bedford's landscape-profile approach using HGM classification to develop profiles for wetlands in the Portland, Oregon, USA metropolitan area. The authors identified regional classes using the principles described by Brinson (1993) and Smith et al. (1995) and also defined three regional "atypical" classes to characterize aberrant combinations of wetland morphology and geomorphic setting found in many of the wetlands (Table 1). Wetlands in the atypical classes are distinguished from wetlands in the regional classes by morphologies inconsistent with their geomorphic settings. Due to human modification, the wetlands have depressional characteristics in settings where unmodified wetlands would be slope or riverine wetlands. Identifying features include some combination of 1) an exaggerated depressional morphology, characterized by steep banks often cut to the angle of repose of the substrate; 2) large areas of open, often deep, standing water; 3) a berm isolating the wetland from the adjacent stream channel, except under flood conditions; and/or 4) excavation within a stream channel, with the resulting site often having a channel orders of magnitude larger than the original stream. Comparison of two landscape profiles by Gwin et al. (1999), one for naturally occurring wetlands and a second for all study wetlands, showed that management activities have significantly changed the wetland mosaic in the Portland urban landscape, decreasing the proportion of slope and riverine wetlands and greatly increasing the proportion of depressional types of wetlands.

The work presented in this manuscript had several objectives. First, to characterize the range of hydrologic conditions in freshwater emergent/open water wetlands in the Portland, Oregon, metropolitan area, we monitored water levels in a large sample of wetlands from late 1993 through January, 1997. Second, to determine the utility of the HGM classification approach, we classified and compared wetlands to assess whether wetlands with different structure and geomorphic setting, as defined by HGM class, have substantive differences in their hydrologic regimes. This objective extended work of Gwin et al. (1999) by testing the utility of HGM for characterizing wetland hydrology and by evaluating whether wetlands in the atypical classes have distinct hydrologic regimes or if conditions in them are similar to those of wetlands in one (or more) of the regional HGM classes. To determine how human disturbance (mostly mitigation in our sample of wetlands) is changing the hydrology of wetlands, we compared conditions in wetlands with and without human-made structural modifications. Finally, we assessed whether other wetland attributes (e.g.,

Table 1. Summary of distinguishing features of wetlands in regional and atypical HGM classes, acronyms used to identify them in other places in this manuscript, and sample sizes for wetlands in each class. Descriptions of HGM classes summarize detailed descriptions by Gwin et al. (1999). Sample numbers for 1993 are for the study described by Magee et al. (1993) and data used by Gwin et al. (1999).

			Sample Size		
Class	Acronym	Regional or Atypical	1993 Study	This Study	Distinguishing Features
Slope	SL	Regional	9	6	Occurs on sloping land; lacks closed contours; unidirectional downslope flow; predominant water source is ground water
Riverine	RIV	Regional	31	10	Occurs in floodplains and riparian corridors; unidirectional flow from overbank flooding; water from overbank flow and ground water
Depression	DEP	Regional	12	7	Naturally-occurring topographic depression with closed contours; low hydraulic energy; water sources are precipitation, ground water and interflow
Depression-in-riverine setting	DR	Atypical	19	10	Depression (impoundment or excavated pond) placed in floodplain beside stream channel, isolated from stream channel by berm; water sources are ground water, inflow from (often intermittent and/or culverted) tributaries, and overbank flow
Depression-in-slope-setting	DSL	Atypical	4	3	Depression placed at base of slope wetland; excavated pond or impoundment retains standing water supplied from ground water; water level usually regulated at outlet
In-stream-depression	ISD	Atypical	19	9	Depression created by excavation or impoundment placed within stream channel; water supplied by streamflow; water level usually regulated at outlet

soils, land use) should be considered with, or as alternatives to, HGM class for describing hydrologic variability among wetlands.

METHODS

Study Area and Site Selection

The study area is located in northwestern Oregon, within the Portland Urban Growth Boundary (ODLCD 1992) and in the Willamette Valley Plains subregion of the Willamette Valley ecoregion (Omernik 1988, Clarke et al. 1991). The wetlands studied are small (≤ 2 ha) palustrine wetlands with herbaceous vegetation and range from sites dominated by emergent vegetation to sites dominated by open water. These types of wetlands were, historically, the most common in the Willamette Valley (Davis 1995, Guard 1995) and are those most frequently built as mitigation for losses of freshwater wetlands in the Portland area and in the State of Oregon (Kentula et al. 1992a, b). Most wetlands are located along tributaries of the Tualatin River or on the floodplains of the Tualatin and Columbia Rivers (Figure 1) in land-use settings ranging from undeveloped and agricultural lands to sites surrounded by residential or commercial/industrial lands. Wetlands occur along a continuum of hydrologic and geomorphic settings, from headwater seeps and convergent zones, to floodplains of low order (mostly second or third order) streams, and to the floodplains of main-stem (Tualatin and Columbia) rivers. The area of study wetlands ranged from 0.01 to 1.77 ha (median 0.20 ha). There was wide variability in the area of wetlands but no significant difference in area among wetlands in different HGM classes.

The climate of the study area is mild, with minimum average temperatures in January (4.2°C) and maximum temperatures in August (20.3°C). Long-term average annual precipitation varies from 92 to 114 cm across the study area, with almost all occurring as rainfall. Precipitation is strongly seasonal; about 70% of annual rainfall occurs during the five-month period from November to March and less than 10% from July to September. Precipitation varied greatly during the study period; for the first nine months of study in 1994, precipitation was only 74% of normal, while there was record

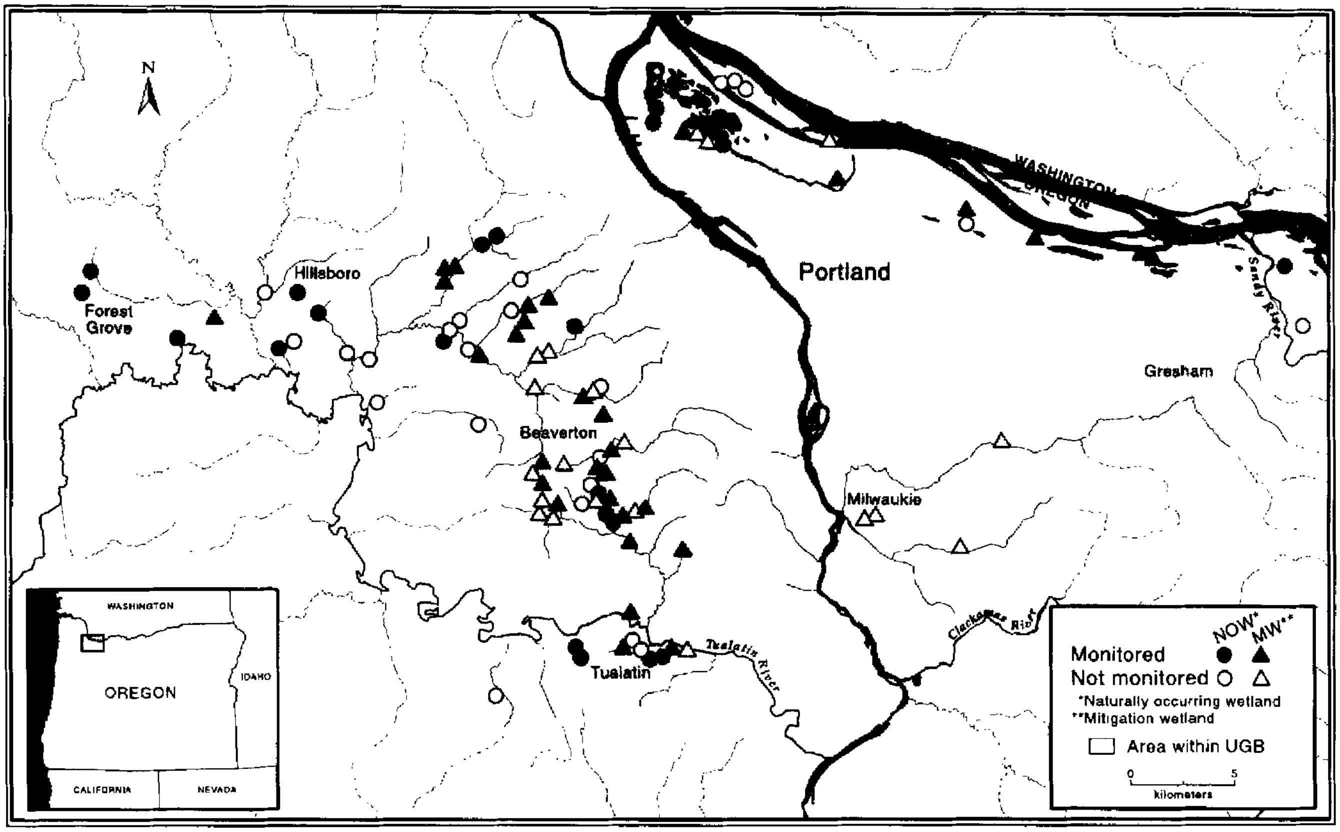

Figure 1. Map of the Portland, Oregon area showing the study area within the urban growth boundary (UGB), also showing streams and major rivers and identifying the type and location of wetlands sampled in a 1993 characterization of open water and emergent wetlands in the same study area (Magee et al. 1993).

precipitation (163% of normal) in 1996, including two major regional floods (NCDC 1995, 1996, 1997).

We collected hydrologic data for approximately half of the 96 wetlands sampled during a field study in 1993 (Magee et al. 1993). Sites were selected to provide a cross-section of the 1993 sample in terms of 1) naturally occurring wetlands (NOWs) and mitigation wetlands (MWs), 2) land use, and 3) location (Tualatin River basin or Columbia River floodplain). The wetlands monitored for hydrology initially included 24 NOWs and 28 MWs. Seven sites were subsequently dropped from monitoring or data analysis for reasons including permitted destruction of a wetland, withdrawal of permission for site access, and inability to reliably calculate the complete set of hydrologic variables used in our analyses. In addition, three wetlands were reclassified from NOW to MW based on new information obtained during the study. These changes resulted in a final sample of 45 wetlands (16 NOWs, 29 MWs) used for data analysis.

Hydrologic Monitoring

Each wetland was instrumented with a staff gauge and shallow well installed late in 1993 or early in 1994. Wells were installed by driving well points into the substrate to a depth of about one meter. The well points were made of 3.2-cm inside diameter steel pipe with a pointed steel head attached at the lower end to facilitate placement in the soil, perforations at 1-cm intervals, and screening on the outside to prevent clogging. We extended the depth of a few wells during the first summer of monitoring by adding pipe and driving the assembly deeper into the soil. Staff gauges and wells were placed adjacent to one another in the portion of each wetland with the lowest elevation identified when wetlands were surveyed in 1993 (Magee et al. 1993). Elevations of gauges and wells were surveyed to benchmarks established in each wetland in 1993 so that water levels could be adjusted to a local datum (the lowest ground surface elevation found during the 1993 field study). By referencing water levels to the 1993 datum, an adjusted stage of zero became an important indicator of water conditions, as water levels ≥ 0 indicate the occurrence of standing water on at least part of the wetland, whereas values < 0 denote a water level below the lowest ground surface in the wetland, indicating that no standing water is present anywhere on the site.

Water levels were determined at two-week intervals, starting at the time of gauge installation and continuing through January, 1997. When standing water was present, stage was read directly from the staff gauge. Below-ground water levels were measured in the wells by lowering a calibrated tape and determining either the depth at which it broke the plane of the water or the depth at which a coating of chalk was washed off the tape. Data for the three-year period from February 1, 1994 through January 31, 1997 were used for analyses reported in this manuscript, with two exceptions. We included data for one site at which monitoring was discontinued due to withdrawal of permission for site access and for a second site destroyed by a permitted fill. For these sites, truncated data sets for a 12 or 24 month monitoring period (February 1994 through January 1995 or 1996) were used for analysis. An average of 75 water-level measurements per wetland were used in data analysis.

Along with monitoring equipment and procedures described above, we also maintained continuous water-level recorders on a subset of wetlands. The biweekly data obviously do not characterize short-term variability in water-level dynamics, but comparative analysis of data for four sites shows very close agreement in water-level distributions between continuous monitoring data and the biweekly data. As might be expected, biweekly data underestimated maximum stage, by an average of 13 cm, but for minimum water levels and for estimates of the 10th, 25th, 50th, 75th, and 90th percentile of stage, the median difference between biweekly and gauging station values for the four sites was only 1.4 cm.

Wetland Attributes Used to Characterize Variability in Hydrology

Several attributes of the study wetlands and their surrounding areas were characterized to allow analysis of potential relationships with wetland hydrology. Each attribute is described briefly below. For a 100-m perimeter around each wetland, we estimated the fraction of the area in each of four land-use classes (undeveloped, agriculture, residential, commercial/industrial/transportation corridor). We defined the land use occurring in the highest proportion of the 100-m-perimeter area as the predominant local land use. We evaluated possible relationships between land use and hydrologic conditions of study wetlands because land use is known to substantially affect the amount of runoff and because urbanization (e.g., increases in impervious surface, channelization of runoff) strongly affects the magnitude and timing of stormflow (Dunne and Leopold 1978).

Soil associations were identified from general county soil surveys (Green 1982, 1983, Gerig 1985). Soil association was included in analyses because the primary attributes used to define soil associations in general soil maps of the study area (landscape setting and soil features such as depth, drainage, and texture) have the potential to influence (or reflect) hydrologic regime. All but one of the monitored wetlands were located in Washington or Multnomah County, so associations defined for those counties were used. The lone wetland located in Clackamas County was classified with the most appropriate Washington County association, based on the landform and characteristics of soils in the wetland.

The presence or absence of a water-retention structure (i.e., an excavated pond or a human-made impoundment in or immediately downstream from the wetland) was reported as "structure present" or "structure not present" for each wetland. Assignments were based on site maps and notes prepared by the field crews in 1993 and verified during subsequent visits to each wetland. In preliminary analyses, we defined separate classes for excavated ponds and for impoundments (sites with a control structure), but we combined them into a single "structure present" class when we failed to identify any substantive differences between them for the hydrologic variables under consideration. Water-retention structures were included in analyses because they were built to change the hydrology of the wetlands or adjacent lands by creating areas of standing water and in many cases regulating water levels, thus substantially changing the occurrence and duration of standing water and affecting the temporal variability of water levels.

The HGM class assigned for each wetland by Gwin et al. (1999) was also included in analyses. A summary of characteristics of wetlands in each HGM class, along with numbers of wetlands in each, is listed in Table 1. We anticipated that HGM class and hydrology would be significantly related because the variables used for defining HGM class (landscape position, water source, and hydrodynamics) are all directly associated with hydrology.

An important consideration in the interpretation of results is that there are very close associations among some of the wetland attributes described above, notably among occurrence of a water-retention structure, wetland type (NOW or MW), and HGM class. The presence or absence of a water-retention structure is strongly associated with wetland type ($p < 0.0001$); only 2 of 16 NOWs had a water-retention structure, whereas all (29 of 29) MWs in our sample had a retention structure. Similarly, while retention structures are uncommon in slope and riverine wetlands, all depressions in our sample and almost all (21 of 22) wetlands in the atypical classes were designed to incorporate a retention structure (Table 2). The presence of

Table 2. Distribution of wetlands by HGM class and presence/absence of a water-retention structure. Acronyms for HGM classes are listed in Table 1. Using Fisher's exact test, we found a significant association between HGM class and presence/absence of a water control structure, at $p < 0.0001$.

Water-Retention Structure	HGM Class						Row total
	SL	RIV	DEP	DR	DSL	ISD	
Absent	5	8	0	1	0	0	14
Present	1	2	7	9	3	9	31
Column total	6	10	7	10	3	9	45

a retention structure is an obvious indicator of human modification of wetland structure, with mitigation being, by far, the most common reason for such disturbance in our sample of wetlands. Data in Table 2 reinforce the critical linkage between human manipulation, as indicated by presence of retention structures and the occurrence of wetlands in the atypical classes.

Data Analyses

The approaches described below were used to summarize and analyze data to identify potential relationships between wetland attributes and hydrologic characteristics. Data analyses considered four aspects of wetland hydrologic conditions: water level, range in water level, extent of wetland inundation, and the occurrence and duration of wetlands becoming dry (i.e., no standing water) during the summer. We looked first at overall patterns in the hydrology of the wetlands, then at relationships between hydrologic variables and land use, soil characteristics, and presence of a water-retention structure, and finally at relationships between hydrologic conditions and HGM class.

Water-level data, recorded to the nearest 0.01 ft, were received as hard copy summaries and subsequently entered into an electronic format, where stage values were verified and converted from English to metric units, then adjusted to the local datum for each wetland. Two measures of the range in water level were computed; we first calculated the total range in water level as the difference between the maximum and minimum water level observed in each wetland during the three-year study period. In addition, to characterize normal seasonal variability in water levels, we determined 90-day average maximum and minimum water levels. Starting with the first sample date more than 90 days after the initiation of sampling at each site, we computed a moving average water level for the 90-day period ending on each subsequent sample date. We then identified the highest and lowest average water levels for each year for each wetland, averaged the three maximum and minimum levels for each site, and defined the difference between them as the average seasonal variability.

For each site and sampling date, we estimated the extent of inundation as a percentage of wetland area, based on data for the distribution of ground-surface elevations from a systematic grid survey of each wetland in 1993 (Magee et al. 1993). The extent of inundation was computed as the proportion of grid points with elevations lower than the water level on each sample date. This approach could underestimate the extent of inundation if there were areas of local ponding, perched above the water level defined by the staff gauge, but based on frequent observation of study sites, we believe the occurrence of such conditions to be minimal and unlikely to substantively affect data or analyses. We also computed the extent of inundation by > 20 cm and > 50 cm water as the proportion of grid points with an elevation more than 20 or 50 cm lower than the water level. For five sites that had areas with water too deep to traverse during sampling in 1993, the extent of inundation was computed as the sum of 1) the fraction of wetland area with water too deep to sample plus 2) the fraction of wetland area that was sampled multiplied by the proportion of grid points with an elevation lower than the water level.

To determine whether (and when) wetlands lacked standing water, we checked for occurrence of water levels < 0 m for each wetland. The onset was defined as the first sampling date in the year on which the water level in a wetland was < 0 m, and the duration was computed as the number of days between the first and last sample dates when the stage was < 0 m. For sites in which water levels fluctuated above and below 0 m more than once during the year, duration was computed as the total number of days when stage was $<$ 0 m. Lack of standing water was determined for each wetland for each year of monitoring, and the average of yearly values for each site was used in analyses.

Summary statistics were generated and data analyses performed using SAS (release 6.11, SAS Institute, Inc., Cary, NC) to compare water regimes in wetlands with different land uses, soil associations, with/without a water-retention structure, and different HGM classes. For hydrologic variables that are single valued for each wetland (e.g., minimum water level), one-way analysis of variance was performed. To compare water level and inundation conditions, we used a multivariate repeated measures analysis of variance model, which considers within-site temporal variability (i.e., the repeated measure) by using site and month as treatments in a two-way ANOVA (Milliken and Johnson 1984). For this analysis, because not all sites were sampled on the same dates, stage and flooding data for each wetland were aggregated to average monthly values prior to analysis. To compare distributions of numbers of wetlands among attributes (e.g., HGM class and presence/absence of a water-retention structure), and to compare the likelihood of wetlands in different attribute classes losing standing water, we used Fisher's exact test to identify significant associations among attributes (Stokes et al. 1995). Differences between means were considered significant at $p < 0.05$.

RESULTS

Overview of Hydrologic Conditions

Hydrologic conditions in the 45 wetlands were highly variable during the study period, in terms of both within- and among-site variability. The overall average water level for all wetlands was 0.64 m for the three-year period, with individual wetland averages between -0.28 and 1.96 m. Mean stage was > 1.0 m in 14 wetlands and < 0 m in six wetlands. Seventeen wetlands were without standing water at least once during the study period, for periods of 8 to 217 days; there was no standing water on a majority of these wetlands (11/17) every summer. Water levels within wetlands were also quite variable; the mean within-site difference between minimum and maximum water level was 1.18 m, with a minimum range of 0.26 m and a maximum of 2.32 m. Seasonal variability in water levels was much smaller; the mean difference between the 90-day maximum and minimum water levels was 0.42 m, with ranges in individual wetlands of 0.06 to 1.14 m.

The heterogeneity of water levels is reflected in diverse inundation conditions in the wetlands. The time-averaged mean extent of inundation for the 45 wetlands was 47% of wetland area, with average inundation in individual wetlands of 2% to 89% of wetland area. Thirteen sites were completely inundated on at least one sampling date, and 17 sites had no standing water at least once. Temporal variability in the extent of inundation was high; the average within-site difference between minimum and maximum inundation was 62% of wetland area. Seven wetlands had conditions that ranged from complete inundation to no standing water, but there were also several wetlands in which the difference between minimum and maximum inundation was less than 20% of wetland area. Some of these sites were never extensively flooded (e.g., inundation never exceeded 20% of the area of three wetlands), while three sites had standing water on more than 75% of wetland area throughout the three year period.

Figure 2 shows examples of the diverse water levels and fluctuation patterns occurring in study wetlands. The hydrographs illustrate the timing and magnitude of temporal variability in water levels. Seasonality was pronounced and consistent from year to year at many sites, especially in slope and riverine wetlands. Conversely, in many in-stream depressions and depression-in-slope wetlands, seasonal variability in water levels was almost nonexistent. In a third group of wetlands, conditions varied from year to year with differences in precipitation.

Relationships Between Hydrologic Conditions and Wetland Attributes

We evaluated relationships between hydrologic conditions and land use, soils, wetland area, and presence of a water-retention structure to determine if attributes related to geomorphic setting and/or wetland structure might provide a straightforward explanation of hydrologic variability among wetlands. We did not find significant relationships between local land use and hydrologic variables, as illustrated by p-values for the relationship between land use and mean stage ($p = 0.86$) and between land use and the mean extent of inundation ($p = 0.33$). Similarly, we did not find significant relationships between hydrologic conditions and soil association (e.g., $p = 0.66$ for mean stage, $p = 0.32$ for mean percent inundation) or wetland area ($p = 0.21$ for mean stage, $p = 0.12$ for mean percent inundation). In contrast, we found very significant differences in hydrologic conditions in wetlands with/without a water-retention structure (Table 3). Water levels and extent of inundation were significantly higher in wetlands with a retention structure, while total and seasonal ranges in water level were significantly smaller. Only one wetland without a retention structure, compared to 26 of 31 sites with a retention structure, had standing water throughout the three-year study period (Table 3). Moreover, in wetlands that dried out, absence of standing water occurred, on average, more than two months earlier in wetlands without a retention structure and had an average duration about three times as long.

Given the very close relationship between water-retention structure and wetland type (NOW/MW) noted earlier, it is not surprising that conditions in MWs and NOWs are almost identical to those for wetlands with and without a water-retention structure, respectively. NOWs have lower water levels and less extensive inundation than MWs and are much more likely than MWs to lack standing water. Data for NOWs and MWs are not presented because they do little more than reproduce data in Table 3. In addition, by emphasizing the occurrence of a retention structure, rather than wetland type (NOW/MW), we also maintain a focus on the cause of observed hydrologic differences (i.e., management decisions resulting in modification of wetland morphology and control of water levels),

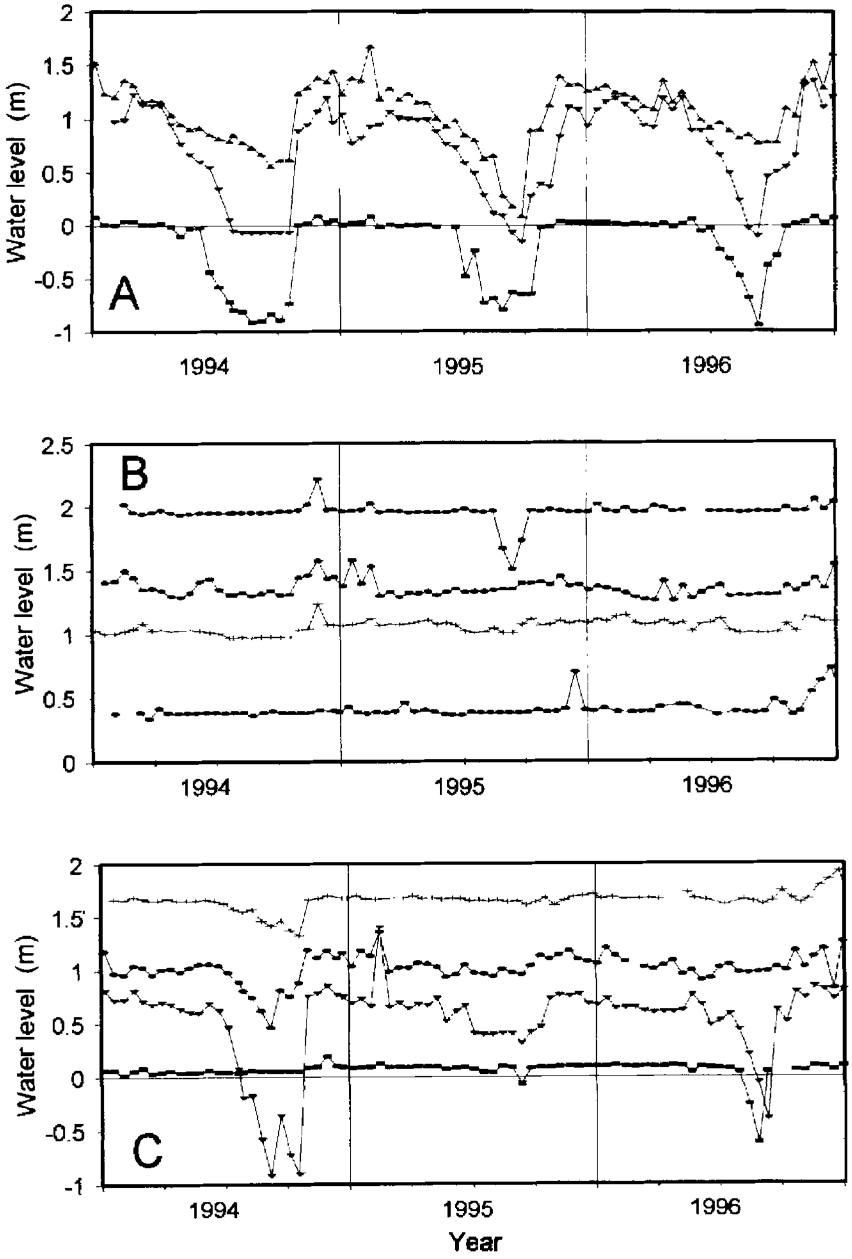

Figure 2. Examples of hydrographs for individual study wetlands, showing variability in water levels among wetlands. Stage values > 0 m indicate presence of standing water, whereas values < 0 m indicate lack of standing water. Breaks in data indicate missing data points. The plots include examples of wetlands with (A) significant and recurring seasonal variability in water level, (B) little temporal variability in water level and essentially no seasonal variability, and (C) occurrence and extent of seasonal variability that change from year to year with changes in precipitation. HGM classes for wetlands shown are slope (■), riverine (▲), depression-in-slope-setting (+), in-stream-depression (●), and depression-in-riverine-setting (▼).

rather than on the impetus for those decisions (usually, but not always, mitigation).

Comparison of Hydrologic Conditions among HGM Classes

We found consistent, significant patterns of differences in hydrologic variables for wetlands in different HGM classes. Mean water level differed among classes, with the lowest average stage in slope wetlands, intermediate water levels in riverine wetlands, and high water levels in depressions and in wetlands in the atypical classes (Figure 3A, Table 4). The highest average water level occurred in depressions-in-slope-setting. Relationships were similar for minimum and maximum water levels and for 90-day minimum and

Table 3. Comparison of hydrologic conditions in wetlands with or without a water-retention structure. Reported values are means ± one standard error.

Hydrologic Attribute	No Retention Structure Present	Retention Structure Present	ANOVA Results	
			F	p-Value
Sample size	14	31	—	—
Stage (m)				
• Mean[a]	0.17 ± 0.11	0.85 ± 0.08	19.43	0.0001
• Minimum[b]	−0.59 ± 0.09	0.37 ± 0.10	32.75	0.0001
• Maximum[b]	0.89 ± 0.14	1.41 ± 0.09	8.88	0.0047
• 90-day Minimum[b]	−0.19 ± 0.12	0.66 ± 0.09	31.02	0.0001
• 90-day Maximum[b]	0.43 ± 0.09	0.99 ± 0.08	16.12	0.0002
Range in water level (m)				
• Minimum to maximum[b]	1.49 ± 0.11	1.04 ± 0.09	8.81	0.0049
• 90-day Max–90-day Min[b]	0.62 ± 0.08	0.32 ± 0.04	13.02	0.0008
Extent of inundation (% area)				
• ≥ 0 cm H_2O[a]	26.1 ± 6.1	56.2 ± 4.1	12.99	0.0009
• ≥ 20 cm H_2O[a]	12.8 ± 5.9	41.5 ± 4.0	13.73	0.0006
• ≥ 50 cm H_2O[a]	2.4 ± 1.0	22.4 ± 3.4	18.21	0.0001
Likelihood of wetlands losing standing water				
• Sites that lose standing water	12[c]	5		<0.0001[d]
• Percent of sites	92[c]	16		
• Average date of onset	May 29	August 24		
• Average duration (days)	120 ± 19	38 ± 8		

[a] Statistical analyses conducted using a multivariate repeated measures ANOVA to incorporate effects of within-site variability.

[b] Single-valued variable (one value per wetland); one-way ANOVA used for statistical analysis.

[c] n = 13 for this analysis only; the status of one wetland at low water could not be determined.

[d] Determined using Fisher's exact test.

maximum water levels (Figure 3A, Table 4), with lowest water levels in slope wetlands, high levels in all depressional wetland classes (depressions and wetlands in the atypical classes), and the highest water levels in depressions-in-slope-setting.

Figure 4 presents mean monthly water-level data for wetlands in each HGM class and shows persistent differences in water level and in the extent of seasonal variability in water level among classes. To the extent that water levels undergo seasonal changes, the timing of changes is similar in all classes, with water levels highest in late fall and winter and lowest in late summer and early autumn. Seasonality in stage was pronounced in slope, riverine, and depression-in-riverine-setting wetlands but was very weakly expressed in wetlands in the classes depression-in-slope-setting and in-stream-depression.

The within-site range in water levels varied greatly among HGM classes. Ranges were significantly smaller in depressions-in-slope-setting and in-stream-depressions than in slope, riverine, and depression-in-riverine-setting wetlands for both total range in water level and for difference between 90-day maximum and minimum water levels (Table 4). Seasonal variability also accounted for a smaller fraction of the total range in water level in depressions-in-slope-setting and in-stream-depressions (18–20% of total range) than in wetlands in the other HGM classes (28–40% of total range). The smaller variability in water levels in depressions-in-slope-setting and in-stream-depressions, especially for seasonal range in water levels, indicates a hydrologic regime in the wetlands in these classes that is fundamentally different from conditions found in wetlands in the regional classes and in depressions-in-riverine-setting.

Along with differences in water levels, we found large, significant differences in the average extent of wetland inundation among HGM classes (Figure 3B, Table 4). Average inundation was lowest in slope wetlands, intermediate in riverine wetlands, and high in depressions and wetlands in the atypical classes. Depths of standing water also varied greatly among classes. In slope wetlands, < 2% of wetland area had an average water depth ≥ 20 cm, and < 1% had ≥ 50 cm of water. In contrast, the average water depth exceeded 20 cm on 32% to 58% of the area of depressions and wetlands in the atypical classes, and wetlands in these classes had an average of 15% to 42% of wetland area with ≥ 50 cm of water (Table 4).

Flood-duration curves in Figure 5A show the sys-

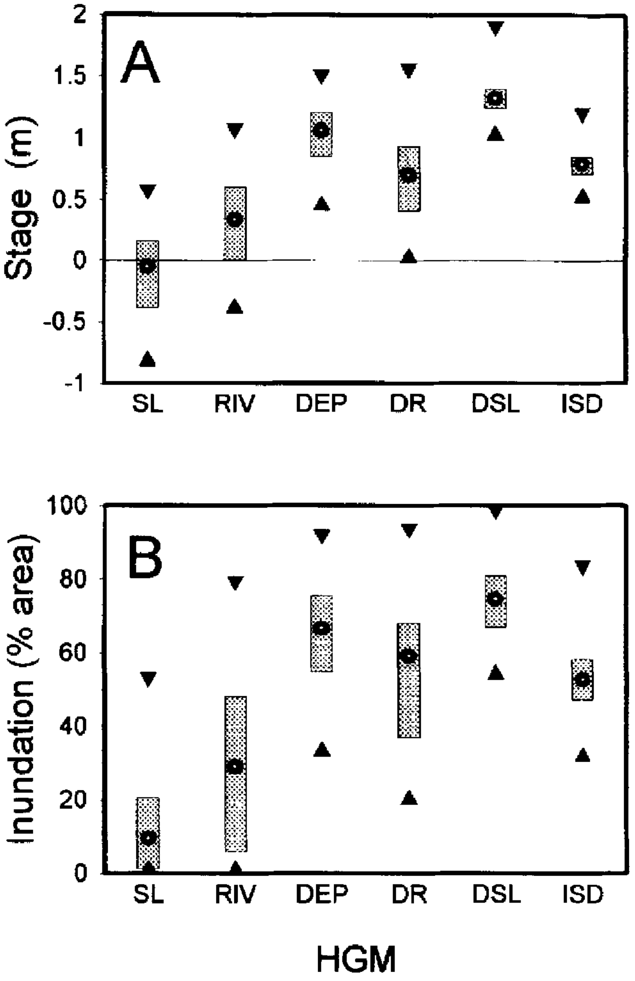

Figure 3. Comparisons of (A) water levels and (B) extent of inundation for wetlands in different HGM classes. For wetlands in each class, circles denote mean values, triangles indicate average minimum and maximum values, and the bar indicates the range between mean 90-day minimum and maximum stage or percent inundation. Acronyms for HGM classes are listed in Table 1.

tematic differences in the spatial extent of inundation for wetlands in the regional classes during the three year study period. Over the entire distribution, inundation is least extensive in slope wetlands, intermediate in riverine wetlands, and most extensive in depressions. The flood-duration curves also describe differences in the extent and duration of inundation within each class. In slope wetlands, for instance, average maximum extent of inundation was 53% of wetland area, but only about half that area had standing water more than 10% of the time; median inundation in slope wetlands was only 2% of wetland area, and average minimum inundation was 0% (no standing water). Inundation in depressions, in contrast, was much more extensive. Under the wettest conditions, there was standing water on an average of 91% of wetland area, and under the driest observed conditions, an average of about one-third of wetland area was inundated; none of these wetlands ever lacked standing water.

Flood-duration curves for wetlands in the three atypical HGM classes are, in some respects, very similar to those for depressions. Wetlands in each class were characterized by extensive inundation throughout the study period (Figure 5B), with average maximum inundation of 83% to 98% of wetland area and minimum inundation of 21% to 55% of wetland area. Like the small range of variability of water levels in depressions-in-slope-setting and in-stream-depressions, there was little variability in the extent of inundation in these wetlands across most of the distribution, as expressed by the flat curves for wetlands in these classes. Low variability in the extent of inundation, in depressions-in-slope-setting and in-stream-depressions, is again indicative of conditions fundamentally different from those occurring in wetlands in the regional classes and depressions-in-riverine-setting.

The differences in water level and extent of inundation among HGM classes also result in significant differences among classes in the likelihood of wetlands lacking standing water and in the duration and date of onset. Wetlands in only three of the HGM classes were without standing water during our study period (Table 5), including all slope wetlands, 80% of riverine wetlands, and 33% of depressions-in-riverine-setting, but none of the depressions, depressions-in-slope-setting, or in-stream-depressions. On average, slope wetlands were the first to lose standing water, in early June, and they remained without standing water for almost four months. In contrast, the depressions-in-riverine-setting that lost standing water did so in late summer and remained without standing water for a much shorter period of time.

DISCUSSION

Our results show that HGM classification can be an effective tool for organizing hydrologic data to understand and describe the hydrologic regimes of wetlands and for characterizing the effects of human modifications on wetland hydrology. For four types of descriptors of hydrologic conditions considered in our analyses—water level, range in water level, extent of inundation, and likelihood of lacking standing water—we found consistent differences among HGM classes that reflect the role of both wetland setting and structure as important influences on hydrologic regimes of wetlands. Wetlands in the three regional HGM classes have distinct hydrologic regimes, demonstrated by the substantial differences in minimum, mean, and maximum water level, and in the extent, depth, and duration of inundation. The extent, depth, and duration of in-

Table 4. Comparison of hydrologic conditions in wetlands in different HGM classes. Acronyms for HGM classes are listed in Table 1. For each attribute, mean values with the same letter are not significantly different from one another. Reported values are means ± one standard error.

Attribute	Average Value for Attribute						ANOVA Results	
	SL	RIV	DEP	DR	DSL	ISD	F	p-Value
Sample size	6	10	7	10	3	9	—	—
Stage (m)								
● Mean*	-0.05 ± 0.15^{a}	0.34 ± 0.12^{a}	$1.07 \pm 0.14^{b,c}$	0.71 ± 0.12^{b}	1.32 ± 0.21^{c}	0.79 ± 0.12^{b}	10.04	0.0001
● Minimum**	-0.80 ± 0.12^{a}	$-0.37 \pm 0.13^{a,b}$	0.47 ± 0.18^{c}	$0.04 \pm 0.11^{b,c}$	1.05 ± 0.16^{d}	$0.54 \pm 0.15^{c,d}$	11.71	0.0001
● Maximum**	0.56 ± 0.24^{a}	$1.06 \pm 0.13^{a,b}$	$1.49 \pm 0.13^{b,c}$	$1.54 \pm 0.14^{b,c}$	1.89 ± 0.28^{c}	1.19 ± 0.15^{b}	4.89	0.0014
● 90-day Minimum**	-0.39 ± 0.16^{a}	$0.00 \pm 0.15^{a,b}$	$0.85 \pm 0.15^{c,d}$	$0.41 \pm 0.08^{b,c}$	1.24 ± 0.22^{d}	0.72 ± 0.19^{c}	10.58	0.0001
● 90-day Maximum**	0.16 ± 0.05^{a}	0.61 ± 0.10^{b}	$1.21 \pm 0.17^{c,d}$	$0.94 \pm 0.09^{b,c}$	1.39 ± 0.21^{d}	$0.85 \pm 0.18^{b,c}$	7.31	0.0001
Range in water level (m)								
● Minimum to maximum**	$1.36 \pm 0.19^{a,b}$	$1.43 \pm 0.13^{a,b}$	$1.03 \pm 0.13^{b,c}$	1.50 ± 0.12^{a}	0.84 ± 0.34^{c}	0.64 ± 0.08^{c}	5.85	0.0004
● 90-day Max–90-day Min**	0.55 ± 0.14^{a}	0.60 ± 0.10^{a}	$0.35 \pm 0.09^{a,b}$	0.53 ± 0.07^{a}	0.15 ± 0.06^{b}	0.13 ± 0.02^{b}	5.13	0.0010
Extent of inundation (% area)								
● ≥ 0 cm H_2O*	9.6 ± 7.5^{a}	29.0 ± 5.8^{b}	66.6 ± 6.9^{c}	58.9 ± 5.8^{c}	74.4 ± 10.6^{c}	52.6 ± 6.1^{c}	9.18	0.0001
● ≥ 20 cm H_2O*	1.7 ± 6.8^{a}	12.3 ± 5.4^{a}	57.5 ± 6.5^{b}	$47.7 \pm 5.4^{b,c}$	55.4 ± 9.8^{b}	31.8 ± 5.7^{c}	11.02	0.0001
● ≥ 50 cm H_2O*	0.6 ± 6.5^{a}	4.0 ± 5.0^{a}	41.8 ± 6.0^{b}	27.1 ± 5.0^{c}	30.8 ± 9.1^{c}	14.8 ± 5.3^{a}	7.35	0.0001

* Statistical analyses conducted using a multivariate repeated measures ANOVA to incorporate effects of within-site variability.

** Single-valued variable (one value per wetland); one-way ANOVA used for statistical analysis.

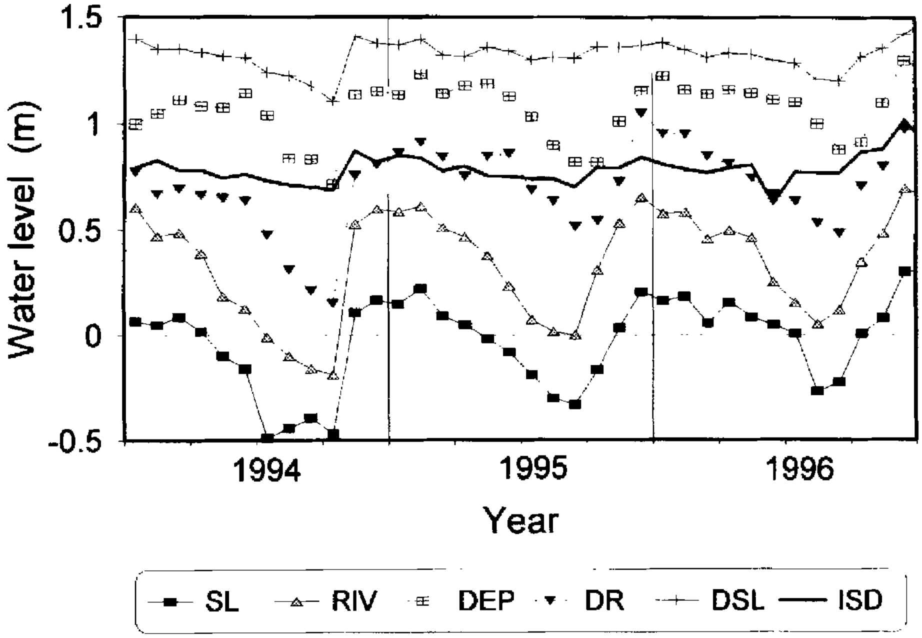

Figure 4. Hydrographs showing average water levels in wetlands in each HGM class for 1994 through 1996. Values are monthly averages of individual water-level measurements for wetlands in each class. Acronyms for HGM classes are listed in Table 1.

undation were lowest in slope wetlands and greatest in depressions, as would be expected based on their landscape settings. Dynamics of water levels in wetlands in the regional classes, however, were generally similar; the average range of water levels did not vary significantly among classes, and the timing of seasonal high and low water levels was consistent among classes. This suggests that wetlands in the regional classes may share a common set of forcing functions linked to seasonal variability of ground- and surface-water levels.

Our data also show the effects of human modification on wetland hydrology and support the decision of Gwin et al. (1999) to establish separate regional "atypical" HGM classes. The emplacement of a depression within slope or riverine wetlands profoundly changes the hydrology of the resulting systems and largely overrides geomorphic setting as a determinant of hydrologic conditions. Hydrologic conditions in depression-in-riverine-setting wetlands bear little resemblance to those found in riverine wetlands. Differences between slope and depression-in-slope wetlands are even more pronounced; in our sample, slope wetlands had the lowest water levels and lowest extent/duration of inundation of any class, while depression-in-slope wetlands had the highest water levels and greatest extent/duration of inundation. Wetlands in the atypical classes most closely resemble depressions, with average water levels and extent of inundation comparable to those in depressions. An analysis limited to consideration of average conditions would likely conclude that depressions and wetlands in the atypical classes are comparable and that atypical wetlands could be classified with depressions. Such analysis, however, would overlook substantial differences between these groups of wetlands. Ranges in water levels are significantly smaller in depressions-in-slope-setting and in-stream-depressions than in the regional classes, while the range in depressions-in-riverine-setting is larger than in depressions. Some depressions-in-riverine-setting also lose standing water during the summer, a behavior not observed in any of the depressions in our sample. The small range in water levels and in the extent of inundation in depressions-in-slope-setting and in-stream-depressions represent conditions unique to these wetlands in our sample that are likely to have a significant impact on habitat functions of wetlands in these classes.

Because we monitored water levels but not water inputs and outputs, our data alone don't characterize controls on water levels. Based on frequent observation of the wetlands, however, it seems that water-level control structures and the stability of water inputs are both important factors affecting water-level regime. In wetlands without a control structure, water levels are driven by seasonal patterns of precipitation and runoff/evapotranspiration. Resulting water levels are high and relatively stable from about November to April then decrease to low levels until sometime in the autumn, when they rise rapidly with the onset of the wet sea-

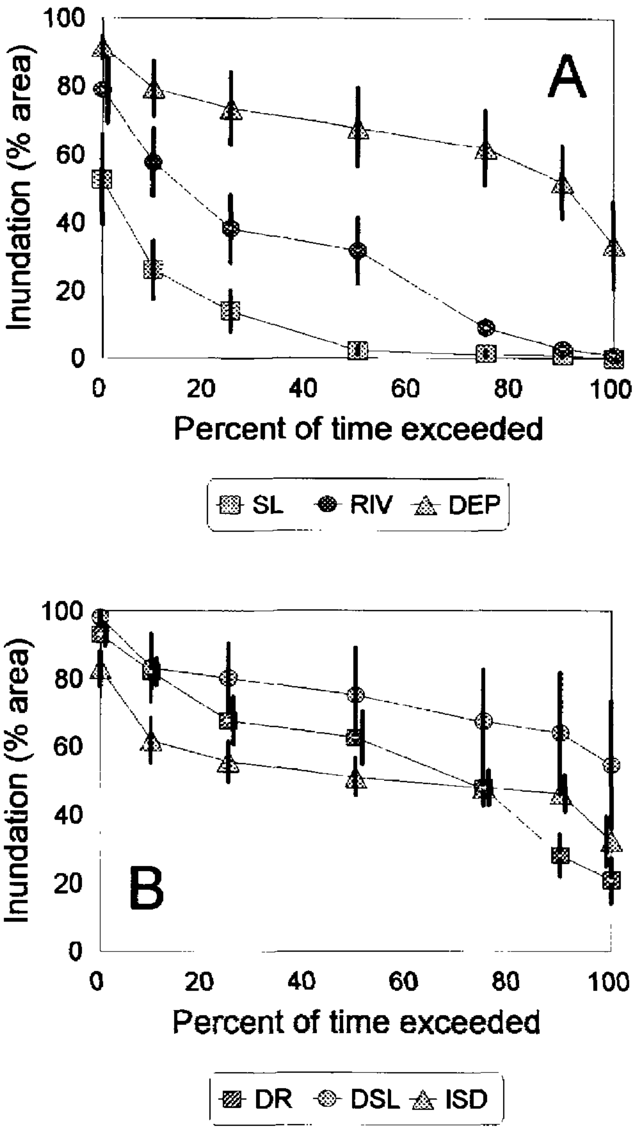

Figure 5. Inundation-duration curves showing the average extent and duration of inundation for wetlands in (A) regional HGM classes and (B) atypical HGM classes. Values of 0 and 100 on the X-axis indicate the average maximum and minimum extent of inundation. Error bars indicate ± one standard error; some of the error bars are offset for presentation purposes to prevent overlapping of bars. Acronyms for HGM classes are listed in Table 1.

son. This water-level pattern occurs commonly in slope and riverine wetlands and in some depression-in-riverine-setting wetlands (Figure 2a, Figure 4). Emplacement of a control structure, however, stabilizes water levels, sharply reducing the natural variability in water levels. As long as water inputs exceed evaporation and seepage losses, water levels remain relatively constant except for transient increases during storm events. Most depression-in-slope-setting and in-stream depression wetlands in this study have both a control structure and a perennial water supply, conditions that explain the very small variability of water levels in these types of wetland (e.g., Figure 2b, Figure 4). Other wetlands, from a variety of HGM classes, had water-level control structures but not a perennial water supply, resulting in a third type of water-level dynamics. In those systems, water levels were stable most of the time (sometimes year-round), but when water inputs stopped, the wetlands were subject to rapid, sometimes severe, decreases in water level (lowest traces in Figure 2c). The observations suggest the desirability of considering water inflows along with wetland structure and setting for characterizing and predicting water-level dynamics, especially for project design.

Overall, our work provides a test of, and important support for, HGM classification as a tool for characterizing wetlands in a geographic region in which HGM has not been previously applied. Using regional HGM classes, we were able to identify subsets of wetlands with significant differences in hydrology in more detail than was possible using other attributes such as presence of a water-retention structure. In addition, like Cole et al. (1997), we found hydrologic conditions to be generally consistent among wetlands within individual HGM classes. Our results, if confirmed by additional research in other wetland types and geographic areas, suggest the potential to use HGM classification to generalize results from a relatively small sample of wetlands to the larger population of wetlands within a landscape.

Our results build on those of Gwin et al. (1999) by documenting consequences of wetland management decisions, especially those related to mitigation, on hydrologic attributes of wetlands at the landscape scale. Gwin et al. (1999) developed landscape profiles (*sensu* Bedford 1996) showing that mitigation, through modification of wetland structure, has resulted in significant changes in the relative abundance of wetlands in different HGM classes. Changes in relative abundance, in combination with differences in the hydrology of the wetlands, are resulting in a broad shift in water regimes at the landscape scale. In the Portland area, a landscape historically dominated by seasonally-inundated wetlands with shallow standing water is being converted into one with an abundance of perennially-flooded wetlands, often with deep standing water and near-static water levels. If one additionally considers that recent wetland losses in the Portland area have been biased toward "drier-end" wetlands (Holland et al. 1995) and that most mitigation in the Portland area has involved two naturally occurring wetlands (one destroyed, a second converted as mitigation to a different HGM class by "exchange") (Gwin et al. 1999), the overall shift in wetland hydrologic regimes in the Portland landscape has been an even more severe loss of

Table 5. Likelihood of wetlands losing standing water (stage < 0 m), for different HGM classes. Acronyms for HGM classes are listed in Table 1.

HGM Class	n	Sites Losing Standing Water		Average Date of Onset	Average Duration (days)
		Number	Percent		
SL	6	6	100	June 2	119 ± 32[a]
RIV	10	8	80	June 16	97 ± 22
DEP	7	0	0	—	—
DR[b]	9	3	33	Aug. 25	46 ± 8
DSL	3	0	0	—	—
ISD	9	0	0	—	—

[a] Mean ± one standard error.

[b] n = 9 for depressions in a riverine setting for this analysis; the status of one wetland at low water was not determined.

riverine and slope wetlands than is suggested just by landscape profiles.

An important result of the shift in relative abundances of wetlands among HGM classes is a simplification of wetland resources in space and time. Simplification includes both a homogenization of wetland types and a reduction in the dynamic range of water levels in the atypical wetlands. Wetlands in the regional HGM classes have distinct morphologies and hydrologic regimes, but they are being supplanted on the landscape by wetlands in the atypical classes, almost all of which are depressional in character. Moreover, most wetlands in the atypical classes have water-retention structures designed to maintain standing water and limit temporal variability of water levels. If this trend continues, the future landscape will become dominated by depressional wetlands with perennial standing water, a morphology that was historically uncommon in the region (Guard 1995, Gwin et al. 1999). In essence, hydrologically diverse and dynamic wetland resources are being replaced by a set of morphologically similar, hydrologically static systems, a shift that may have considerable consequences for other wetland attributes and functions. This concern was expressed by Bedford (1996) and supported by references cited therein, which suggested that management decisions are changing the relative abundances of wetland types nationwide. Recent work by Cole and Brooks (1999) also supports this concern, as the authors found that wetland mitigation projects in Pennsylvania differ hydrogeomorphically from wetlands that would naturally occur in the geomorphic settings of the projects.

Inevitably, function follows form. Our results have shown that diversity in the structure and geomorphic setting of wetlands in regional HGM classes results in diversity of their extant hydrology. As a direct consequence of their design and placement in the landscape, however, wetlands in the atypical classes have simplified hydrologic regimes that do not have naturally occurring analogues. Because hydrology is a critical forcing function for other wetland attributes, changes in hydrology can be assumed to have significant effects on a variety of wetland functions. Changes in the relative abundance of wetlands in different HGM classes are leading to changes in the landscape mosaic of wetland hydrologic regimes, contributing to pressures on native flora and fauna (e.g., Ehrenfeld and Schneider 1991, 1993, Corkran and Thoms 1996, Kiesecker and Blaustein 1997), while creating new types of habitats that may exacerbate invasion of exotic species. Wetland hydrology derives from hydrodynamic and geomorphic setting, and other attributes in turn derive from hydrology (Brinson 1993). Unless wetlands are restored or created in a manner that reproduces the hydrogeomorphic characteristics of naturally occurring wetlands in a region, management activities are unlikely to maintain or replace hydrologic and other valued functions of wetlands, and restoration, as defined by the National Research Council (1992), will remain an elusive, unrealized goal.

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